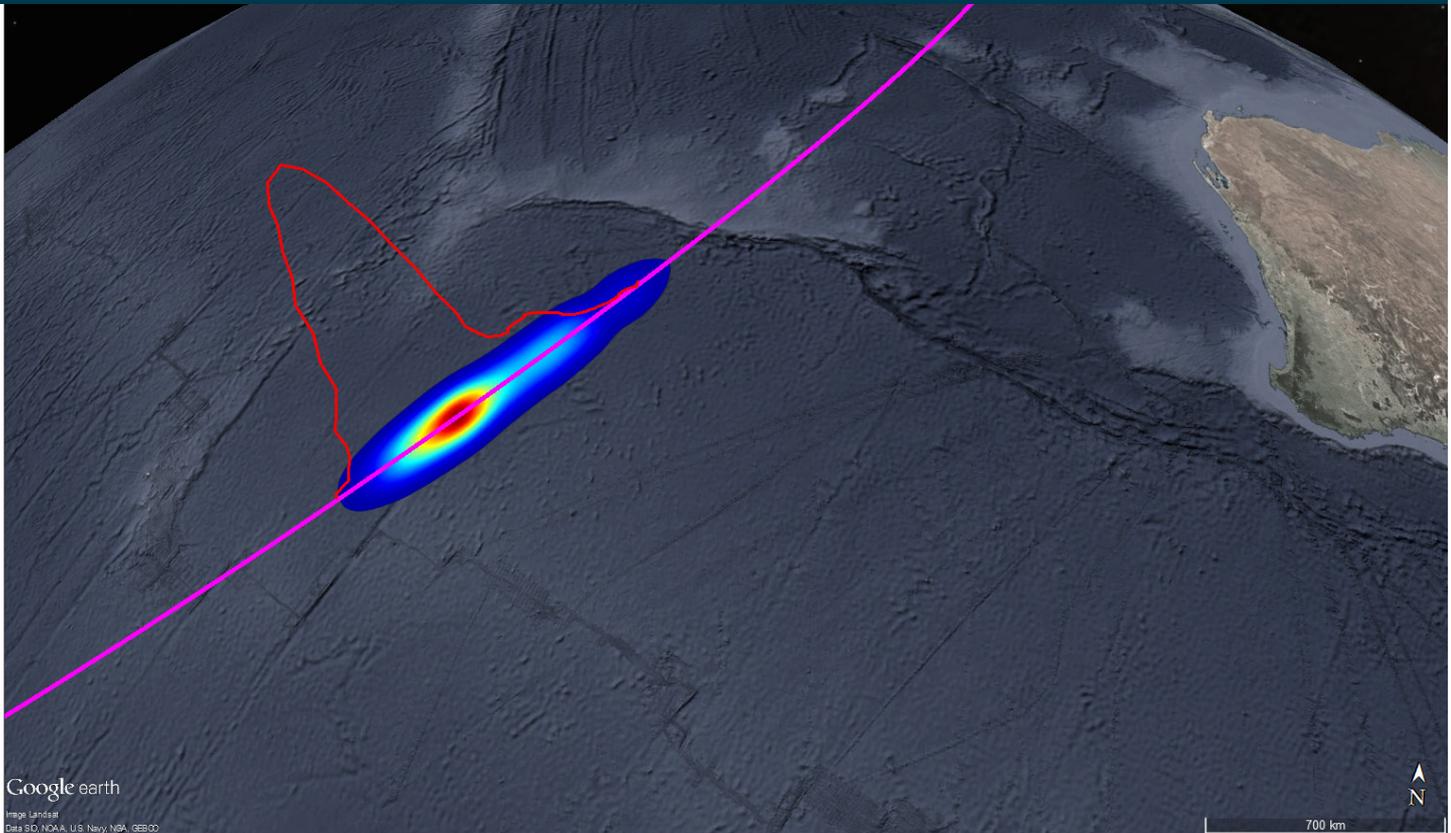




Australian Government
Australian Transport Safety Bureau

MH370 - Definition of Underwater Search Areas

3 December 2015



Investigation

ATSB Transport Safety Report
External Aviation Investigation
AE-2014-054
3 December 2015

Executive summary

This report provides an update to the MH370 search area definition, described in previous ATSB reports. For background information, please see the following ATSB publications available online at www.atsb.gov.au - *Definition of underwater search areas*, 18 August 2014 and *Flight Path Analysis Update*, 8 October 2014.

Analysis of available data has been ongoing since the search for MH370 commenced. Initial results assisted the search and rescue mission, and later refinements have formed the basis for the underwater search areas.

The Australian Defence Science and Technology (DST) Group¹ conducted a comprehensive analysis of the available data. The analysis used models of the Inmarsat satellite communications (SATCOM) data and a model of aircraft dynamics. Recorded meteorological data (wind and air temperature) were also modelled in the analysis. The SATCOM model was calibrated using SATCOM data and flight data from B777 flights including previous flights of the accident aircraft. Validation experiments were conducted to ensure that predictions aligned with actual flight data.

The output of the DST Group analysis was a probability density function (PDF) defining the probable location of the aircraft's crossing of the 6th arc. These results were then extrapolated to the 7th arc. The analysis indicated that the majority of solutions only contained one significant turn after the last recorded radar data. DST Group have written a book called 'Bayesian methods in the search for MH370' detailing the entire analysis. This book is available for download from the ATSB website.

Performance analysis by Boeing produced a series of achievable ranges, with time intervals, for different cruise altitudes. It was noted that maintaining a constant altitude of FL350 or higher gave range values that closely matched the region on the arc corresponding to the DST Group analysis results. The DST Group and Boeing results were obtained independently and it is significant that they were in general agreement.

In contrast to the series of data points that were recorded from the SATCOM system, only the following indirect information was available to assist the ATSB in determining the end-of-flight scenario and therefore determine a search area width:

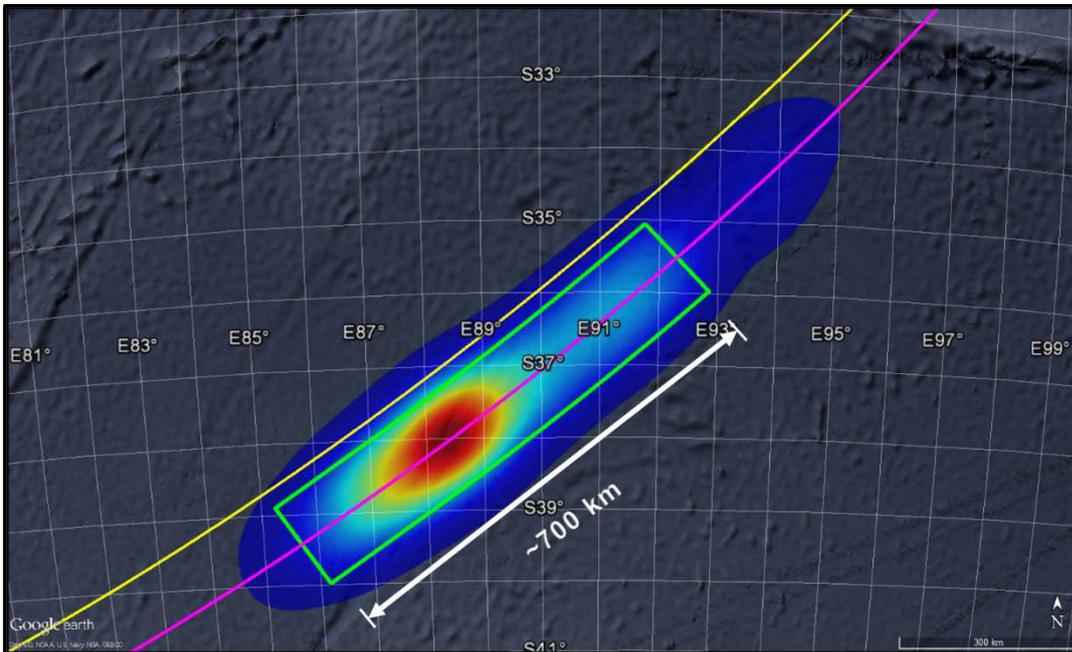
- probable aircraft systems status
- simulator results
- review of previous accidents
- glide distance.

The original ATSB underwater search area definition report published in August 2014 identified a width of 20 NM behind the arc and 30 NM forward of the arc as the priority search area width. This primary priority width has been adjusted to make it symmetrical about the arc (20 NM on both sides). The ATSB has also defined and prioritised additional search area widths.

¹ Formerly the Defence Science and Technology Organisation (DSTO).

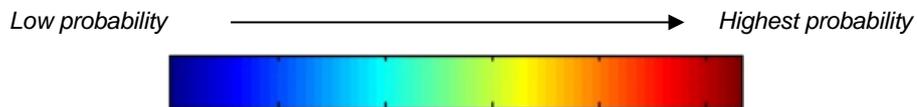
The probability distribution of the location of the aircraft is shown in Figure 1.

Figure 1: Probability distribution of the location of MH370



Source: ATSB / Google Earth

Figure 1 is a graphical representation of the results from the DST Group analysis combined with the ATSB end-of-flight scenario. The colours in the area represent the different location probabilities as follows:



The yellow and pink lines are the 6th and 7th arcs respectively. The green line outlines the main area of interest representing approximately 90% of the PDF.

Ongoing work:

- Any further evidence that becomes available, and may be relevant to refining the search area, will be considered.

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Estimated aircraft flight path

Introduction

Analysis of available data has been ongoing since the search for MH370 commenced. Initial results assisted the search and rescue mission, and later refinements have formed the basis for the underwater search areas.

The following factual data was available:

- radar information
- satellite information
- performance characteristics of the aircraft
- meteorological data.

Technical specialists from Boeing, Inmarsat, Thales and other system component manufacturers as well as the Australian Defence Science and Technology (DST) Group have assisted the ATSB throughout the analysis. Investigation agencies from the US (National Transportation Safety Board) and the UK (Air Accidents Investigation Branch) have also provided valuable assistance. These technical experts assisted the ATSB by providing estimations of the likely flight path of the aircraft.

The results of these analyses were described in the previous ATSB publications (*Definition of underwater search areas*, August 2014 and *Flight Path Analysis Update*, October 2014). These results provided, in a relatively short amount of time, enough information to begin conducting an underwater search. There was some variance in the results due to the different analytical techniques applied.

To minimise this variance, the ATSB requested further assistance from DST Group to provide additional expert data analysis. DST Group was tasked to examine the systems involved and the available data to determine the most appropriate analytical method.

The resulting methodology used by DST Group was a Bayesian statistical approach which modelled the following inputs:

- satellite communications (SATCOM) data
- aircraft dynamics
- environmental effects.

The output of the analysis was a probability density function (PDF) of the location of the aircraft.

To explain how the current priority underwater search areas were determined, a brief summary is provided below. DST Group analysts have written a book called *'Bayesian methods in the search for MH370'* describing the entire analysis in detail. This book is available for download from the ATSB website www.atsb.gov.au/mh370-pages/updates/reports.aspx.

DST Group analysis

All measurements from physical systems have some inaccuracy. Understanding this inaccuracy allows the probability distribution of any error to be characterised. The satellite communication system, subject of the analysis in the search for MH370, is one such physical system.

The primary purpose of the SATCOM system was to transmit aircraft and telephony data to and from the aircraft. In the process, the Burst Timing Offset (BTO) and Burst Frequency Offset (BFO) of the communication messages were recorded. These measurements are related to the location, direction and speed of the aircraft.

The probability distributions of the BTO and BFO were characterised by comparing the derived information with actual flight data, recorded from Boeing 777 aircraft flights.

Modern commercial aircraft are primarily controlled during flight through an autopilot system. There are various modes available to flight crew, which assist them to control the speed (airspeed or Mach number), direction (true or magnetic heading) and altitude of the aircraft. The specific settings input into the autopilot in the case of MH370 are unknown. Furthermore, it is also unknown what changes (if any) were made to those settings throughout the accident flight. Therefore, in order to account for this uncertainty, a model covering the range of possible autopilot settings available through the flight was required. This model was calibrated against flight paths of commercial aircraft.

The autopilot manages the speed of the aircraft relative to the air mass through which the aircraft is travelling. The wind speed and direction of this air mass also affect the aircraft dynamics. Therefore, wind speed, direction and air temperature need to be factored in when defining a suitable model. Once these factors are suitably accounted for in a model, a resulting ground path for the aircraft can be determined.

The environmental data mentioned above, was provided by the Australian Bureau of Meteorology (BOM). It must be recognised that this data has its own limited accuracy, and a suitable probability distribution must be applied. Again, this was completed by comparing the BOM environmental data with data recorded on commercial flights.

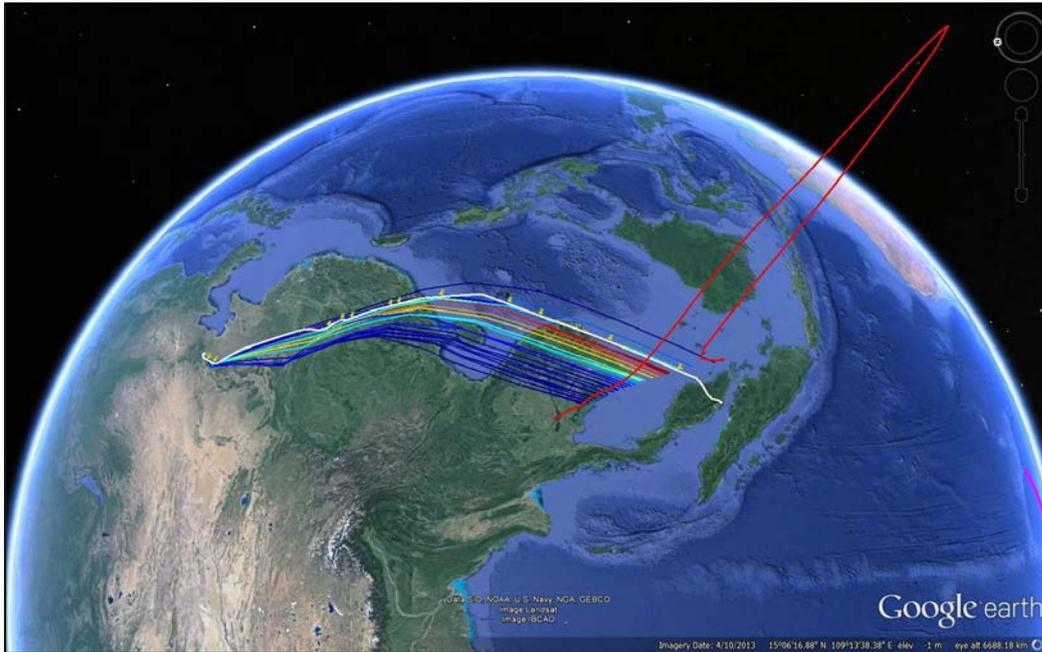
DST Group used a numerical Bayesian approach which combined the uncertainty of the flight dynamics, environmental data and BTO/BFO measurements to produce a resulting probability distribution of the MH370 flight path.

The analysis was validated using several Boeing 777 flights (including some previously recorded flights of 9M-MRO). The analysis was carried out on these flights using approximately hourly BTO/BFO measurements from the Inmarsat logs. The analysis results were compared against the recorded position from the aircraft's flights. The results of these validation experiments are outlined below. More validations and detail is provided in the DST Group publication available on the ATSB website.

Validation experiments

A total of 60 validation experiments were performed using 10 SATCOM data sets from 6 individual flights. Three of these validations are presented below. The analysis results in a probability density function (PDF) at the final measurements point. The PDF is represented by a 3-dimensional plot across the final measurement point of the analysis. The height of the graph indicates the resulting probability of the aircraft crossing that point.

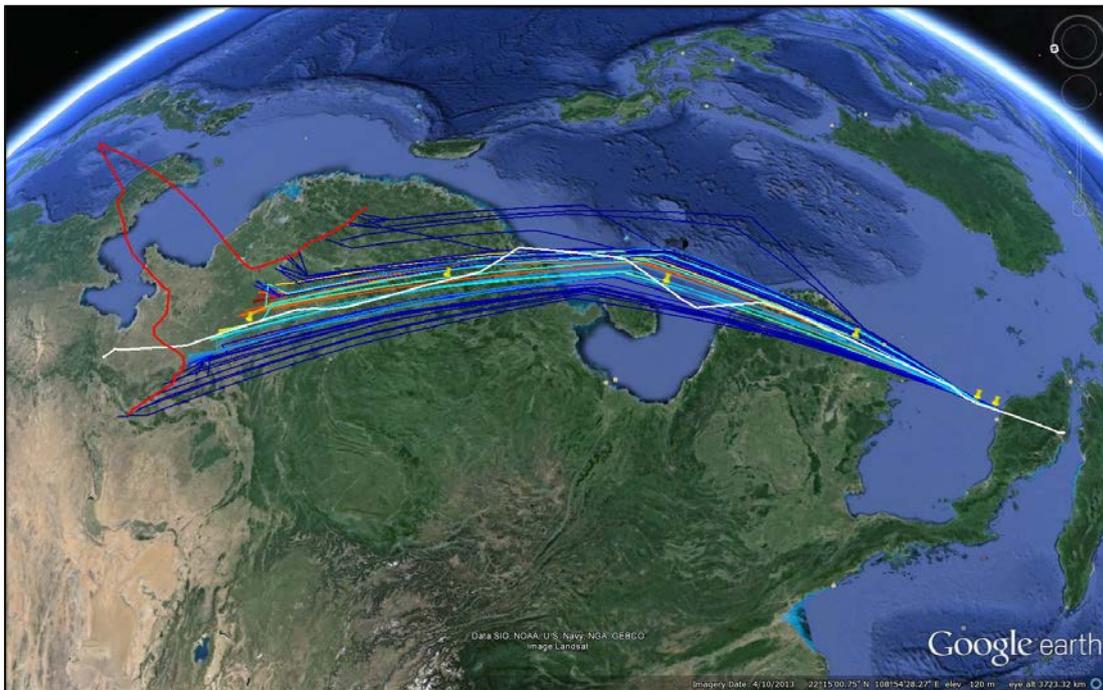
Figure 2: Analysis results for route flown by the accident aircraft on 7 March 2014 from Beijing to Kuala Lumpur.



Source: DST Group

Figure 2 – Pictured are the solution tracks in the colour representing their probability. The analysis results (PDF) is shown in red. The height of the PDF represents the resulting probability of the aircraft crossing that point. The white line indicates actual aircraft path.

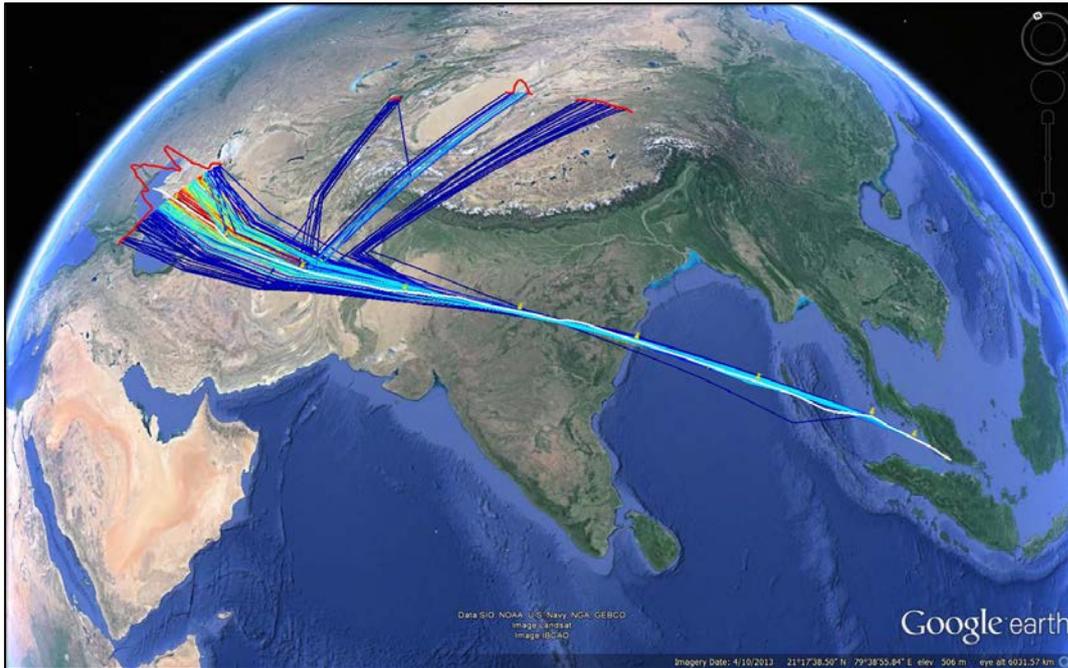
Figure 3: Analysis results for route flown by the accident aircraft on 6 March 2014 from Kuala Lumpur to Beijing.



Source: DST Group

Figure 3 – Pictured are the solution tracks in the colour representing their probability. The analysis results (PDF) is shown in red. The height of the PDF represents the resulting probability of the aircraft crossing that point. The white line indicates actual aircraft path.

Figure 4: Filter estimate for route flown by the accident aircraft on 26 February 2014 from Kuala Lumpur to Amsterdam.



Source: DST Group

Figure 4 – Pictured are the solution tracks in the colour representing their probability. The analysis results (PDF) is shown in red. The height of the PDF represents the resulting probability of the aircraft crossing that point. The white line indicates actual aircraft path.

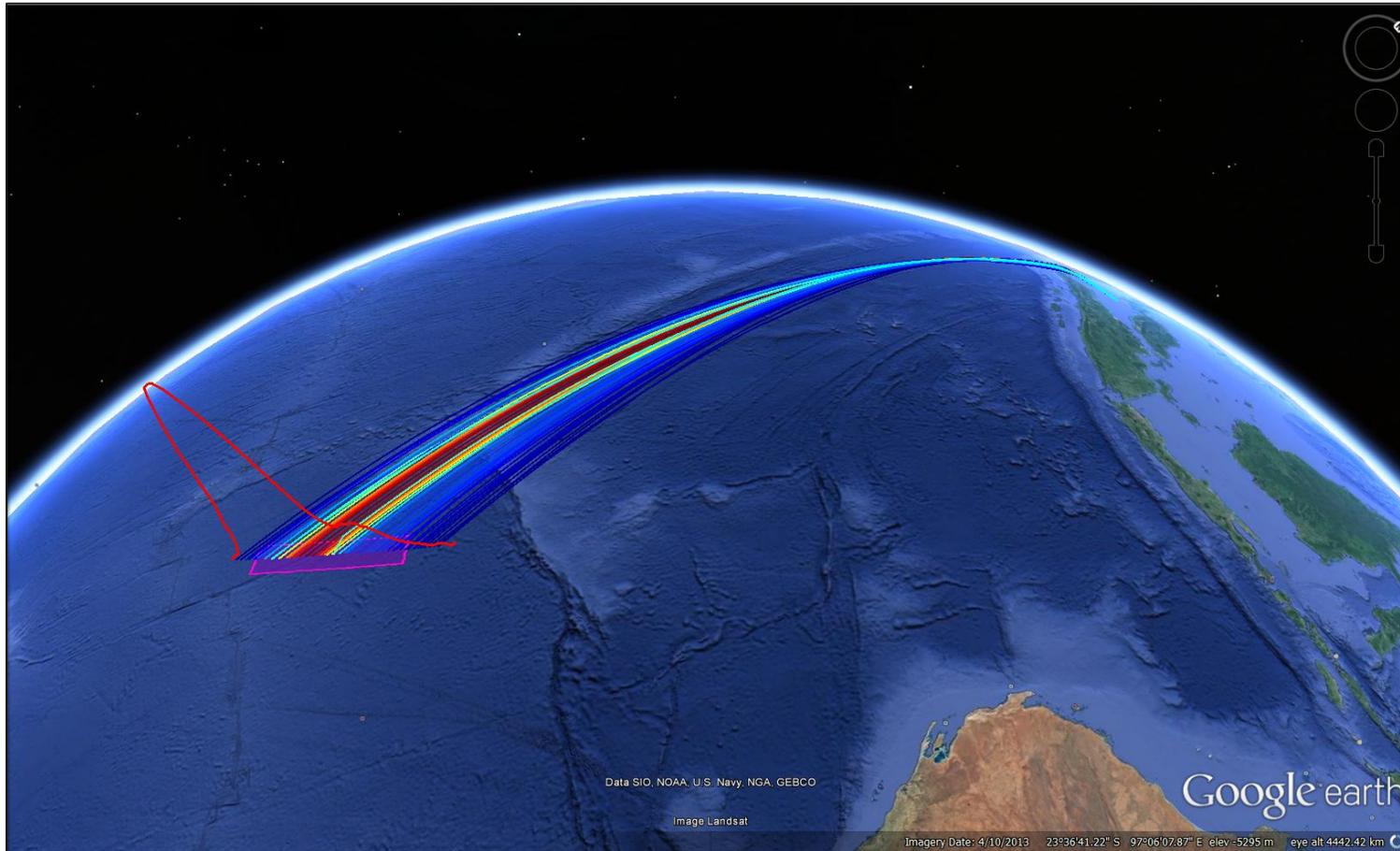
Summary – validation experiments

The complete set of validation experiments performed by DST Group showed that the analytical method was able to produce a PDF that encompassed the actual path of the aircraft. In all cases the path was within the top 85% region of the PDF. Due to the limited number of independent validation experiments the search will focus on at least the 90% limits of the PDF.

Analysis results for MH370

Applying the analysis to the data from MH370 yielded the solution paths and corresponding PDF illustrated in Figure 5.

Figure 5: Analysis results for MH370



Source: DST Group

Figure 5 – Pictured are the solution tracks and the resulting PDF, on the 7th arc, from the DST Group analysis of MH370. The solution tracks are shown in the colour which represents their probability. Red is high probability, blue is low probability. An indicative search area covering approximately the top 90% of solutions is shown in pink.

Other information available from the filter output

The analysis provided a large number of solution flight paths that can be considered to be samples from the probability distribution of all possible flight paths. Information about the likely behaviour of the flight can therefore be deduced from a statistical analysis of these paths. Specifically, the values and changes in the speed, track and altitude. The analysis was able to show that it was most likely that there was only one significant turn and that this turn took place in the earlier stages of the section of flight analysed.

Summary – DST Group analysis

The Australian Defence Science and Technology Group (DST Group) conducted a comprehensive, validated non-linear Bayesian time series analysis that modelled aircraft paths using similar data to that available for MH370. The output of this analysis defined the relative probability of the location of the aircraft at the SATCOM measurement times.

The validation experiment results indicated that a section along the arc defined by the top 90% of the probable solutions should contain the actual flight path.

Using the resulting probability density function, in conjunction with the end of flight information described below, will define the probable location of the aircraft and therefore assist to define the underwater search areas.

The analysis also provided some statistical information on the solution paths. This information indicated that the vast majority of solutions only contained one significant turn after the last recorded radar data.

End-of-flight

In order to define a reasonably sized search area it is important to gain an understanding of the aircraft system status at the end of the flight. Specifically, the events surrounding the final SATCOM transmission from the aircraft at 00:19:29 (log-on request), and the possible variations in aircraft behaviour and trajectory.

Background Information

Auxiliary Power Unit (APU) fuel inlet

The APU fuel inlet is located in the left main tank. The APU is estimated to consume (when electrically-loaded) approximately 2 lb of fuel in 55 seconds. In a standard flight attitude (1° pitch), the difference in location between the left engine fuel inlet and the APU fuel inlet would result in approximately 30 lb of fuel being available to the APU after a left engine fuel exhaustion. From this information, the APU had a *maximum* operating time of approximately 13 minutes and 45 seconds. The pitch attitude would have an effect on the usable fuel for the APU; an aircraft not under control may exhibit dynamic changes in pitch attitude (i.e. phugoid² motion) which could have limited the APU's ability to receive fuel. In-flight acceleration forces could also affect the distribution of fuel in the tanks.

When power is lost from both the left and right AC transfer buses, the APU will automatically attempt to start (auto-start), taking approximately 60 seconds for the electrical generator to come on-line.

Aircraft electrical system

The electrical system on the B777 supplies 115 V AC, 26 V AC and 28 V DC power. The main power sources are a left integrated drive generator (IDG) and a right IDG, driven by the left and right engines respectively. An APU can supply electrical power if either or both of the IDGs are unavailable. The Satellite Data Unit (SDU) was powered by 115 V AC from the left AC bus³ which was normally supplied by the left IDG. If power from the left IDG was lost then a bus tie breaker would close connecting the left and right AC buses allowing the right IDG to power both. Similarly, if power was lost from the right AC bus then the left AC bus would supply power to both. This power switching is brief and the SDU was designed to remain operational during such power interruptions. To experience a power interruption long enough to generate a log-on request, a loss of both AC buses, or a disabling of the automatic switching would be required.

Engine Flame-outs

At 00:19 UTC, the aircraft had been airborne for 7 hours and 38 minutes⁴ and fuel exhaustion was probable. When the usable fuel in a tank is depleted, the corresponding engine would 'flame-out', spool-down and the electrical generator it was driving would drop off-line and no longer provide electrical power to its associated AC bus. Previous accident investigations show that when fuel exhaustion has occurred, typically one engine will flame-out before the other.

In the case of MH370, due to the individual engine efficiency, it is likely that the right engine flamed-out first followed by the left engine. Given the amount of fuel uplifted in KL and historic fuel burn data for each engine, it is estimated that the left engine could have continued to run for up to 15 minutes after the right engine flamed-out.

² A phugoid is a dynamic flight mode where the aircraft makes a sequence of oscillations in altitude. The general principle is that as speed increases, lift increases causing the aircraft to pitch up and climb. The climb then slows the aircraft reducing the lift and causing the aircraft to pitch down. This sequence can then be repeated.

³ 'Bus' is a term for the electrical distribution of power to various equipment. In an aircraft, there are multiple busses some of which can be tied together for redundancy.

⁴ A typical flight time from Kuala Lumpur to Beijing was 5 ½ hours.

Response of aircraft systems to engine flame-outs

Following the loss of power on both the left and right AC buses:

- the autopilot and auto-throttle would disconnect
- the ram air turbine⁵ (RAT) would deploy and provide emergency hydraulic and electrical power. Emergency electrical power was also available from batteries
- half of the 6 cockpit display units would be lost, with the Captain’s PFD, Captain’s ND and the upper EICAS display remaining powered
- the APU would attempt to auto-start.

Power interruption to the Satellite Data Unit (SDU)

The SDU receives power from the left AC bus. In the aircraft’s normal configuration, this is powered by the left engine generators. If the left engine flames-out, then AC power will be supplied by the right engine through a bus tie. The SDU was designed to remain operational during the short power interruption that occurs during this switching process.

An interruption to the SDU may be caused by:

- loss of AC power requiring an APU auto-start or
- the cycling of the left generator and backup generator switches with the bus tie isolated (all switches are located on the overhead panel in the cockpit), or
- the circuit breakers in the electronic and equipment bay being pulled and then later reset or
- intermittent technical failures.

Final SATCOM transmissions from the aircraft at 0019 UTC

Understanding the final transmission sequence is also important in determining the end of flight scenario. The final communications were similar to the SDU log-on at 18:25. The satellite data working group found that the most probable reason for these transmissions was a loss of power and subsequent restoration of power to the SDU, triggering the log-on request.

The circumstances surrounding the 18:25 transmission can be summarised as follows:

Time	Event	Comment
17:07:48	ACARS message from aircraft.	Power loss occurred at some time between these times.
18:03:41	GES initiated transmission without response.	
18:24:27	Approximate time of SDU power restoration.	SDU required approximately 60 seconds ⁶ to transmit a log-on request after power application.
18:25:27	SDU initiated log-on request.	SDU began log-on process to satellite system.
18:25:34	Log-on request complete.	SDU successfully logged onto satellite system.
18:27:03	In-Flight Entertainment system (IFE) sets up a ground connection via SATCOM for a SMS/email application.	89 seconds after completion of log-on request.
18:28:05	IFE sets up a ground connection via SATCOM for a built-in test equipment (BITE) application.	151 seconds after completion of log-on request.

⁵ The ram air turbine deploys into the air flowing past the aircraft which forces the turbine blades to rotate. The speed of rotation depends on the speed of the aircraft.

⁶ Previous advice, included in previous ATSB reports, identified this time as 2 minutes and 40 seconds. Further testing conducted by the manufacturer of the SDU has shown that approximately 60 seconds is the correct time.

The circumstances surrounding the 00:19 transmission are summarised below:

Time	Event	Comment
00:11:00	Transmission from SDU to GES.	Hourly ping as previously described.
00:17:30	Approximate APU start time.	APU requires approximately 60 seconds to provide electrical power.
00:18:30	Approximate time of SDU power restoration.	SDU required approximately 60 seconds after power application to begin transmitting a log-on request.
00:19:29	SDU initiated log-on request.	SDU began log-on process to satellite system.
00:19:37	Log-on request complete.	SDU successfully logged onto satellite system.
00:21:06	Expected IFE set up of first ground connection.	IFE set up request did not occur.

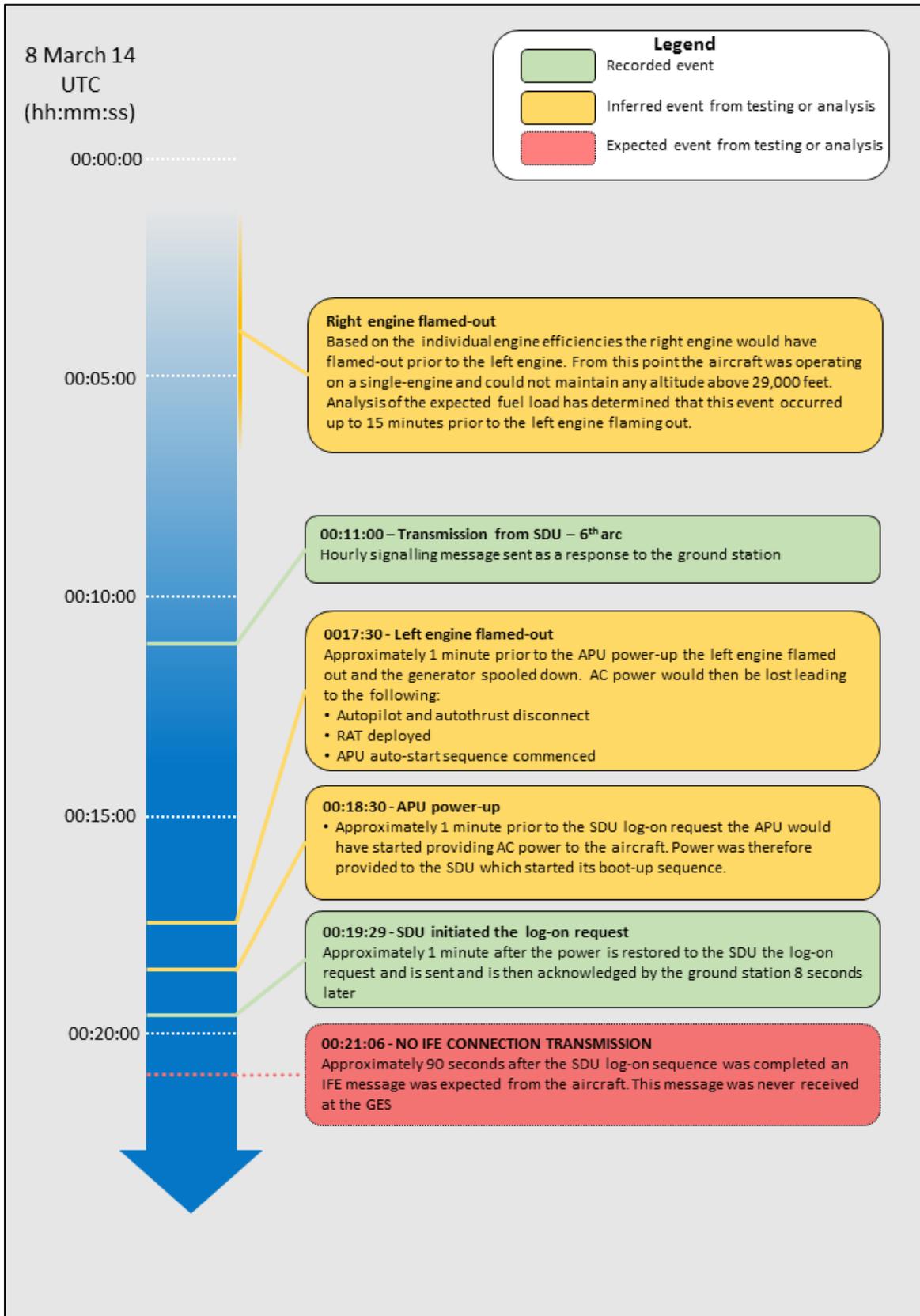
The fact that the expected IFE system transmission was not received could be due to:

- the IFE system being selected off from the cockpit overhead panel at some point after the 18:25 logon
- the IFE and/or SDU unit losing power (APU flame-out), or
- the IFE and/or SDU becoming inoperative (due to impact with the water) before the connections could be set up, or
- an unusual aircraft attitude breaking the line-of-sight to the satellite (aircraft transmission not received by satellite).

Summary – End of flight scenario

A small amount of fuel (30 lbs) is available to the APU fuel inlet after the left engine flamed-out. Assuming small pitch attitude changes and positive acceleration forces, this fuel would be sufficient to supply the APU for the period required by the SDU to initiate a log-on request (around 2 minutes). In this configuration the sequence is shown in Figure 6.

Figure 6: End of flight sequence



Source: ATSB

Other information

Ditching considerations

A controlled ditching scenario requires engine thrust to be available to properly control the direction and vertical speed at touchdown and to provide hydraulic power for the flight controls including the flaps.

The final SATCOM transmission was considered by the satellite working group to be due to a power interruption to the SDU. Given the performance analysis by Boeing, it is entirely reasonable to assume that engine flame-outs triggered the APU auto-start that restored power to the SDU. This evidence is therefore inconsistent with a controlled ditching scenario.

Search area width

The key information available in determining the width of the search area was the assumption of fuel exhaustion. As documented in the previous section, the behaviour of the SATCOM system at the 7th arc, and the fuel performance calculations were consistent with a fuel exhaustion scenario 120 seconds prior to the 7th arc.

The search area width therefore relates to the expected aircraft behaviour once the second engine flamed out. This behaviour is dependent on the attitude, speed and configuration of the aircraft just prior to the second engine flame-out.

The total width can be constrained to the estimated maximum glide distance from the fuel exhaustion point.

The following analyses were used to define the search area width.

BTO measurement at 7th arc

The locations derived from BTO measurements are dependent on the aircraft's altitude. The DST Group analysis included an estimate of the aircraft's altitude throughout, however this analysis stopped being applicable when the aircraft departed normal flight conditions prior to the 7th arc. Therefore, a suitable tolerance (5 NM) on the 7th arc is included in the search area width for the likely change in altitude after fuel exhaustion.

Simulator data

The aircraft behaviour after the engine flame-out(s) was tested in the Boeing engineering simulator. In each test case, the aircraft began turning to the left and remained in a banked turn. In many cases, but not all, a phugoid oscillation in pitch was observed. The final position of the aircraft was within a region defined by 10 NM forward and 10 NM left of the position where the flame-out occurred. Therefore, relative to the arc location, it was determined that 10 NM forward and 10 NM behind the arc would encompass the simulation impact area.

The fidelity of the simulations was limited as:

- the starting altitude and speed were unknown
- the exact system configurations were unknown
- the aircraft may have exceeded its design envelope when it was descending and experiencing phugoid oscillations and
- the aerodynamic model used by the simulator may not be accurate when the speed was outside the flight-tested envelope.

As a result, a further 10 NM was added to the search width on either side.

Basic turn analysis

The ATSB performed a basic trajectory analysis of an uncontrolled, but stable aircraft. The trajectories commenced from estimated flame-out locations and used starting conditions consistent with the DST Group analysis results and ATSB assumptions outlined in previous sections. The analysis included constant and increasing bank angles, but did not include variations in speed or pitch angle. There were many resulting trajectories consistent with an intersection with the 7th arc at the appropriate time. Some of these solutions ended between 20 and 40 nautical miles from the 7th arc.

The majority of the solutions from the turn analysis involved a left turn. A left turn is consistent with the simulation results. A larger proportion of the trajectories ended on the north-western side of the 7th arc.

Review of previous accidents

A large sample of previous accidents was reviewed including the results of an analysis⁷ commissioned by the French investigation authority the Bureau d'Enquêtes et d'Analyses (BEA) during the search for flight Air France 447. However there were no comparable B777 accidents available for review.

The BEA found that in the case of an upset followed by a loss of control, all the resulting impact points occurred within 20 NM from the point at which the emergency began. In the case of MH370, it is not clear where the start of the emergency was, and so while this result assists to define a width, it is appropriate to search beyond this 20 NM.

Glide area

A simulation was performed to determine the glide distance of the aircraft under active control to maintain wings-level attitude. The simulation (from FL330) resulted in the aircraft gliding for a total distance of approximately 125 NM from the point of the second engine flame-out.

In order to make this distance the aircraft would travel approximately 15 NM in the first 2 minutes of the descent (approximate time required to start the APU and initiate the log-on sequence). Therefore, from the 7th arc, the aircraft has the potential to glide around 110 NM. Due to the initial direction of travel and the wind conditions on the day, around 100 NM is a more realistic value.

Without any additional data after the 7th arc, the direction of a potential glide is unknown. If this low probability area is to be searched, further analysis will be needed to guide the direction to search.

Summary – Search area width

There is limited data available to assist the ATSB in determining the width of the search area. The data that is available was derived via simulations, systems analysis and historical data. This is in contrast to the data that was recorded from the SATCOM system.

The ATSB assessed the information presented above in determining the search area width. The simulation data was the most reliable source of information and was weighted accordingly.

The turn analysis provided some indicative paths of an aircraft entering a banked (often increasing) turn until impacting the ocean. Due to the generic nature of this analysis it was given a lower weighting.

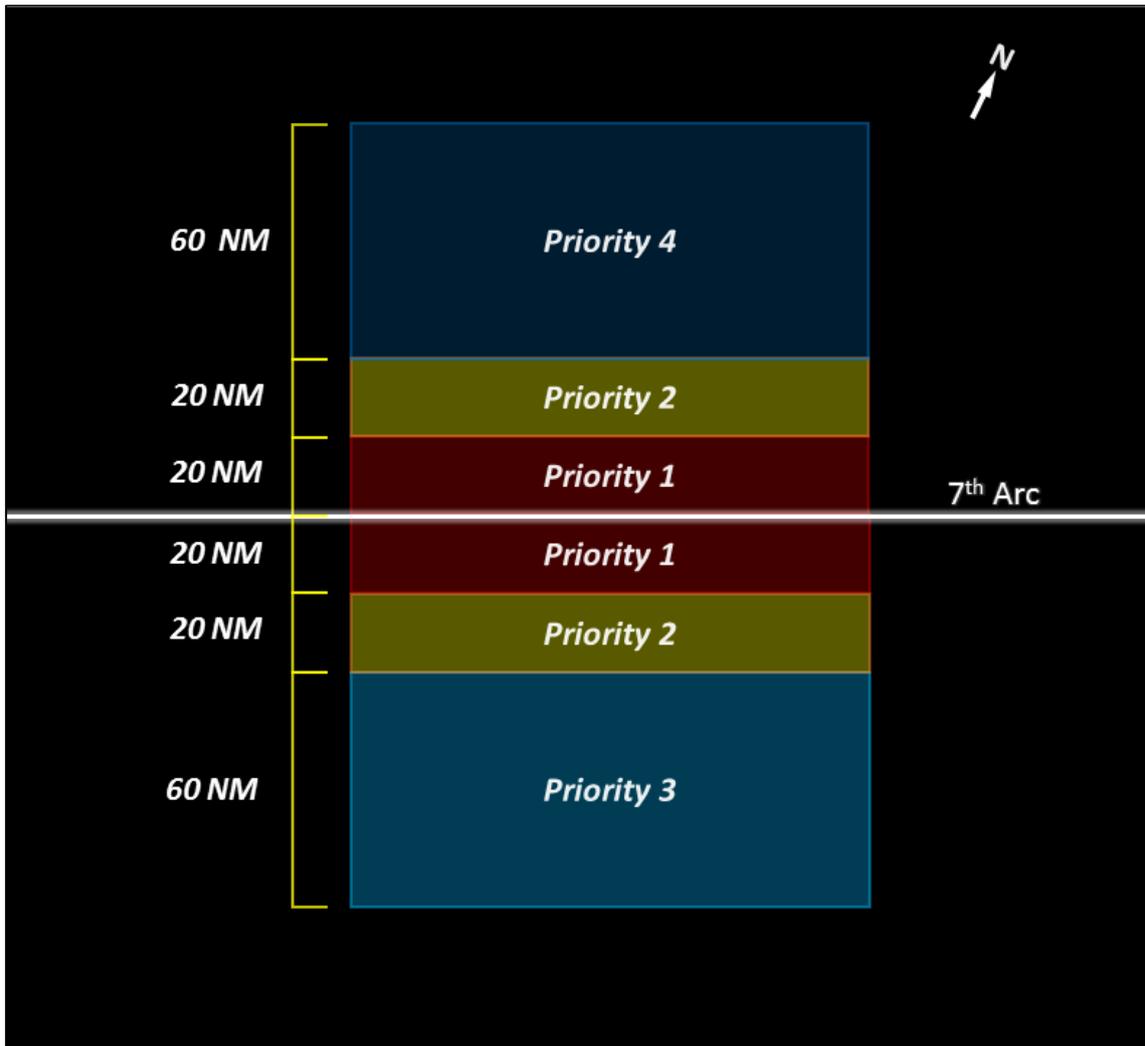
The glide path simulation was consistent with the possible glide range provided by the aircraft manufacturer, and, while this is a reliable distance, there is no evidence to suggest that the aircraft was under controlled flight. The sequence considered in the end-of-flight section above favours a no active control scenario.

The ATSB search area definition report (26 June 2014) identified a distance of 20 NM behind the arc and 30 NM forward of the arc as the highest priority search area width. As a result of further analysis, this width has been adjusted to make it symmetrical about the arc. From the information above, the ATSB has also identified two additional distances to assist in defining the ongoing search areas.

- Highest priority width – a ± 20 NM width from the 7th arc derived from the simulations conducted, the review of previous accidents and the tolerance on the 7th arc.
- Secondary priority width – an additional ± 20 NM determined from the possible uncertainty in the simulation results and the trajectories from the turn analysis.
- Low priority width – a further ± 60 NM encompasses the possible but less probable controlled glide scenario.

⁷ Metron Scientific Solutions Report: *Search Analysis for the Location of the AF447 Underwater Wreckage* 20 January 2011.

Figure 7: Search area width priorities



Source: ATSB

Figure 7 – The identified priorities for searching relative to the 7th arc are shown in this figure. These can be interpreted as the probabilities of finding the aircraft in these locations based on the current assumptions about the end-of-flight scenario. Note that due to assumptions made by the analysis, Priority areas 3 and 4 are significantly lower probability as they rely entirely on a controlled glide flight scenario.

Aircraft performance analysis

Cost index

The cost index is the ratio of the time-related cost of an aircraft operation and the cost of fuel. The value of the cost index reflects the relative effects of fuel cost on overall trip cost as compared to time-related direct operating costs. For a B777 the cost index ranges from 0 – 9,999.

The flight crew enters the company specified cost index into the control display unit of the Flight Management Computer (FMC). The FMC then uses this number and other performance parameters to calculate economy (ECON) climb, cruise, and descent speeds. Entering zero for the cost index results in maximum range airspeed and minimum trip fuel. This speed schedule ignores the cost of time.

The flight-planned cost index for MH370 was ECON 52. This cost index places a higher value on fuel costs relative to time-related costs and is within the typical range for airline operations.

Typical cruise operations

The following two extracts from the B777 Flight Crew Training Manual provides background information on cruise altitude and cruise speed considerations:

- “Flight plans not constrained by short trip distance are typically based on conducting the cruise portion of the flight close to optimum altitude. Since the optimum altitude increases as fuel is consumed during the flight, it is necessary to climb to a higher cruise altitude periodically to achieve the flight plan fuel burn.”
- “Cruise speed is automatically computed by the FMC and displayed on the CRZ and PROGRESS pages. It is also displayed by the command air speed when VNAV is engaged. The default cruise speed mode is economy (ECON) cruise. The pilot can also select long range cruise (LRC), engine out modes, or overwrite fixed Mach or CAS values on the CRZ page target speed line. ECON cruise is a variable speed schedule that is a function of gross weight, cruise altitude, cost index, and headwind component. It is calculated to provide minimum operating cost for the entered cost index. Entry of zero for cost index results in maximum range cruise. Note: Thrust limits or maximum speed limits are generally encountered with cost index entries of 5000 or more. Headwinds increase the ECON CRZ speed. Tailwinds decrease ECON CRZ speed, but not below the zero wind maximum range cruise airspeed. LRC is a variable speed schedule providing fuel mileage 1% less than the maximum available. The FMC does not apply wind corrections to LRC.”

Range limit

Boeing provided a southerly range limit for the aircraft using the following assumptions:

- realistic speeds and altitudes were used throughout the radar section of the flight to give a conservative fuel load at the final radar location at 18:22
- the turn south was modelled at 18:28 – this is the earliest that the turn could be achieved based on the analysis of the satellite data and also provides the maximum southerly range
- constant altitude from 18:28 to the end of the flight
- arc crossing times and locations must be met
- historic engine efficiency values were used
- wind was modelled throughout the flight
- maximum range cruise (MRC) cost index (0) was used.

Speed/altitude considerations

Boeing analysed the aircraft performance for various scenarios ranging from MRC to maximum cruise thrust limit (MCRT). The starting time for the analysis was at 18:28 and the end time was the flame-out at 00:17 (i.e. 2 minutes prior to the 7th arc). This gave a time interval of 5.8 hours.

The Boeing analysis gave a series of ranges and time intervals for different cruise altitudes. It was noted that a constant altitude of FL350 or higher gave sufficient range to reach the region on the arc corresponding to the DST Group analysis. Applying the assumption that a series of step-climbs⁸ had been performed during cruise, produced a range greater than that required to reach the region of interest on the arc.

When considering the scenario where the FMC maintained speed in accordance with the flight-plan cost index of 52 and the aircraft maintained a constant altitude, the initial speed would have been approximately Mach 0.83 decreasing to below Mach 0.80 as the aircraft gross weight decreased due to fuel burn. The range resulting from this scenario was consistent with the required range and the known time interval.

Summary

The performance calculations gave a maximum range that was consistent with the DST Group PDF. These two sets of results were obtained independently and it is significant that they were in general agreement.

⁸ Step-climbs require changes to the auto-flight system at the time the climb is initiated.

Drift analysis

On July 29 2015, a flaperon was recovered from Reunion Island. This flaperon was later confirmed as being from 9M-MRO.

Figure 8: Flaperon recovered from Reunion Island on 29 July 2015



Source: Bureau d'Enquetes et d'Analyses (BEA)

Figure 8 – The flaperon recovered was a part of the flight control system from MH370. Barnacles are visible on the debris from the months of floating in the ocean. The location of the recovered debris is consistent with drift modelling predictions of objects starting in the areas identified as possibly containing MH370.

In order to understand any possible implications of this discovery on the search area, the ATSB engaged CSIRO⁹ drift modelling experts to provide advice.

Data analysts from DST Group worked with the CSIRO to use data from the Global Drifter Program¹⁰ drifting buoys (drifters) to conduct two types of analysis:

1. Drifters known to have arrived in the vicinity of Reunion Island were tracked backwards in time (approximately 500 days) in order to generate a probability distribution of likely source points.
2. For three separate debris start zones on the 7th arc (south of the search area, the search area, north of the search area) a probability distribution of forward drift locations, approximately 500 days later, was produced.

Both analyses indicate a slightly lower likelihood for the southern section of the area identified by the DST Group analysis of the satellite communications data. However these results made no meaningful changes to the ATSB search area due to the relative weighting of the significance of the drift analysis in comparison with the analysis based on the satellite data. While this debris find is consistent with the current search area it does not provide sufficient information to refine it. If additional debris is identified it will be included in the analysis to provide further information on the location of source areas.

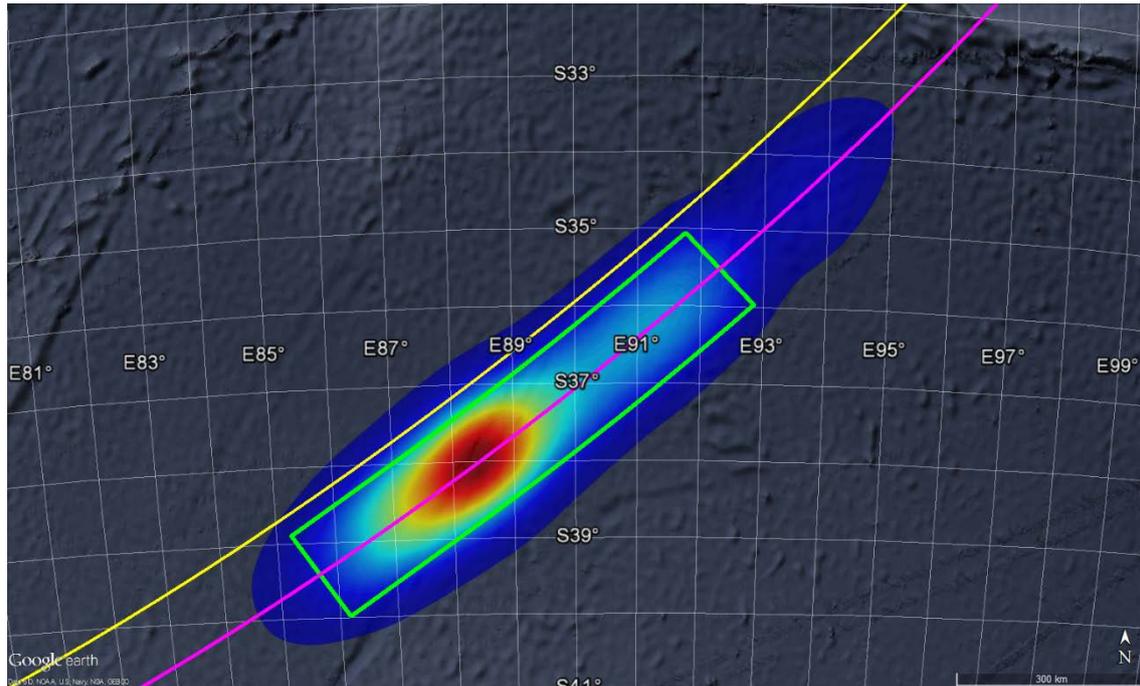
⁹ Commonwealth Scientific and Industrial Research Organisation.

¹⁰ www.marine.csiro.au/~griffin/MH370/

Probability distribution of the location of the aircraft

The results of the DST Group analysis, in conjunction with the priority widths from Figure 7, were used to produce a distribution in two dimensions of the likely aircraft location Figure 9. The colours in Figure 9 represent different probabilities, dark blue is the lowest probability and dark red indicates the highest probability.

Figure 9: Probability of the location of MH370



Source: ATSB / Google Earth

Figure 9 is a graphical representation of the results of the DST Group analysis with the ATSB end-of-flight scenario. The colours in the area represent the different location probabilities as follows:

Low probability Highest probability



The yellow and pink lines are the 6th and 7th arcs respectively. The green line outlines the main area of interest representing approximately 90% of the PDF.

Using the results from the validation experiments, a 90% region of probability will be used to define the search areas. This area is approximated by the green line in Figure 9.

Appendix A - Updated information from previous ATSB publications

Note: This Appendix provides updates to topics already defined in previous ATSB reports. For the background information please see the ATSB *Definition of Underwater Search Areas*, 18 August 2014 and *Flight Path Analysis Update*, 8 October 2014.

Update to the satellite communications model

SATCOM recorded data

Figure 10: Key recorded satellite communications data from flight MH370

Time (UTC)	SU Type	Channel	BFO (Hz)	BTO (µs)	Note
16:42:32	0×62 - Acknowledge User Data (R-channel)	IOR-R1200-0-36ED	125	14900	
16:55:53	0×22 - Access Request (R/T-Channel)	IOR-R1200-0-36ED	159	15240	
17:07:19	0×22 - Access Request (R/T-Channel)	IOR-R1200-0-36ED	132	15660	
18:25:27	0×10 - Log-on Request (ISU)/Log-on Flight Information (SSU)	IOR-R600-0-36E1	142	12520	(1)
18:39:58	0×60 - Telephony Acknowledge	IOR-373E-21000	88	–	(2)
19:41:03	0×15 - Log-on/Log-off Acknowledge	IOR-R1200-0-36ED	111	11500	
20:41:05	0×15 - Log-on/Log-off Acknowledge	IOR-R1200-0-36ED	141	11740	
21:41:27	0×15 - Log-on/Log-off Acknowledge	IOR-R1200-0-36ED	168	12780	
22:41:22	0×15 - Log-on/Log-off Acknowledge	IOR-R1200-0-36ED	204	14540	
23:14:03	0×60 - Telephony Acknowledge	IOR-3737-21000	217	–	(3)
00:11:00	0×15 - Log-on/Log-off Acknowledge	IOR-R1200-0-36ED	252	18040	
00:19:29	0×10 - Log-on Request (ISU)/Log-on Flight Information (SSU)	IOR-R600-0-36F8	182	18400	(1)

(1) Modified value, determined by subtracting 4600 µs from measured
(2) Average of 51 values ranging from 86 to 90 Hz. No BTO value available for voice channels
(3) Average of 29 values ranging from 216 to 222 Hz. No BTO value available for voice channels

Source: Inmarsat

Burst timing offset (BTO)

The communications corresponding to the burst timing offsets (BTO) used to determine the location arcs were transmitted on 2 communications channels; the R1200 and the R600 channels. The R1200 log-on acknowledgement BTO measurements that occurred at 18:25:34 and 00:19:37 were initially ignored due to an anomaly in the values. Instead, the R600 BTOs at 18:25:27 and at 00:19:29 were used to create the 1st and 7th arcs.

Because the R1200 BTO measurements were assessed as having a lower standard deviation, identifying the cause of the anomaly, in order to possibly correct it, would improve the accuracy of the model.

An analysis of similar transmissions from the previous flight was conducted which identified a variable offset coefficient with a factor of approximately 7820 µs (i.e. N*7820).

The manufacturers of the SDU and the ground station equipment were unable to determine a specific reason for the offset, however they did note that the reference clock used for the time slots was 128 Hz, which equates to 7812.5 µs.

C-Channel Burst frequency offset bias (BFO)

The use of the C-Channel BFO information was key to the search as it provided the first frequency value that implied a southerly direction of travel. This relies on the C-Channel bias being similar to the R-Channel bias. Initial analysis performed on similar transmissions indicated that it was highly likely that this was the case.

Due to the importance of this information it was deemed favourable to confirm these results via a flight test. Using a sister ship to 9M-MRO, several phone calls were made to the aircraft under controlled conditions. Each call produced a large number of C-Channel measurements which were analysed. The C-Channel BFO bias was found to be equivalent to the R-Channel BFO bias.

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- Commonwealth Scientific and Industrial Research Organisation (CSIRO)
- 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 hopefully bring closure to the families of the passengers and crew of MH370.

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Investigation

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