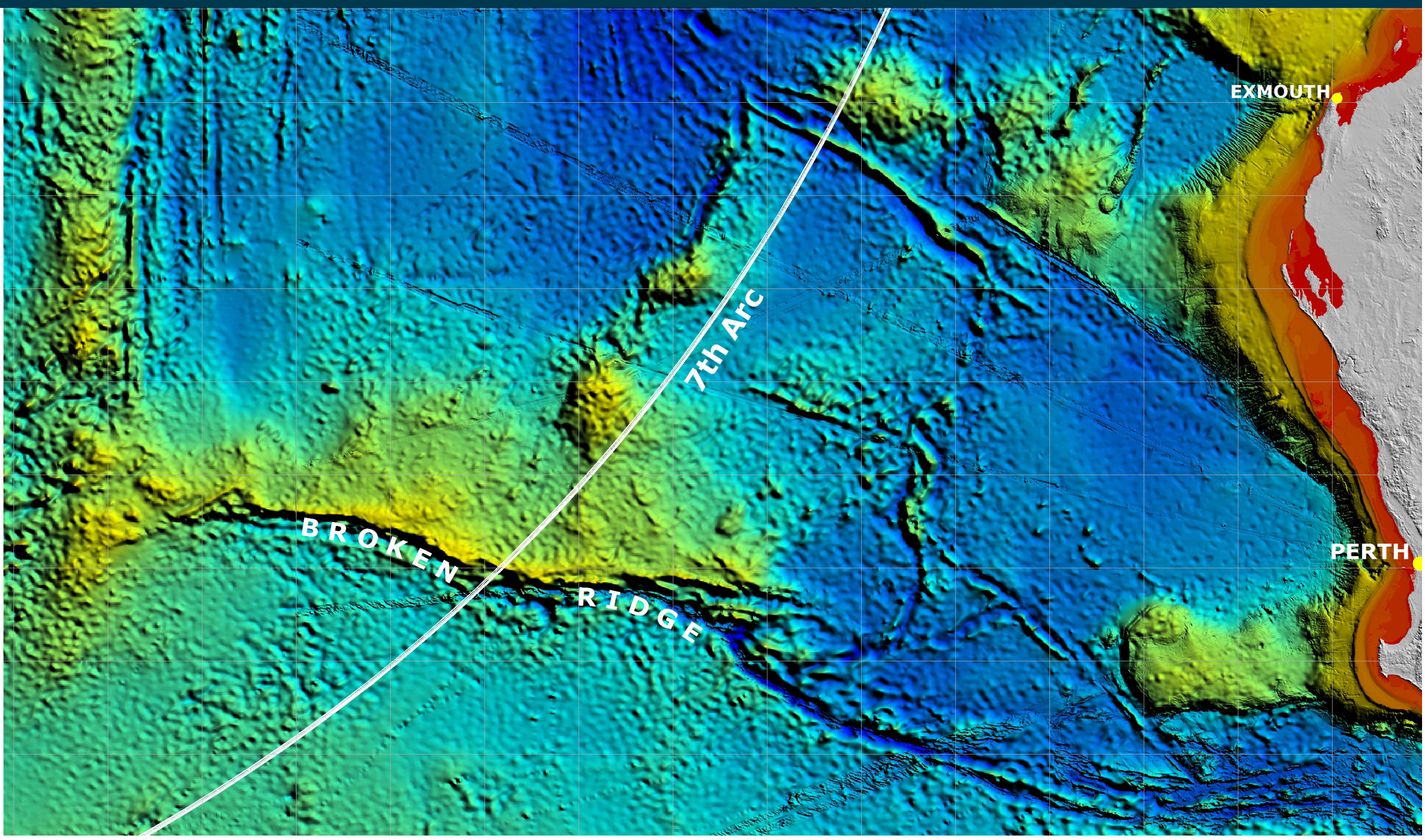
Australian Government
Australian Transport Safety Bureau

MH370 - Definition of Underwater Search Areas

26 June 2014



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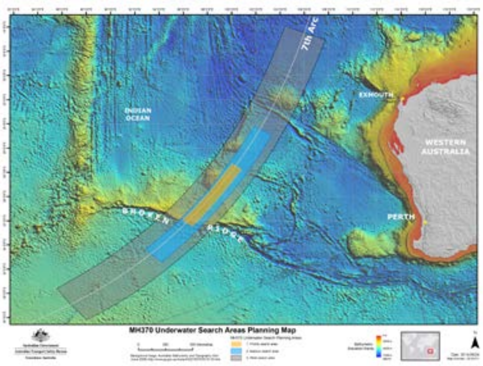
Addendum

Page	Change	Date
57	Additional explanatory material relating to the Perth GES partial compensation	13 Aug 2014
58	Table 5 and Table 6 updated – Previous parameter Uplink Doppler changed to Aircraft Doppler (uplink), notes updated for clarity. Previous parameter Downlink Doppler (Satellite movement) separated into its two components Satellite Doppler (uplink) and Satellite Doppler (downlink) for clarity	13 Aug 2014
58	Correction to Table 5 and 6 typographical errors introduced in13 Aug update	15 Aug 2014
58	Correction to Table 6 typographical errors introduced in 13 Aug update	18 Aug 2014
1	Correction to typographical error on first sentence	30 July 2015

Executive summary



On 08 March 2014, flight MH370, a Boeing 777-200ER registered 9M-MRO, lost contact with Air Traffic Control during a transition of airspace between Malaysia and Vietnam. An analysis of radar data and subsequent satellite communication (SATCOM) system signalling messages placed the aircraft in the Australian search and rescue zone on an arc in the southern part of the Indian Ocean. This arc was considered to be the location where the aircraft's fuel was exhausted.

A surface search of probable impact areas along this arc, coordinated by the Australian Maritime Safety Authority, was carried out from 18 March – 28 April 2014. This search effort was undertaken by an international fleet of aircraft and ships with the search areas over this time progressing generally from an initial southwest location along the arc in a north-easterly direction. The location of the search areas was guided by continuing and innovative analysis by a Joint Investigation Team of the flight and satellite-communications data. This analysis was supplemented by other information provided to ATSB during this period. This included possible underwater locator beacon and hydrophone acoustic detections.

No debris associated with 9M-MRO was identified either from the surface search, acoustic search or from the ocean floor search in the vicinity of the acoustic detections. The ocean floor search was completed on 28 May 2014.

Refinements to the analysis of both the flight and satellite data have been continuous since the loss of MH370. The analysis has been undertaken by an international team of specialists from the UK, US and Australia working both independently and collaboratively. Other information regarding the performance and operation of the aircraft has also been taken into consideration in the analysis.

Using current analyses, the team has been able to reach a consensus in identifying a priority underwater search area for the next phase of the search.

The priority area of approximately 60,000 km^2 extends along the arc for 650 km in a northeast direction from Broken Ridge. The width of the priority search area is 93 km. This area was the subject of the surface search from Day 21-26.

Work is continuing with refinements in the analysis of the satellite communications data. Small frequency variations can significantly affect the derived flight path. This ongoing work may result in changes to the prioritisation and locale of search activity.

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Introduction

On 7 March 2014 at 1722 UTC[1] (8 March 0122 local time Malaysia), flight MH370, a Boeing 777-200ER registered 9M-MRO, lost contact with ATC during a transition of airspace between Malaysia and Vietnam. An analysis of radar data and subsequent satellite communication (SATCOM) system signalling messages placed the aircraft in the Australian search and rescue zone in the southern part of the Indian Ocean.

On 17 March 2014, Australia took charge of the coordination of the search and rescue operation. Over the next 6 weeks from 18 March, an intensive aerial and surface search was conducted by assets from Australia, Malaysia, China, Japan, Korea, UK and the USA.

During this period, the Australian Maritime Safety Authority (AMSA) and the ATSB jointly determined a search area strategy correlating information from a Joint Investigation Team (JIT[2]) located in Malaysia and other government and academic sources.

On 28 April 2014, the aerial search concluded and the search moved to an underwater phase. More details of the search effort can be found on the Joint Agency Coordination Centre website www.jacc.gov.au.

The ATSB is responsible for defining a search area. Since May 2014, a search strategy group, coordinated by the ATSB, has been working towards defining the most probable position of the aircraft at the time of the last satellite communications at 0019. The group brought together satellite and aircraft specialists from the following organisations:

- Air Accidents Investigation Branch (UK)
- Boeing (US)
- Defence Science and Technology Organisation (Australia)
- Department of Civil Aviation (Malaysia)
- Inmarsat (UK)
- National Transportation Safety Board (US)
- Thales (UK)

The group was faced with the challenge of using data from a communications satellite system and aircraft performance data to reconstruct the flight path of MH370. This was in effect using a satellite communications system as a navigation tracking system. Two pieces of information recorded by a satellite ground station at the time of a transmission with MH370 were used to estimate the track of the aircraft. These transmissions occurred only 7 times after loss of radar contact.

This report presents the results of analysis conducted by this group and the ATSB's determination of a priority 60,000 km^2 search area.

On 4 June 2014, the ATSB released a request for tender to acquire the services of a specialist company capable of conducting a deep-water search for 9M-MRO under ATSB direction. Bathymetry of the ocean floor in areas of the search zone commenced in mid-May using an ATSB contracted vessel and a Chinese military vessel.

1 All times used in this report are referenced to Coordinated Universal Time (UTC) using the format hhmm.ss
2 The Joint Investigation Team comprised specialists from Malaysia, China, US, UK and France

Figure 1: B777 9M-MRO

Source: Seth Jaworski

Background on over-water searches

Over-water aircraft accident locations are usually found by conducting a broad-area aerial search. The search area is generally determined by a combination of:

- Position information from ground-based radar systems (maximum range is generally 250 NM)
- Position information automatically transmitted from the aircraft at regular intervals
- Position reports from the crew
- Re-tracing the flight-planned route
- Eye-witness reports (possibly located on the shore, on other aircraft or on ships)

Uncertainty in the position of an accident location increases with time from the aircraft's last known position (fix) so the search area will expand accordingly as the position data becomes 'stale'.

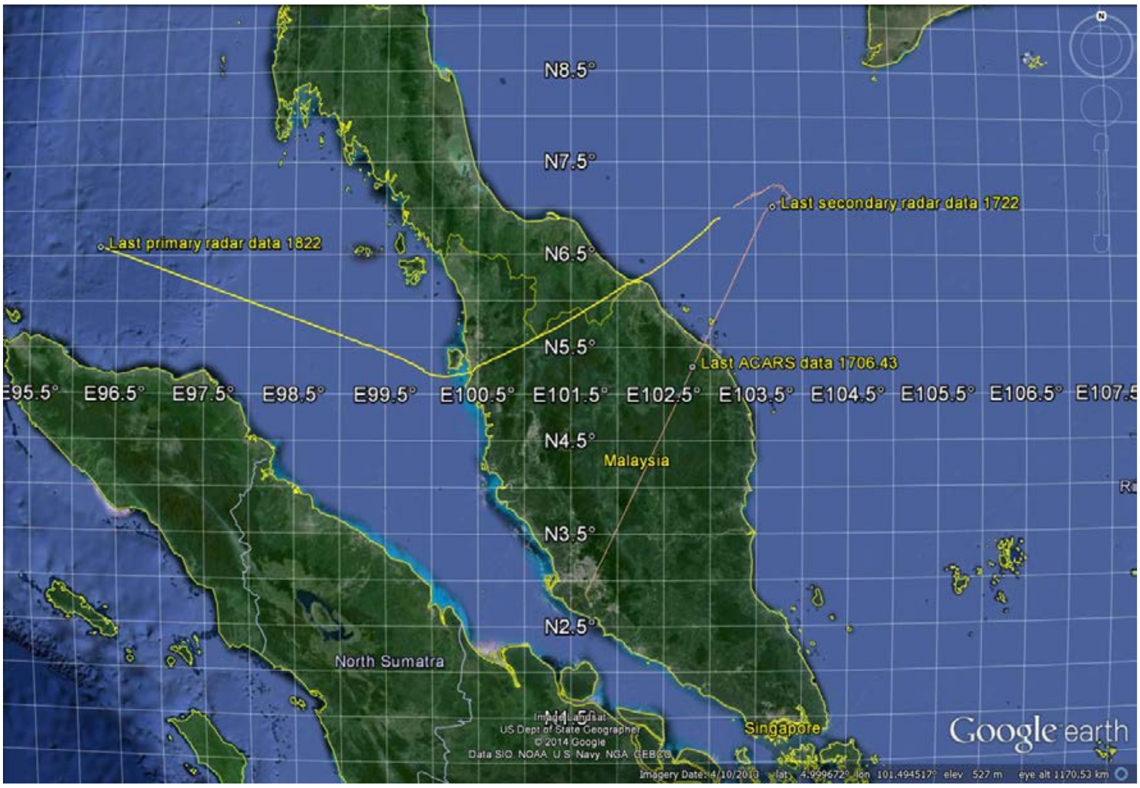
Once floating wreckage is observed, reverse-drift techniques can be used to determine the aircraft impact location. Only a small-area underwater search is then required to locate the wreckage and map the wreckage field. This underwater search can be aided by the underwater locator beacons fitted to the flight recorders. As they have a limited operational duration of nominally 30 days, and to minimise the inaccuracies of the reverse-drift calculations, it is important that an aerial search is commenced as soon as possible and the floating debris is found quickly.

In the case of MH370:

- The aircraft departed Kuala Lumpur on 7 March 2014 at 1641
- The final automatically transmitted position from the aircraft occurred at 1707
- No radio notification of a problem was received from the crew
- No radio communications were received from the crew after 1719
- The final ATC (secondary) radar fix occurred at 1722
- At 1725 the aircraft deviated from the flight-planned route

- The final primary radar fix occurred at 1822 (Figure 2)
- The satellite communications log indicated the aircraft continued to fly for another 6 hours until 8 March 0019
- No confirmed eye-witness reports were received
- No Emergency Locator Transmissions were received
- The search in the Australian search and rescue zone commenced on 18 March (10 days after the aircraft went missing)

Figure 2: MH370 flight path derived from primary and secondary radar data



Source: JIT/Google Earth

These factors have meant that the search area for MH370 has remained very large.

A comparison with the search for Air France flight 447, which crashed in the Atlantic Ocean on 1 June 2009, is useful. The search for the aircraft began on 1 June 2009 and the first wreckage was discovered on 6 June 2009, 5 days after the accident.

Air France 447 (AF447) accident search area definition[3]

The ACARS system, is used to transmit non-voice messages between an aircraft and the ground by VHF radio or satellite communication. The AF447 aircraft was programmed to automatically transmit its position approximately every 10 minutes.

On 1 June 2009, the last position report occurred at 0210 and 24 maintenance messages were received between 0210 and 0215. These messages were all transmitted via the same satellite (Atlantic Ocean West, operated by the Inmarsat Company) and SITA's ACARS network.

The maximum distance the aircraft could have feasibly travelled was computed from the time of its last reported position to the time when a scheduled response from the ACARS system was not received. The impact time was estimated based on the time of the last ACARS message received

[3] BEA Report 18 March 2011: Triggered Transmission of Flight Data Working Group, page 27.

and the expectation (unfulfilled) of a subsequent message in the next 60 seconds. This analysis indicated that the end of the flight occurred between 0214.26 and 0215.14, which makes a flight time since the last reported position of about 5 minutes. Considering a maximum ground speed of 480 kt (or 8 NM/min), this makes a search area in the shape of a circle of radius 40 NM centred at the last known position. This area extended over more than 17,000 km² and was situated more than 500 NM from any coastline. After a search effort involving five separate phases, the aircraft wreckage was located on 3 April 2011.

MH370 search area definition

As none of the conventional sources of data was able to be used to locate the aircraft wreckage from MH370, novel sources of data and analysis techniques were required. This has led to a larger than typical search area and changes in its location as refinements occur to the analysis after validation and calibration checks have been performed.

Surface search for MH370

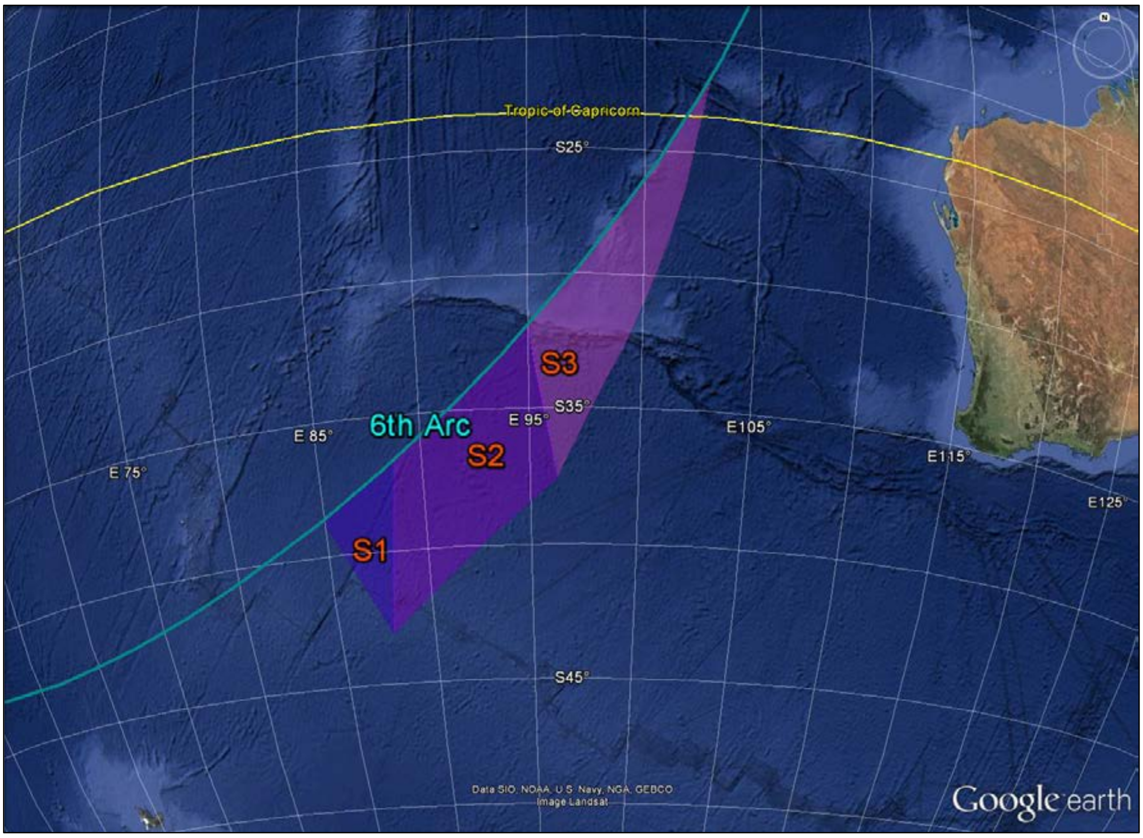
On 17 March 2014 (Day 10[4]), Australia assumed responsibility for coordinating the search and rescue effort in the southern Indian Ocean. AMSA as Australia's search and rescue authority was responsible for this activity. More details of the surface search effort can be found on the AMSA website www.amsa.gov.au/media/mh370-timeline.

Possible impact areas

On 17 March 2014 (D10) the initial search area was determined by a Joint Investigation Team (JIT)[5] to be a 600,000 km^2 area approximately 2,500 km from Perth, WA. The initial search area was determined following analysis of satellite communications data to and from MH370 during the accident flight that was recorded at a ground station in Perth, WA. The data indicated the aircraft flew an additional 6 hours after the last radar contact with a track south to the Indian Ocean. The area was determined using only limited radar, satellite and performance data and assumed a southern turn of MH370 at the north-west tip of Sumatra, Indonesia.

Areas in the Southern Indian Ocean designated S1 –S3[6] were defined from the aircraft's predicted performance and endurance (Figure 3). Two speeds resulted in the longest, straightest tracks to the 6th arc[7] and were used to define possible impact locations within areas S1 and S2.

Figure 3: Possible southern final positions S1-S3 based on MH370 max range and time



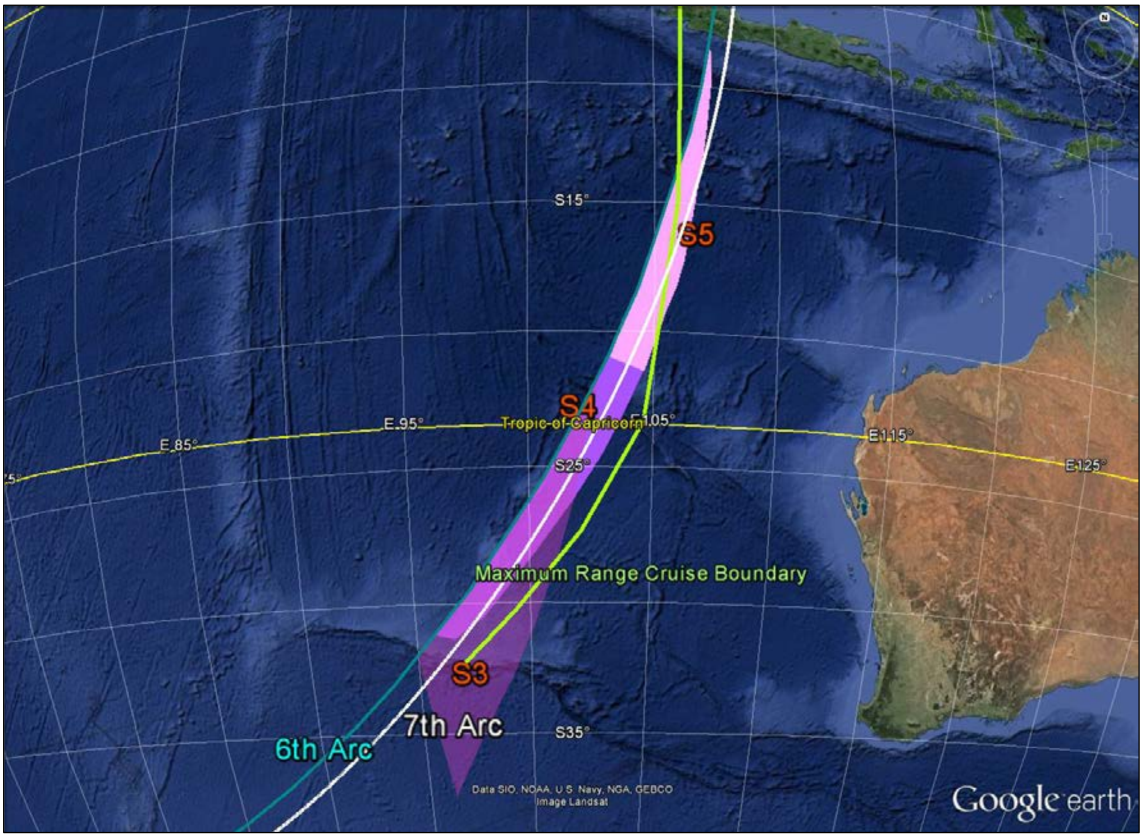
Source: JIT/Google Earth

4 8 March 2014 is considered to be Day1 (D1), the date In Malaysia when MH370 departed Kuala Lumpur, Malaysia.
5 US and UK investigation agencies and their technical advisers with representatives from Malaysia, China and France.
6 JIT designation of areas – Note Malaysian designation of areas was in opposite direction.
7 Refer to Burst Timing Offset (BTO) section in Defining the Search Area section of this report

Over the following days regions of S1 and S2 were drifted[8] and provided surface search areas. Some possible satellite debris sightings were also incorporated to produce additional search areas.

On 27 March (D20), the JIT advised they now had more confidence in the increased speeds provided by primary radar near Malaysia. This increased the aircraft fuel burn and the most probable track moved north to the S3 area. The JIT additionally had more confidence that a 7th arc was a fuel exhaustion point. Two new search areas designated S4 and S5 were defined. The most probable impact location was moved to the bottom of the S4 area on the 7th arc within the S3 area. On 28 March (D21) a surface search of a drifted S3/S4 area (Shape A in Figure 6) was commenced.

Figure 4: Possible final positions S4-S5 with 7th arc and max range cruise line



Source: JIT/Google Earth

On 1 April (D25) the JIT advised AMSA/ ATSB of further aircraft performance and path analysis starting at a distance further NW of Sumatra that had the effect of shifting the most probable area NE within S4 and into S5. Probable impact areas red, yellow and green were defined within S4/S5 (Figure 5).

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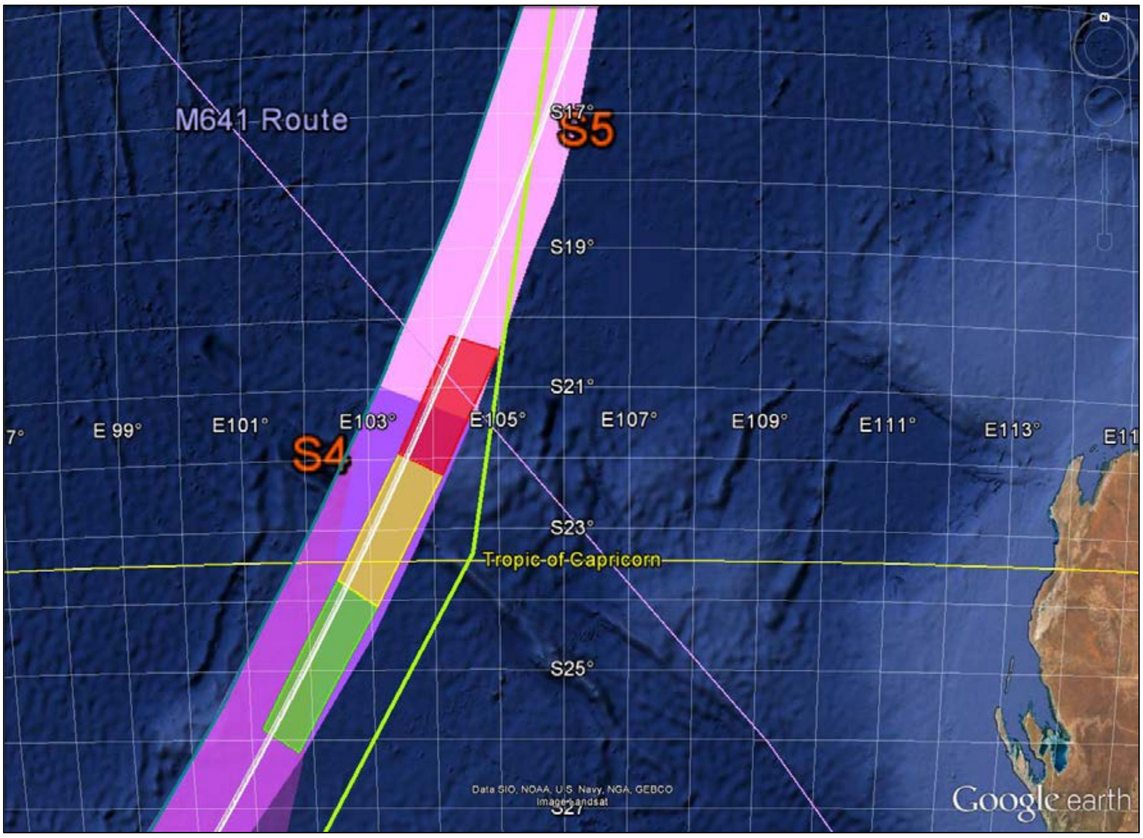
8 A drifted area is the computer modelled movement of a body of water over the period of time since 8 March to the search day. This modelling incorporated wind and current effects on a variety of debris characteristics.

Figure 5: Red, yellow and green boxes within S4-S5 and M641 route



Source: JIT/Google Earth

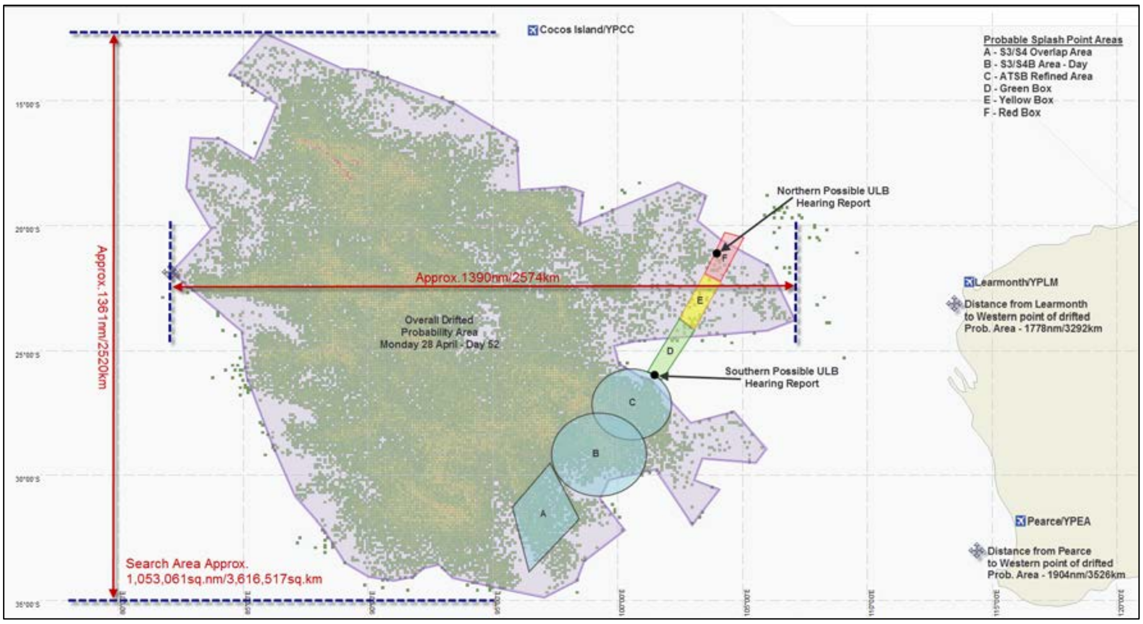
The S4/S5 boundary on the 7th arc was considered the best starting location due to convergence of a number of candidate paths using independent techniques and because airways route M641 passed through that location. By this stage drifted area B in Figure 6 was being searched. On 2-3 April (D26/ D27) a surface search of a drifted red area was commenced.

A summary of data used in planning search area refinements is shown at Appendix A: Information used in determining and refining search areas.

Drifted search areas

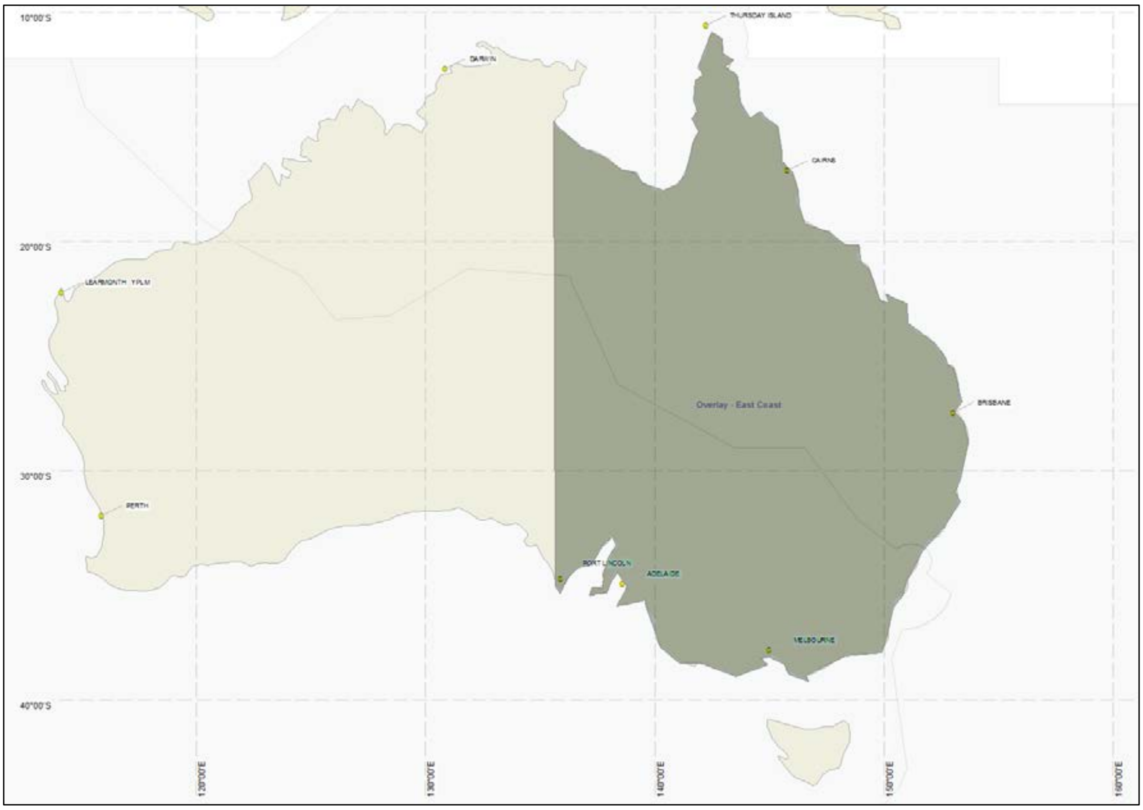
For one month from 28 March (D21), areas along the 7th arc in the S3, S4 and S5 areas were drifted to guide the conduct of the surface search. The original and drifted areas are shown in Figure 6, comparison to other regions shown in Figure 7 - Figure 10.

Figure 6: Original and drifted search areas 28 Mar - 29 Apr (D21-D52)



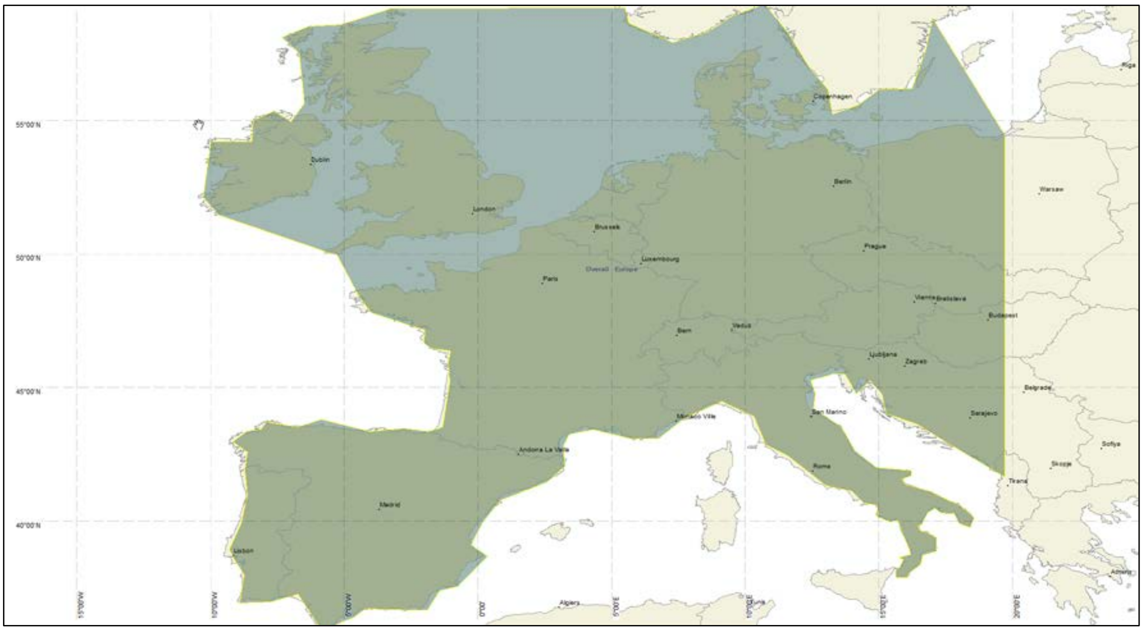
Source: AMSA

Figure 7: D21-52 drifted area comparison – East Coast Australia



Source: AMSA

Figure 8: D21-52 drifted area comparison – Europe



Source: AMSA

Figure 9: D21-52 drifted area comparison – North America

Source: AMSA

Figure 10: D21-52 drifted area comparison – China

Source: AMSA

Debris sightings

A number of items were sighted by aircraft especially from Area A, though most of the sightings were unable to be relocated by surface assets and no debris considered to be from MH370 was recovered.

Acoustic search

Underwater locator beacons

The flight recorders fitted to 9M-MRO were equipped with Dukane DK100 underwater acoustic beacons that activate on immersion in salt or fresh water. The beacons had the following characteristics:

- Operating frequency: 37.5 ± 1 kHz
- Pulse Length: 10 ms
- Repetition rate: 1 pulse per second
- Operating life following immersion: minimum 30 days[9]

The nominal distance at which an underwater locator beacon (ULB) may be detected is considered to be between 2,000 m to 3,000 m[10]. However, the detection may be made at greater range, about 4,500 m, under more favourable conditions. Many conditions influence the actual detection range, environmental noise, the ability of the water to conduct the acoustic signal, and the sensitivity of the equipment used to make the detection. In reality for a robust search a maximum range to target area of approximately 1 km is used.

Acoustic search area definition

Search vessels with equipment capable of acoustic detections were en route to or near the 7th arc on 2 April. The most probable arc crossings current on 2 April 2014 were the red/ yellow/ green areas in Figure 6. The areas had been sized so that the primary TPL system embarked on Australian Defence Vessel (ADV) *Ocean Shield* could cover the red area prior to the predicted expiry of the flight recorder ULB batteries. ULB detection resources were deployed to commence operations at the S4/S5 boundary within the red box and on the 7th arc.

Acoustic detections

HMS Echo

On 2 April 2014, the UK defence vessel HMS *Echo*, using a hull-mounted acoustic system reported a possible ULB detection close to the 7th arc and S4/S5 boundary. The hull mounted system was designed to provide high accuracy deep water positioning by monitoring the location of subsea transponders operating between 27 kHz and 30.5 kHz. The acoustic system was retuned to 37.5 kHz, by the crew of HMS *Echo*, to enable detection of the flight recorder ULB. On 3 April, following tests, this detection was discounted as being an artefact of the ship's sonar equipment.

MV Haixun 01

On the 4 April 2014, the crew of the Chinese Maritime Safety Administration vessel, MV *Haixun 01*, were operating Benthos pinger detector equipment from a rescue boat at the Southern end of the green zone in ocean depths of about 4,500m. The crew detected a pulsed signal with a frequency of 37.5 kHz, repeating at once per second. A second detection on the same frequency was made the next day, at a position about 3 km west of the first detection. The second detection was reported to be a much weaker strength signal than the previous day.

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[9] The manufacturer predicted maximum life of the ULB batteries was 40 days.

[10] Underwater Communications Specialist, Visiting Fellow, Australian Defence Force Academy, Canberra

The Benthos pinger locator specifications include:

- Detectable frequency range: 5 kHz to 80 kHz
- Practical ULB detection range: 2,000m

ADV Ocean Shield

The Australian Defence Vessel *Ocean Shield* (ADV-OS) was deployed from Perth, Western Australia to the search area on 31 March 2014, equipped with a Phoenix International towed pinger locator (TPL) system. The system included two towfish (Figure 11) with the following specifications:

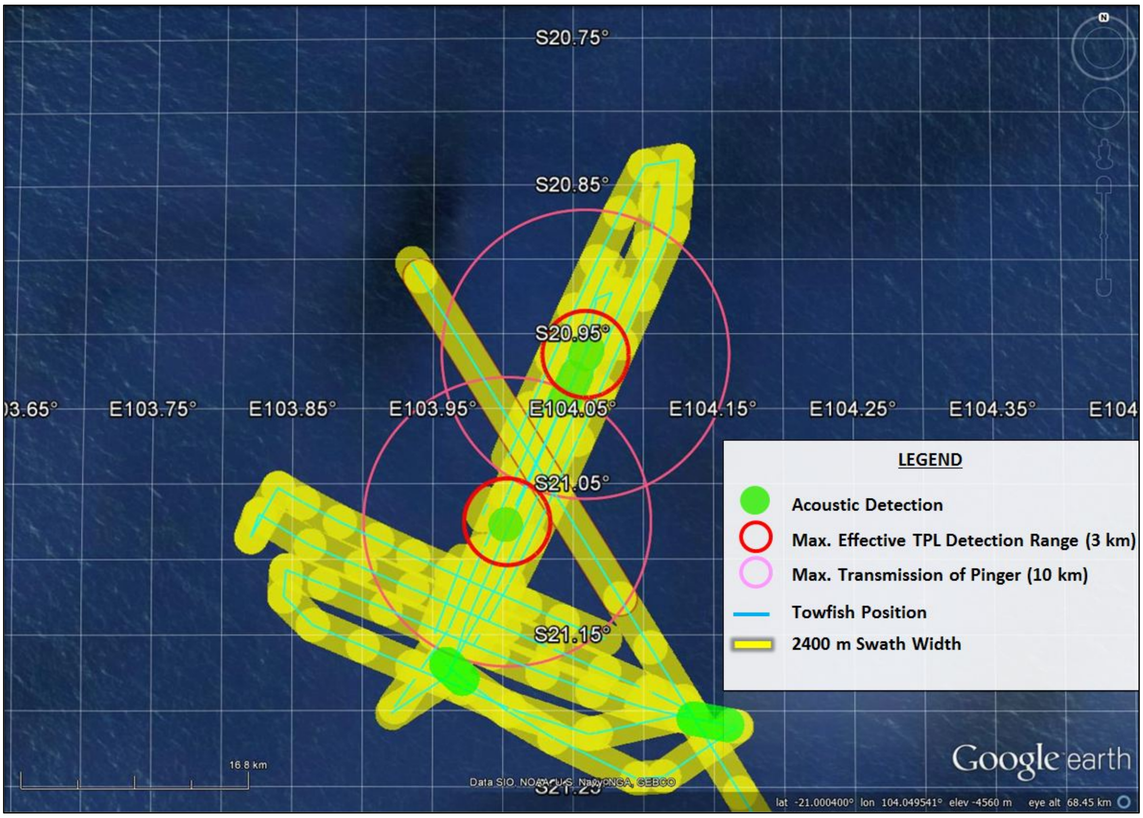
- Detectable frequency range: 3.5 kHz – 50 kHz
- Maximum operating depth: 6,000 m

Figure 11: TPL towfish

Source: RAN

The ADV-OS deployed the first towfish on 4 April 2014. The first towfish exhibited acoustic noise and was required to be changed out with the second towfish. The second towfish was deployed on 5 April 2014 and shortly after, whilst descending, detected an acoustic signal at a frequency of approximately 33 kHz. Further detections were made on 5 April 2014 and on 8 April; however, none were able to be repeated when following an opposing track. The first towfish was redeployed with no detections.

Figure 12: Ocean Shield TPL search coverage 04-14 April



Source: Phoenix International

Analysis of acoustic detections

HMS *Echo* was tasked to the area of the MV *Haixun 01* detections. HMS *Echo* reported that the detections were unlikely due to the depth to the seafloor, surface noise and the equipment utilised. A submarine tasked to the area was unable to get any detections.

A review of the *Ocean Shield* acoustic signals was undertaken independently by various specialists. The analyses determined that the signals recorded were not consistent with the nominal performance standards of the Dukane DK100 underwater acoustic beacon. The analyses also noted that whilst unlikely, the acoustic signals could be consistent with a damaged ULB. However, it was decided that that an ocean floor sonar search should be performed to fully investigate the detections.

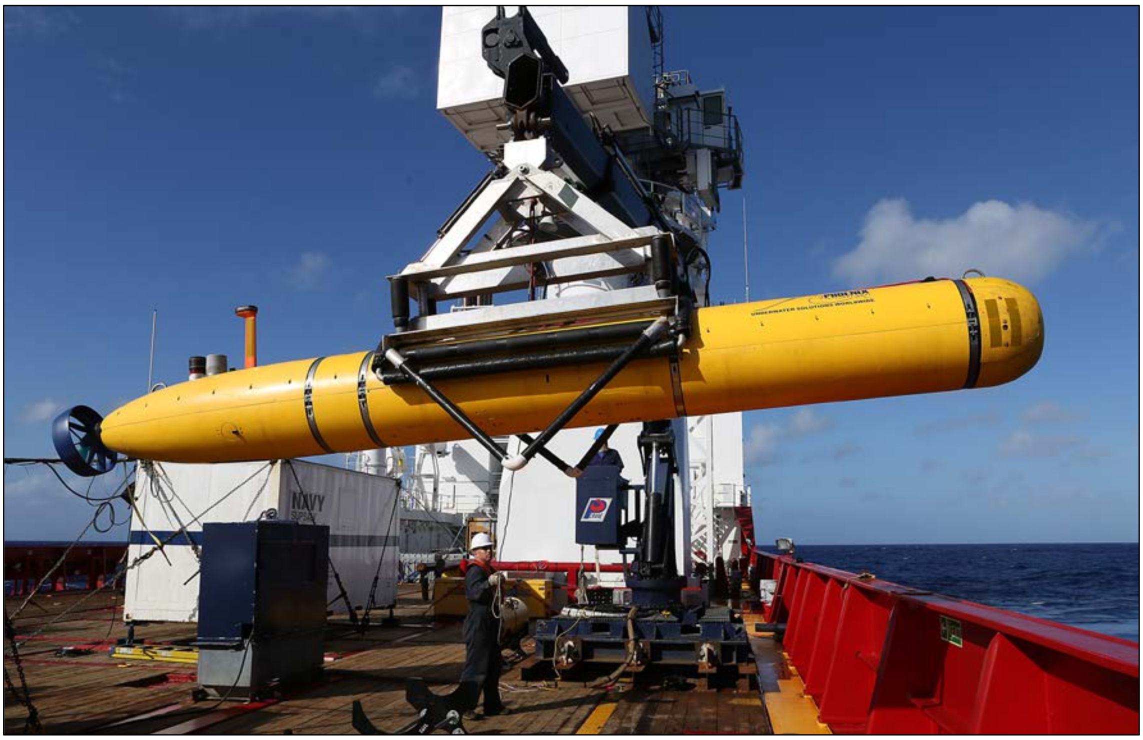
AP-3C sonobuoy acoustic search capability

When Australia joined the international effort to locate flight MH-370, the Australian Defence Force and Australian Defence Industry worked together to enhance the search capabilities available to the coordinating authorities. They provided an ability to detect a ULB signal at a range of up to 4,000 m water depth. This capability from an AP-3C aircraft was achieved by deploying sonobuoys at a depth of 300m beneath the ocean surface. One sortie was capable of searching an area of approximately 3,000 km^2. Sonobuoy drops were undertaken from 6-16 April (D30-D40). These sonobuoy drops were in the region of the 7th arc where depths were favourable and specifically in the location of the *Ocean Shield* and Curtin University hydrophone bearing (see later section) acoustic detections. No acoustic detections considered to be related to ULB transmissions were detected using sonobuoys.

Ocean floor sonar survey in area of Ocean Shield acoustic detections

Based on the analysis of the acoustic detections on ADV-OS, an underwater sonar survey using an autonomous underwater vehicle (AUV) commenced on 14 April 2014. 30 missions to depths between 3,800 - 5,000 m were completed. The side scan sonar tasking comprising a 10 km radius area around the most promising detection and a 3 km radius area around the other three detections was completed on 28 May. The total area searched during this time was 860 km^2 with nil debris or wreckage detected. The ATSB considers that the search in the vicinity of the ADV-OS acoustic detections is complete and the area can now be discounted as the final resting place of MH370.

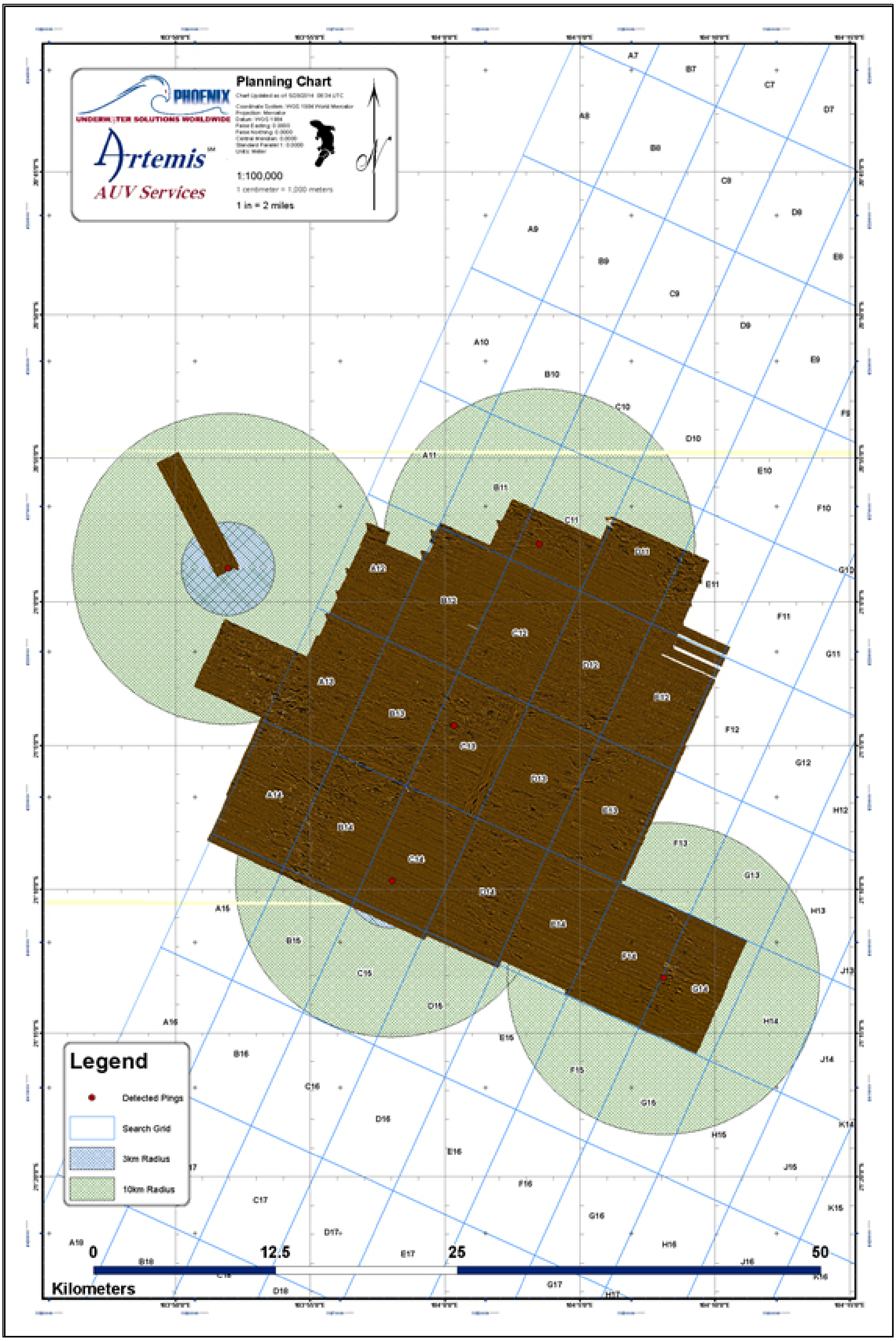
Figure 13: Ocean Shield AUV



Source: RAN

Further work is being carried out in an attempt to determine the likely source of the ADV-OS acoustic detections.

Figure 14: *Ocean Shield* AUV coverage 14 April-28 May 2014 (Note Western detection was a sonobuoy detection of different frequency)



Source: RAN

Defining the search area

Search area introduction

Three factors were important in defining the search area along the 7th arc:

- The position of the turn to the South from the previous North-West heading along the Malacca Strait
- Aircraft performance limitations
- Analysis of the satellite-communications data

There was uncertainty associated with each of these factors.

Position of the turn to the South

The last primary radar return related to MH370 was at 1822 – this was the final positive fix for the aircraft. At this time the aircraft was tracking north-west along the Malacca Strait. BFO data associated with the satellite arc at 1825 indicated that it was likely that the aircraft was still tracking north-west at this time. However, by the time of the 1941 arc, the BFO data indicated that the aircraft was tracking in a south/south-easterly direction.

As no evidence was available to conclusively determine where the turn(s) to the south occurred, two approaches were taken:

- the satellite data analysis was performed using a range of assumed locations for the turn.
- analyse the satellite data independently without assuming where the turn occurred. In this case the better matching solutions should be checked for realistic times and distances between their starting point and the position of the last primary radar point.

Aircraft performance limitations

Altitude, airspeed (Mach number at normal cruising altitudes) and wind are important parameters in determining aircraft range and performance. At 1707, the last ACARS transmission from the aircraft provided the total weight of the fuel remaining on board. Between that time and 1822, while the aircraft was being tracked by primary radar, the aircraft's speed and consequently fuel burn could be estimated.

During the period of the aircraft tracking to the south, there was no altitude or speed data available. While there was wind information available, it varied as a function of time, altitude and location. As a consequence, a variety of speeds and altitudes had to be assumed when calculating possible flight-paths using the satellite data.

The aircraft satellite transmission associated with the 7th arc is assumed to have been triggered by power interruptions on board the aircraft caused by fuel exhaustion. The time of this transmission is consistent with the maximum flight times expected for MH370.

Satellite data analysis

The satellite communications system comprises the on board equipment, satellite and ground earth station. It is a reliable and high-performance communications system. In the case of MH370, and in the absence of other data, it was necessary to use monitoring and maintenance data and, in effect, convert a communications system into a positioning system. Without this data, it would not have been possible to define a restricted search area at all but it should be appreciated that by using the satellite data it was necessary to model and analyse tiny variations in otherwise very stable signals. The satellite carrier frequencies are measured in GHz or 1 billion (1,000,000,000) cycles per second. To put the numbers into perspective, a tolerance of ± 5 Hz in these signals corresponds to a variation of ±0.0000005%.

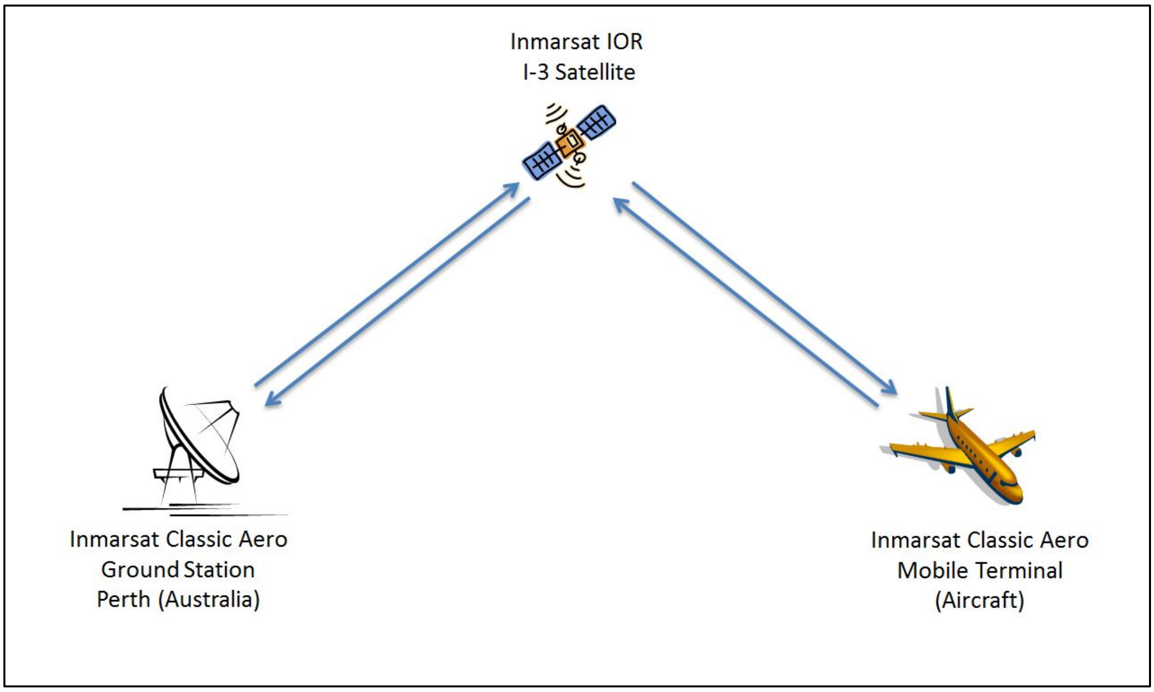
Satellite system Information

Satellite communication (SATCOM) relies on transmissions between a ground station, a satellite and a mobile terminal (the aircraft in this case) (Figure 15). The Boeing 777 uses a satellite link for the following functions:

- Audio communication
- Interface with Aircraft Communication Addressing and Reporting System (ACARS)
- In-Flight Entertainment equipment (IFE)

The system used during flight MH370 consisted of the Inmarsat Classic Aero ground station located at Perth, Western Australia and the Inmarsat Indian Ocean Region (IOR) I-3 satellite. The Classic Aero service uses a single global communication beam per satellite, and contains no explicit information relating to the mobile terminal location being available.

Figure 15: Schematic of basic satellite communications



Source: Satellite Comms Working Group

The aircraft satellite communication system operates on L band[11], transmits at 1.6 GHz and receives at 1.5 GHz for the satellite to/from aircraft RF links. The ground station to satellite RF links use C band[12], transmitting at 6 GHz and receiving at 4 GHz.

There are a number of channels within those bands available for messages to be sent between the satellite and earth station. One of the channels is called the P-Channel which the aircraft continually listens to and is used for signalling and data transmissions from the ground to the aircraft. The R-Channel is used for short signalling and data transmissions from the aircraft to the ground.

In order to connect to the SATCOM system, the aircraft transmits a 'log-on' request on the R-Channel which is acknowledged by the ground station. Once connected, if the ground station

[11] L band refers to a part of the electromagnetic spectrum.

[12] C band refers to a part of the electromagnetic spectrum.

has not heard from an aircraft within an hour[13], it will check that the connection is still operational by transmitting a 'Log-on Interrogation' message on the P-Channel using the aircraft's unique identifier. If the aircraft receives its 'unique identifier', it returns a short message on the R-Channel that it is still logged onto the network. These processes have been described as handshakes.

After the last recorded primary radar data, at 1822, the following were recorded at the ground station:

	hhmm.ss
• 1st handshake initiated by the aircraft	1825.27
• Unanswered ground to air telephone call	1839.52
• 2nd handshake initiated by the ground station	1941.00
• 3rd handshake initiated by the ground station	2041.02
• 4th handshake initiated by the ground station	2141.24
• 5th handshake initiated by the ground station	2241.19
• Unanswered ground to air telephone call	2313.58
• 6th handshake initiated by the ground station	0010.58
• 7th handshake initiated by the aircraft	0019.29
• Aircraft did not respond to log-on interrogation from the satellite earth ground station (failed handshake).	0115.56

For each R-Channel transmission, information is logged at the ground station including the burst timing offset (BTO) and the burst frequency offset (BFO).

The recorded BTO and BFO at each transmission were used to estimate the track of the aircraft. The BTO was used to estimate the distance of the aircraft from the satellite while the BFO was used to estimate the speed and direction the aircraft was travelling relative to the satellite. By combining these three parameters with aircraft performance constraints, a range of candidate paths matching the BTO/BFO data can be found.

Two basic analysis techniques were used across the group:

- Data-driven – attempting to match the BTO/BFO data exactly to a flight path with speed/ heading tolerances then filtering results for a reasonable aircraft flight path with respect to aircraft performance.
- Aircraft flight path/ mode driven – scoring a set of reasonable aircraft flight paths by their statistical consistency with the BTO/BFO data[14].

Burst Timing Offset (BTO)[15]

For system efficiency and for the satellite communication to remain reliable, aircraft R-Channel transmissions are in time slots referenced to the P-Channel as received by the aircraft. The BTO is a measure of how long from the start of that time slot the transmission is received. This is essentially the delay between when the transmission was expected (given a nominal position of the aircraft) and when it actually arrives and is caused by the distance of the aircraft from the satellite (Figure 16).

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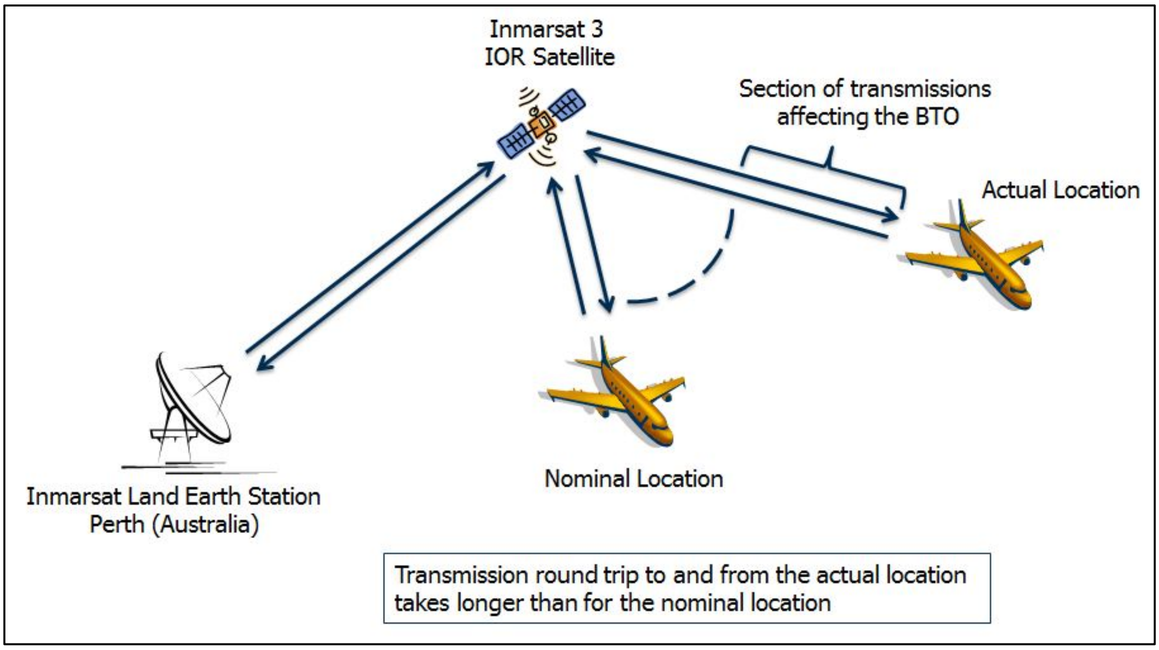
[13] This time is determined by the expiration of an inactivity timer. At the time of the loss of 9M-MRO, the inactivity timer was set to one hour.

[14] The set of likelihood-weighted trajectories represents the Bayesian posterior distribution of aircraft flight path

[15] Some additional information regarding BTO analysis is provided at Appendix G: Explanatory notes on BTO and BFO analysis.

The BTO was only a relatively recent addition to the ground stations data set. It was added at the suggestion of the satellite operator following the AF447 accident to assist in geo-locating an aircraft.

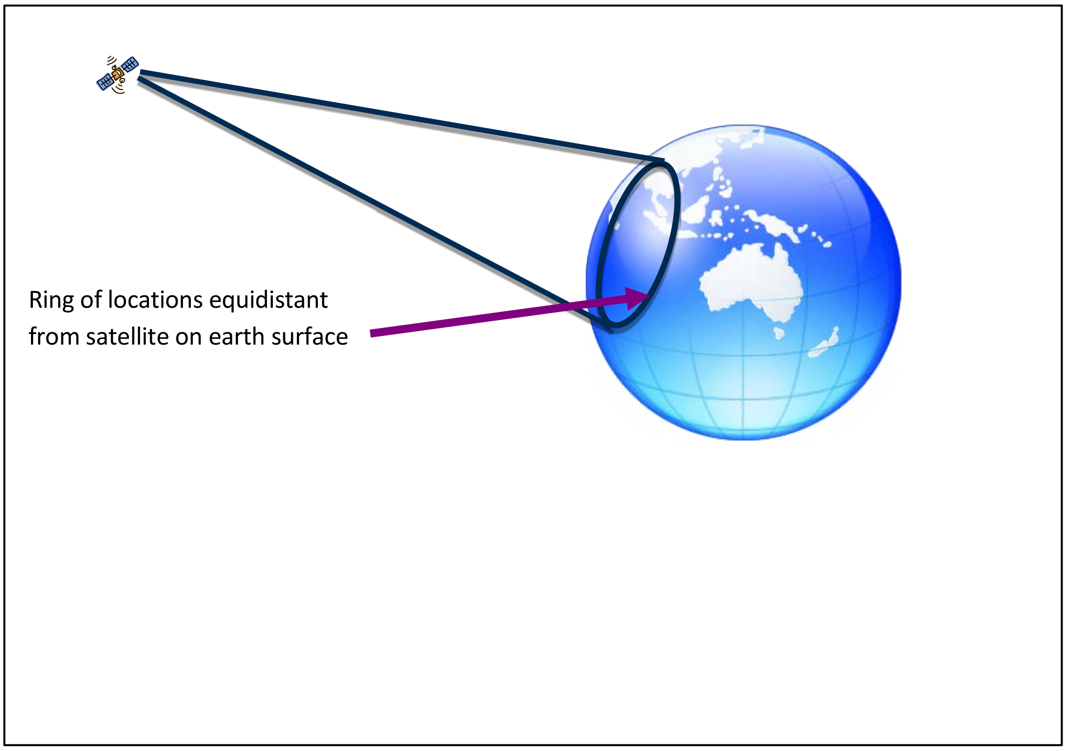
Figure 16: Difference in time delays between nominal and actual locations



Source: Satellite Comms Working Group

A set of locations can be plotted on the surface of the earth at the calculated distance from the satellite. The result is a ring of locations equidistant from the satellite (Figure 17).

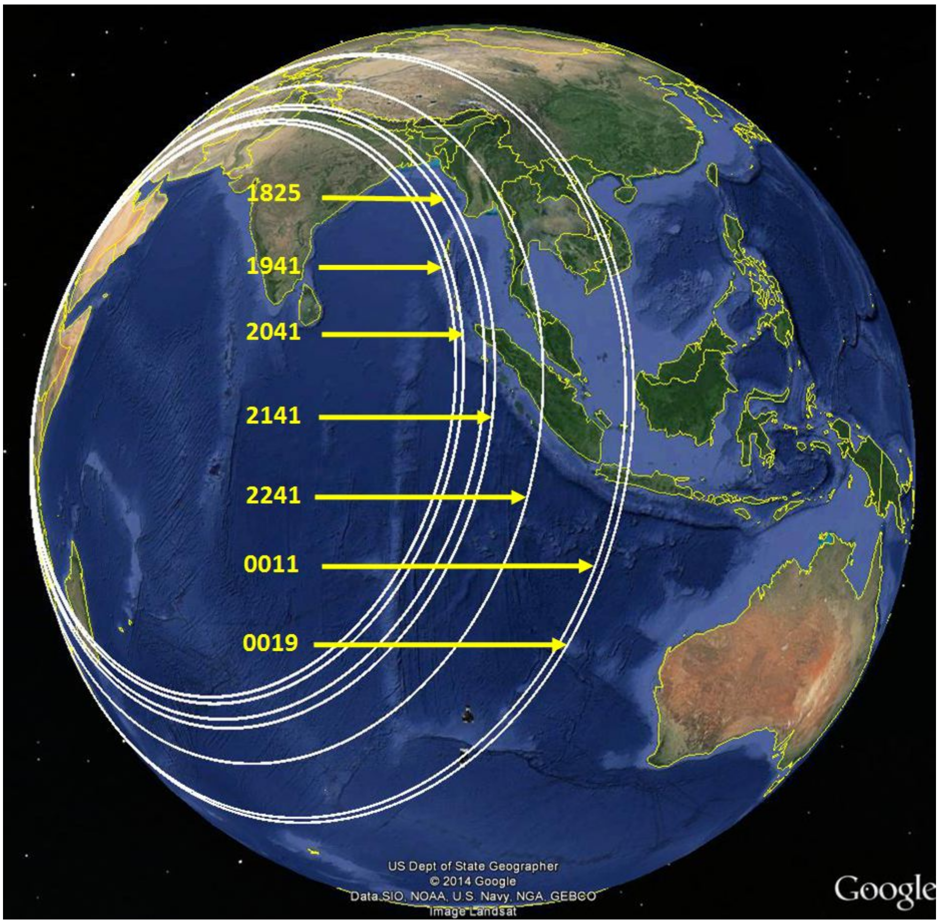
Figure 17: Position ring defined by BTO measurement



Source: Satellite Comms Working Group

For each completed handshake during flight MH370, the ground station recorded a BTO value which defined a location ring solution (Figure 18).

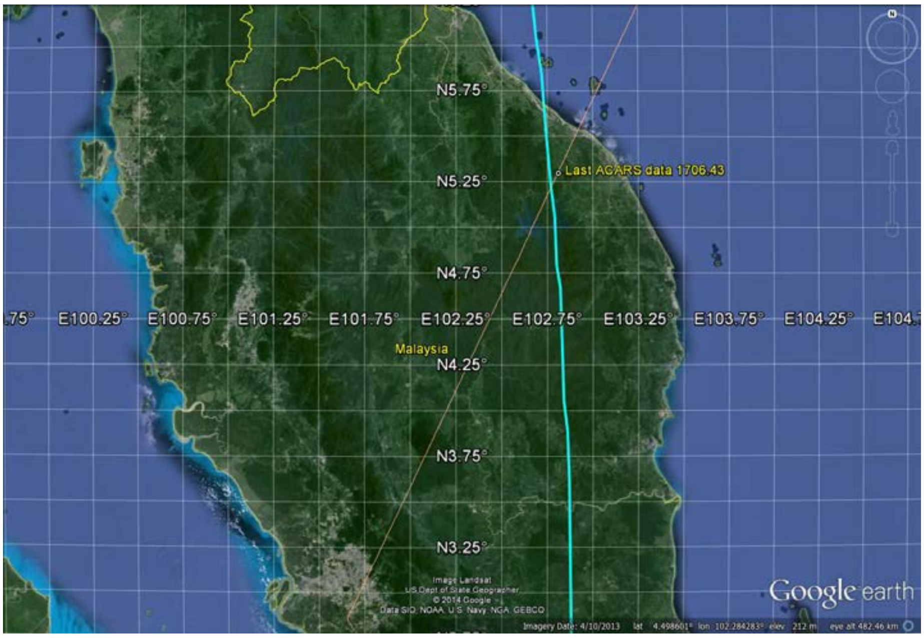
Figure 18: BTO ring solutions for 9M-MRO



Source: Satellite Comms Working Group

An analysis of the SATCOM system parameters, and empirical comparison between the BTO rings calculated for the time period when the aircraft was on the ground in Kuala Lumpur showed that the tolerance was ±10 km. Figure 19 shows a section of the BTO solution for the transmissions associated with the ACARS message overlaid on the flight track from flight MH370. The distance between the transmission location and the BTO arc is approximately 5 km.

Figure 19: BTO solution arc for transmissions related to last ACARS data



Source: Satellite Comms Working Group

The aircraft estimated paths are therefore constrained to be within 10 km of the BTO defined rings at the time associated with the recorded value. There is no information in the BTO to locate the aircraft at any single point on that ring, however knowledge of the aircraft's prior location and performance speed limitations can reduce the ring to an arc.

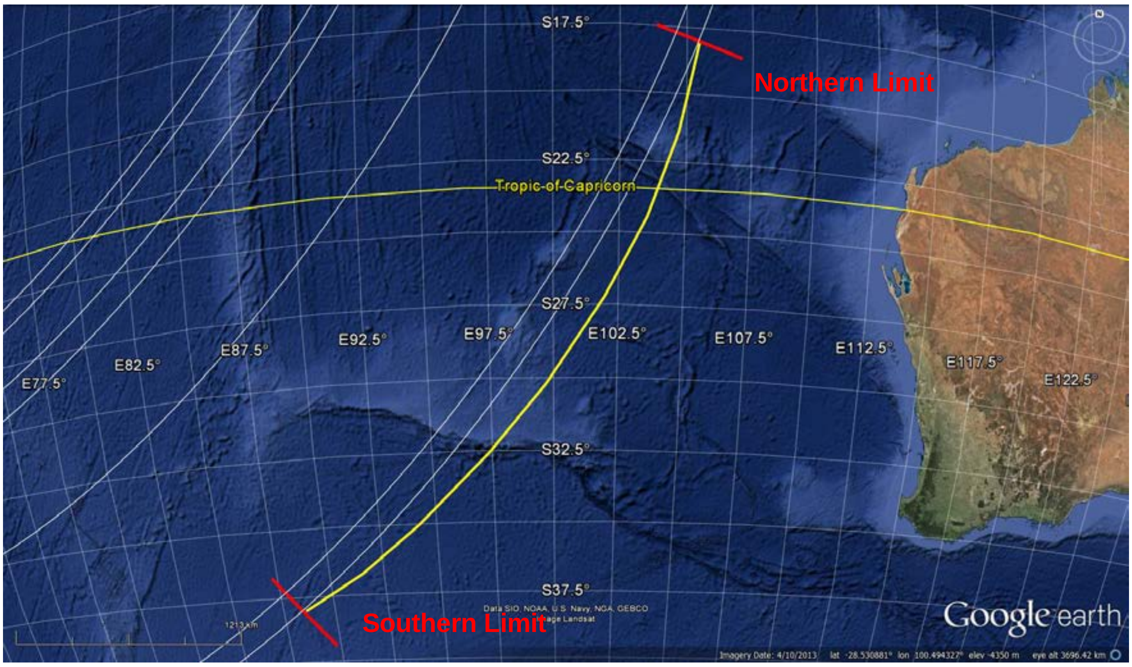
Northern and southern aircraft performance limits

Using the remaining fuel reported at the last ACARS transmission and various assumed flight speeds and altitudes, the range of the aircraft could be estimated. The potential search area can be bounded by these performance limits (Figure 20).

The assumptions made for the performance calculations were the following:

- The aircraft was flown at a constant altitude
- The speed selected was operationally achievable for the given altitude
- Aircraft required to cross the arcs at the times defined by the BTO values
- Before the 1941 arc various path estimates were used including an immediate turn south after the last radar point at 1822 and a turn at the north western limit at 1912
- After the 1941 arc straight line segments between the arcs were flown
- Wind effects were modelled
- Modelling did not include individual engine efficiency

Figure 20: Performance limit of the aircraft in yellow - red lines indicate the intersection of the performance limit and the 7th arc.



Source: ATSB

1st and 7th handshakes

The 1825 and 0019 SATCOM handshakes were log-on requests initiated by the aircraft. A log-on request in the middle of a flight is not common and can occur for only a few reasons. These include a power interruption to the aircraft satellite data unit (SDU), a software failure, loss of critical systems providing input to the SDU or a loss of the link due to aircraft attitude. An analysis was performed which determined that the characteristics and timing of the logon requests were best matched as resulting from power interruption to the SDU.

Approximately 90 seconds after the 1825 log-on request, communications from the IFE (In Flight Entertainment) system on the aircraft were recorded in the SATCOM log. Similar messages would be expected after the 00:19 logon request, however none were received. This could indicate a complete loss of generated electrical power shortly after the 7th handshake.

Because the location of the 0019 arc is also consistent with estimates of the aircraft range calculated from the remaining fuel quantity provided by the last ACARS transmission, the 7th arc is the focus of the search area.

Using the satellite system information, specifically the location rings determined from the BTO and the current understanding of the cause of the 7th handshake (log-on request) as being related to the fuel exhaustion of the aircraft, the focus of the search area will be along the 00:19 arc. The distance from the arc will be discussed in the section on the search area width.

Burst Frequency Offset (BFO)[16]

The burst frequency offset (BFO) is the recorded value of the difference between the received signal frequency and the nominal frequency at the Ground earth station (GES). The BFO consists of three major components:

16 Some additional information regarding BFO analysis is provided at Appendix G: Explanatory notes on BTO and BFO analysis.

- An offset (fixed frequency bias) generated by various components
- Frequency errors related to frequency translation in the satellite
- Frequency errors related to the Doppler Effect on transmissions and associated compensations

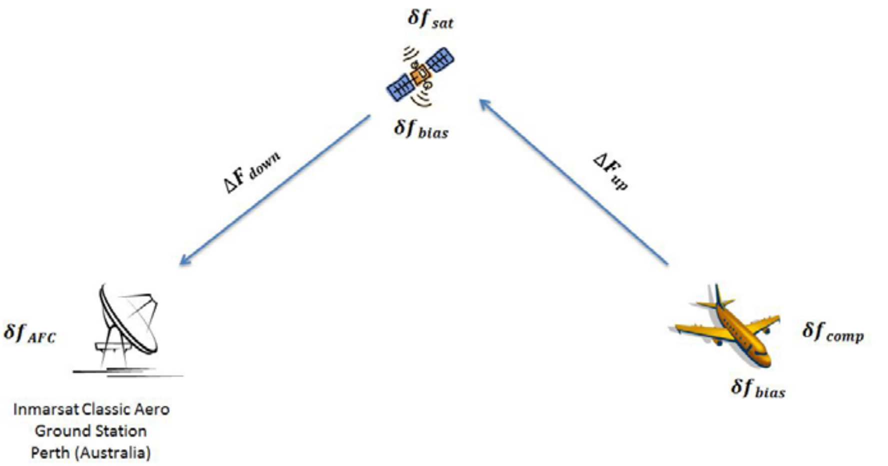
The offset could be estimated from the earlier parts of the flight where the location and behaviour of the aircraft was known. For MH370, the estimate was 150 Hz. Due to an observed tolerance of the data of ±5 Hz, the satellite working group used a variety of offsets from 145-155 Hz.

Frequency translation errors are introduced when the transmission frequency is shifted from the L to the C band at the satellite. Translation errors relate to the characteristics of the local oscillators which perform the translation. For example, the oscillators are sensitive to temperature, so when the satellite is in eclipse (shadow of the earth) the oscillators cool down, affecting the frequency translation.

Doppler errors are introduced by relative motion of the aircraft to the satellite, and the satellite to the ground station. The general principle is that when two objects are moving away from each other the frequency decreases and when they are moving towards each other the frequency increases.

The total contributions to the BFO of the transmissions from MH370 are shown in Figure 21.

Figure 21: Total of BFO contributions



$$BFO = \Delta F_{up} + \Delta F_{down} + \delta f_{comp} + \delta f_{sat} + \delta f_{AFC} + \delta f_{bias}$$

ΔF_{up}	*Doppler on the signal passing from the aircraft to the satellite*
ΔF_{down}	*Doppler on the signal passing from the satellite to the ground station*
δf_{comp}	*Frequency compensation applied by the aircraft, assuming level flight and a fixed satellite location*
δf_{sat}	*Variation in satellite translation frequency*
δf_{AFC}	*Frequency compensation applied by the ground station receive chain*
δf_{bias}	*Fixed offset due to errors in the aircraft and satellite oscillators*

Source: Satellite Comms Working Group

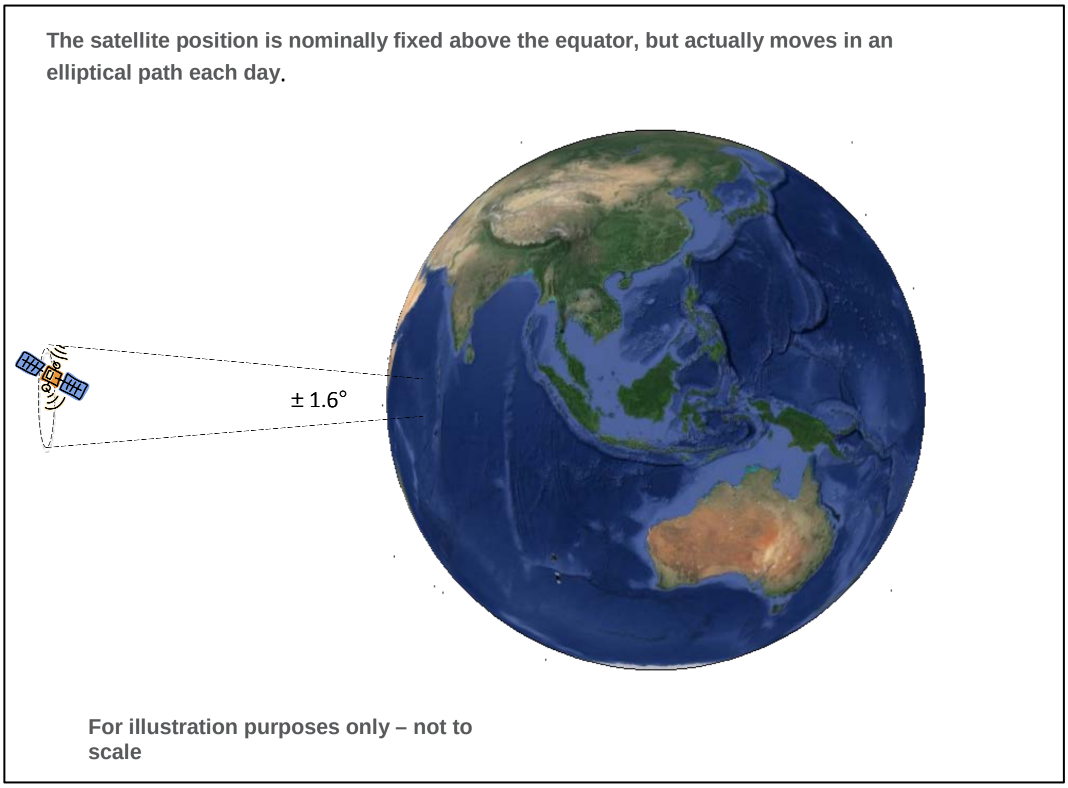
The satellite communication system has controls in place to reduce the changes in frequency in order to ensure that communications are maintained within a channel. Corrections are made on the aircraft and at the ground station for known frequency shifts throughout the transmission. These corrections do not remove all the errors as the magnitude of the offsets are well within the system's normal operating requirements.

The Inmarsat Classic Aero land earth station uses an enhanced automatic frequency control (EAFC) module to correct for Doppler error in the satellite to ground station transmissions and a fixed translation bias.

Inmarsat Classic Aero mobile terminals are designed to correct for Doppler effects on their transmit signals. The method used by the terminal on MH370 is based on computing the speed of the aircraft (using inertial reference system data) in the direction of the satellite; vertical speed of the aircraft is not used. However, the terminal assumes that the satellite is at a fixed location when in fact it is continuously moving due to its inclined geosynchronous orbit (Figure 22). This has the consequence of introducing the following errors:

- The compensation applied by the terminal is calculated along an incorrect direction as the satellite is not at the fixed location.
- No compensation is applied for the relative speed of the satellite in the direction of the terminal.

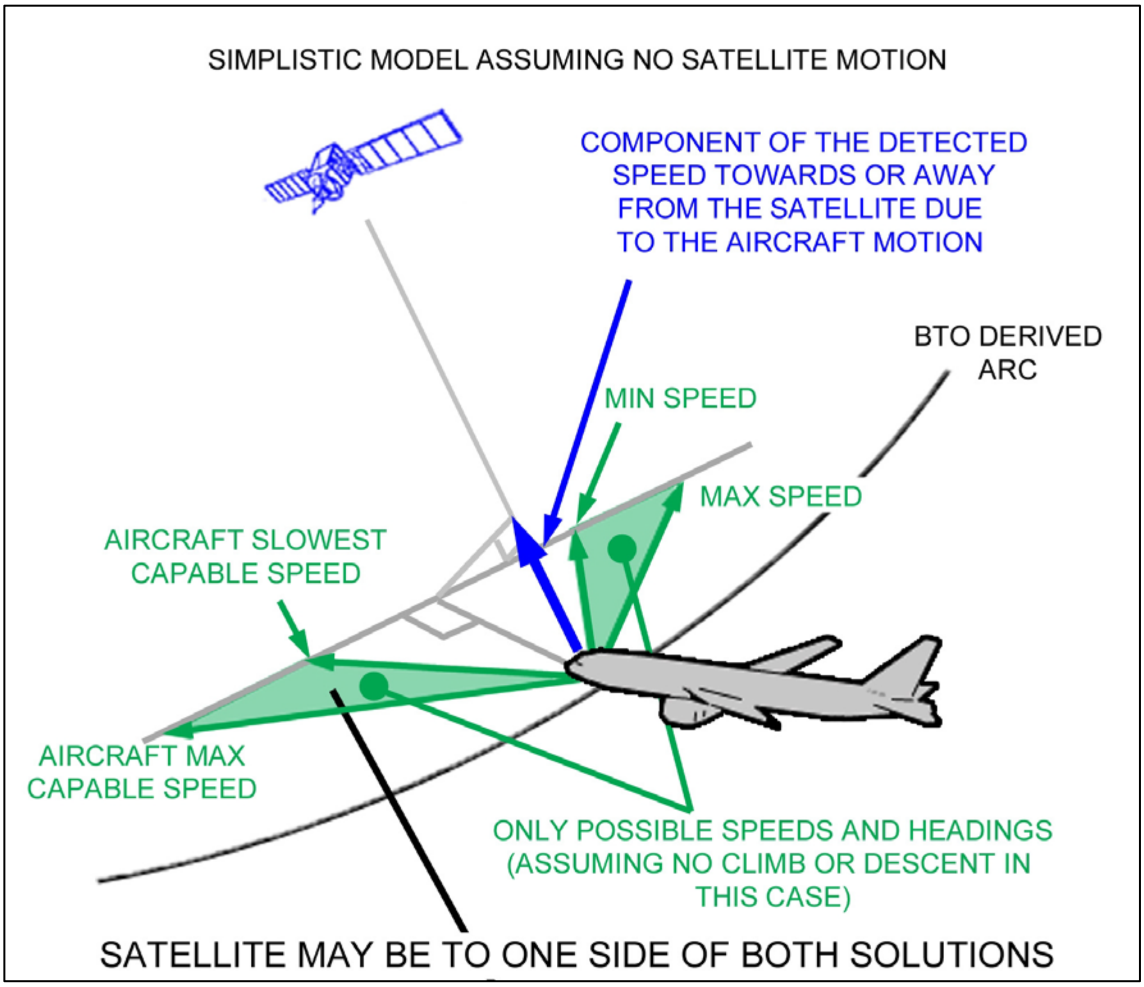
Figure 22: Satellite motion during geosynchronous orbit



Source: Satellite Comms Working Group

Once the known error associated with the BFO is removed, the remainder is the Doppler Effect associated with the relative motion of the aircraft to the satellite ($\boldsymbol{\Delta F_{up}}$). For a given relative motion, there are many combinations of aircraft speed and heading that will produce the correct frequency change (BFO). There is however a limited range of speeds at which an aircraft can operate and therefore the number of feasible speed/direction solutions is limited (Figure 23).

Figure 23: Simplistic model of velocity component affecting BFO measurements showing directions for various speeds within the possible range



Source: Satellite Comms Working Group

Based on various starting assumptions, the satellite working group analyses used combinations of aircraft altitudes, speeds and headings to generate candidate paths and calculated the BFO values at the arc locations for these paths. These values, compared with the recorded BFO values, provided a measure of correlation.

The following are a selection of results from the BFO analysis. Each analysis used different assumptions.

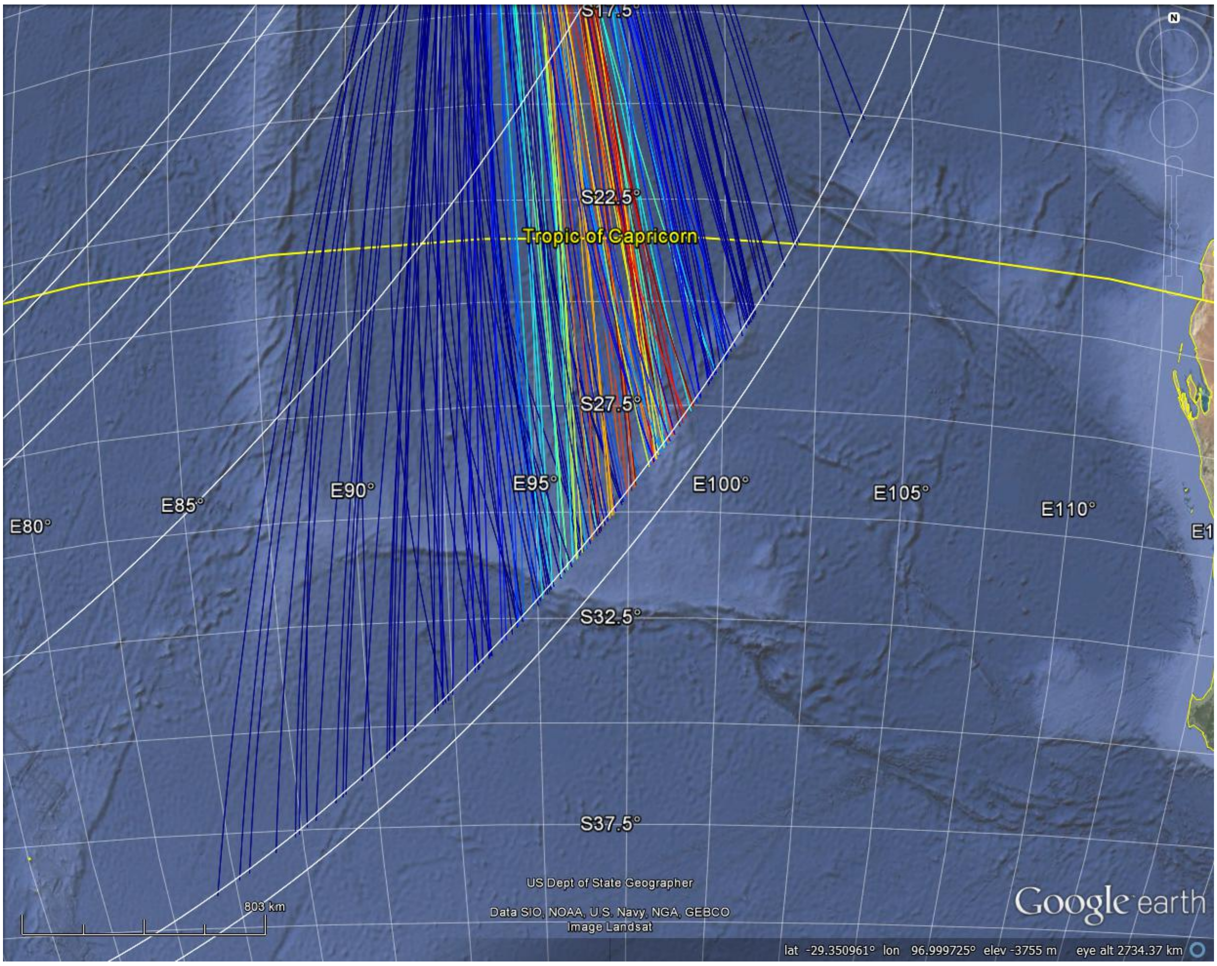
Analysis A:

Assumptions:

- Starting from locations on the 1941 arc within reach from the last known radar point using possible aircraft speeds
- Constant altitude
- Autopilot modes considered include constant true track, constant true heading, constant magnetic track, constant magnetic heading and great circle (in each case, the previously described drift is allowed about the nominal value)

- Speed and heading modelled by a process[17] in which values may drift over time but tend to revert to a fixed (unknown) nominal value
- Wind effects modelled
- Error models used:
- BTO: Gaussian standard deviation of 26 microseconds
  - BFO: Bias uniform (147-152). Random error Gaussian standard deviation 5 Hz
  - Analysis up to 0011 arc
- Generated paths scored according to their statistical consistency with the measured BFO and BTO values

Figure 24: Analysis A results - red / orange/ green paths represent the highest correlation with satellite data



Source: Satellite Working Group

Analysis B

Assumptions:

- Initial track takes a northern hook around the tip of Sumatra
- Constant altitude
- Constant groundspeed
- Heading changes allowed at each arc crossing

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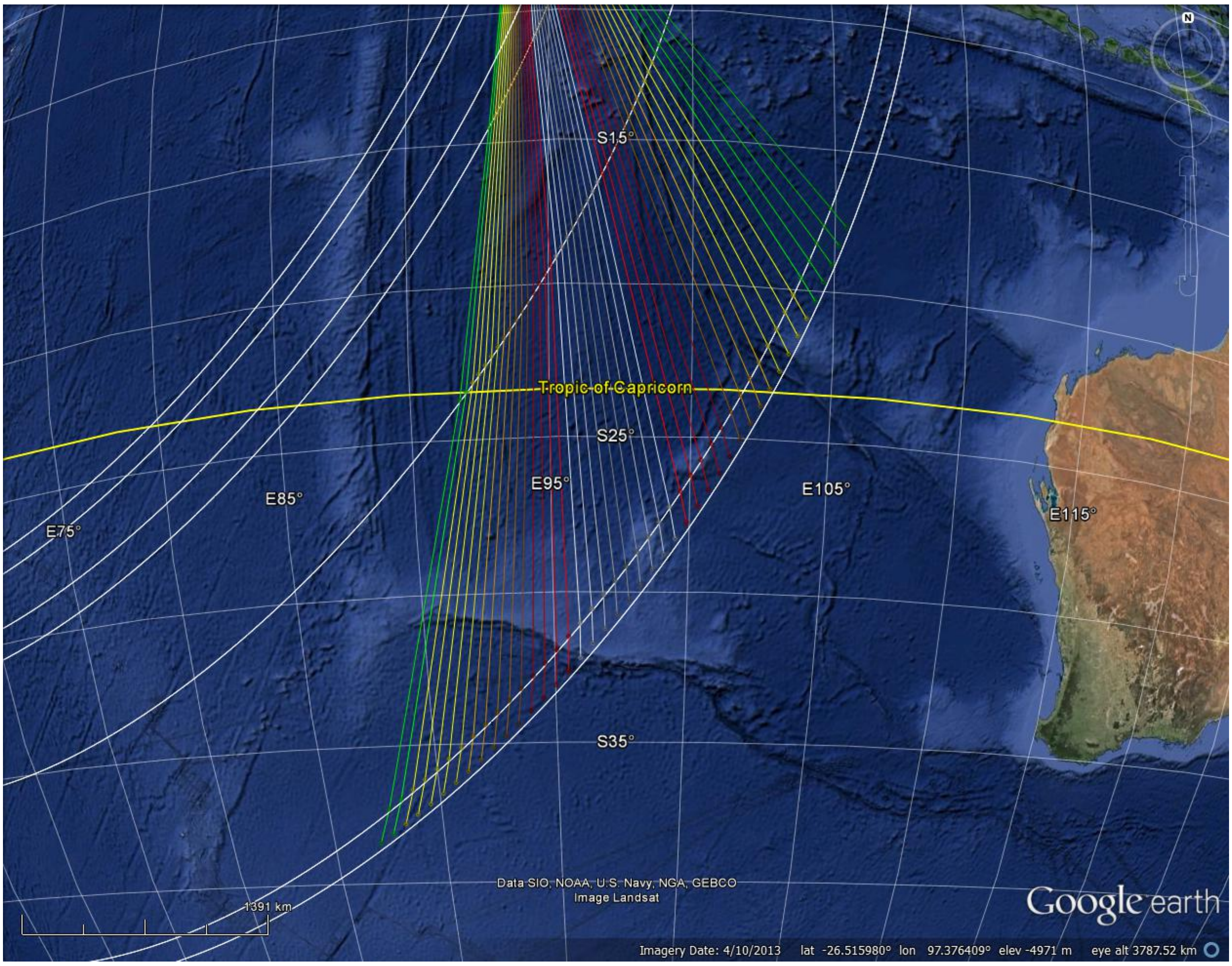
[17] Ornstein-Uhlenbeck stochastic process.

- Straight line segments between arcs

Figure 25: Analysis B results - white paths represent highest correlation with satellite data



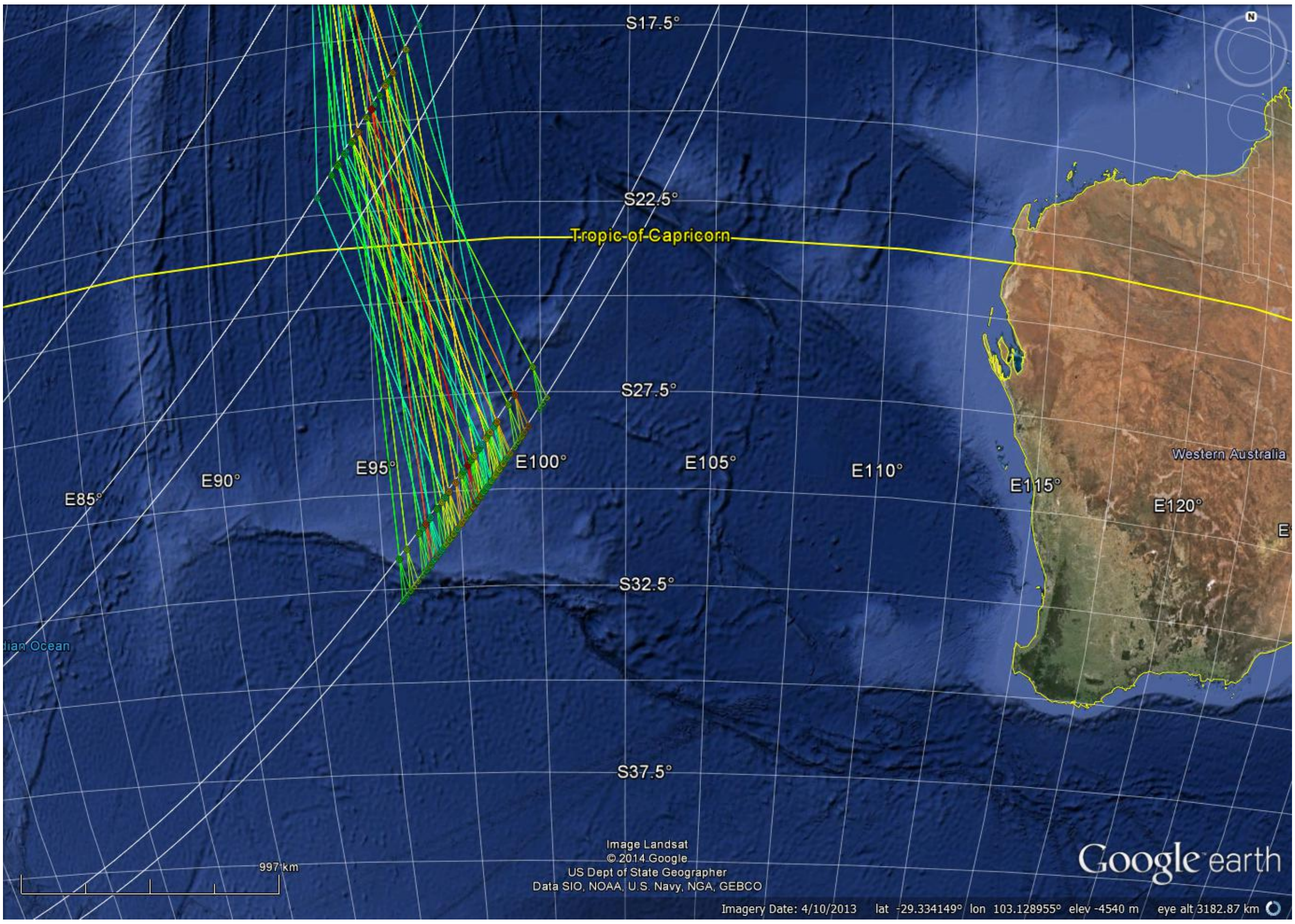
Source: Satellite Working Group

Analysis C

Assumptions:

- Initial track takes a northern hook around the tip of Sumatra
- Constant altitude
- Groundspeed can change at each arc crossing
- Heading changes allowed at each arc crossing
- Straight line segments between arcs

Figure 26: Analysis C results: Showing only the top 100 ranked tracks of 5000 candidates

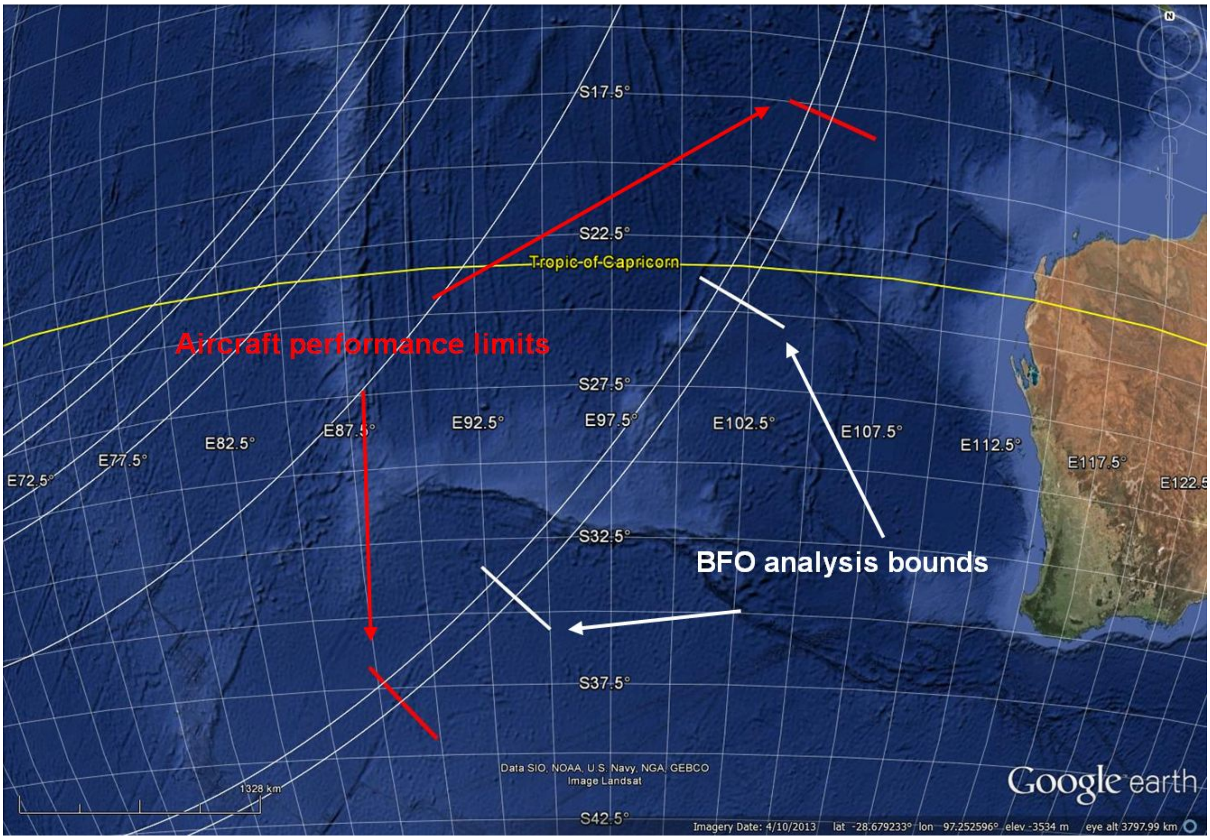


Source: Satellite Working Group

The various results from the analysis were generally in agreement.

From each of the different analyses, the highest correlation paths were compared and each crossed the 7th arc within 450 km of each other. The greatest effect on the paths was from changing the value of the fixed frequency bias. A sensitivity study determined that a change of 1 Hz in the fixed frequency bias was approximately equal to 100 km along the 7th arc. In order to appropriately bound the results, the most northern and southern solutions were used and an error margin of 5 Hz (observed tolerance of the FFB) or 500 km was applied (Figure 27).

Figure 27: Aircraft performance bounds and narrower limits based on the higher correlation area from the BFO analyses with 5 Hz tolerance on fixed frequency bias



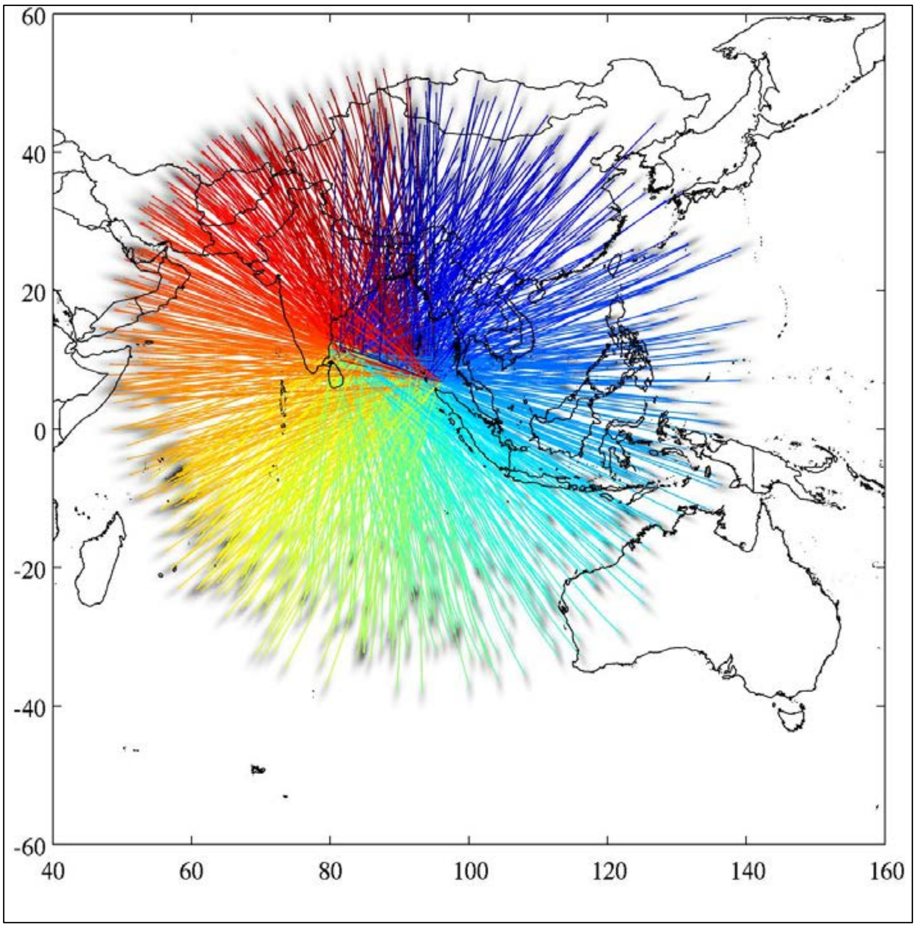
Source: ATSB

Verification and validation of BFO analysis

The BFO analysis was validated by several methods:

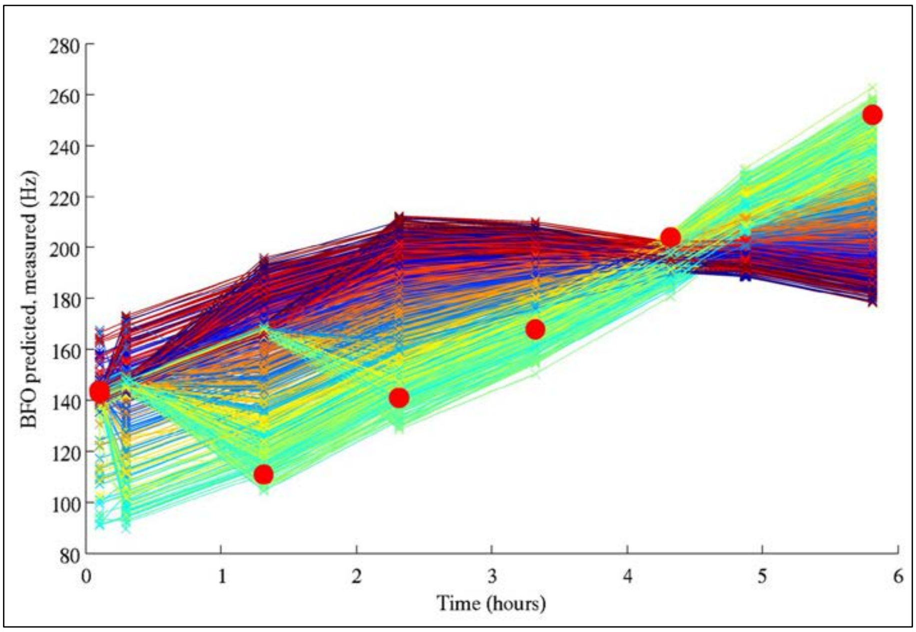
- An independent recreation of the satellite communication system model. This simulation was able to prove definitively that the BFO value is influenced by the location, speed and heading of the aircraft.
- Paths were generated starting from the last radar point assuming a single turn followed by a predominantly straight track. These paths were propagated in all directions, unconstrained by the BTO data locations (Figure 28). The BFO, at the times of the handshakes, was predicted for all the paths. In the paths that intersect the measured BFO values (red dots) are cyan and yellow coloured paths ending in the southern Indian Ocean (Figure 29). This was able to confirm that the southern corridor was the only valid solution.

Figure 28: 1000 paths generated, unconstrained by the BTO and BFO values.



Source: Satellite Working Group

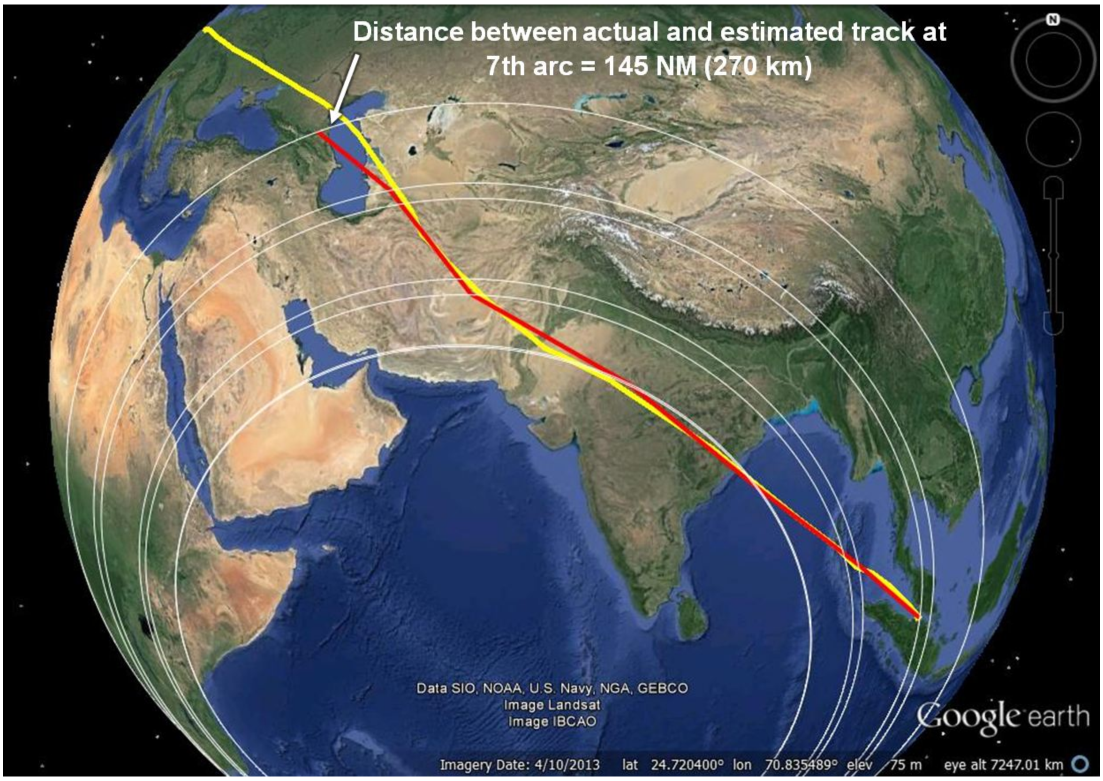
Figure 29: Above 1000 paths predicted BFO - red dots are the recorded values from MH370



Source: Satellite Working Group

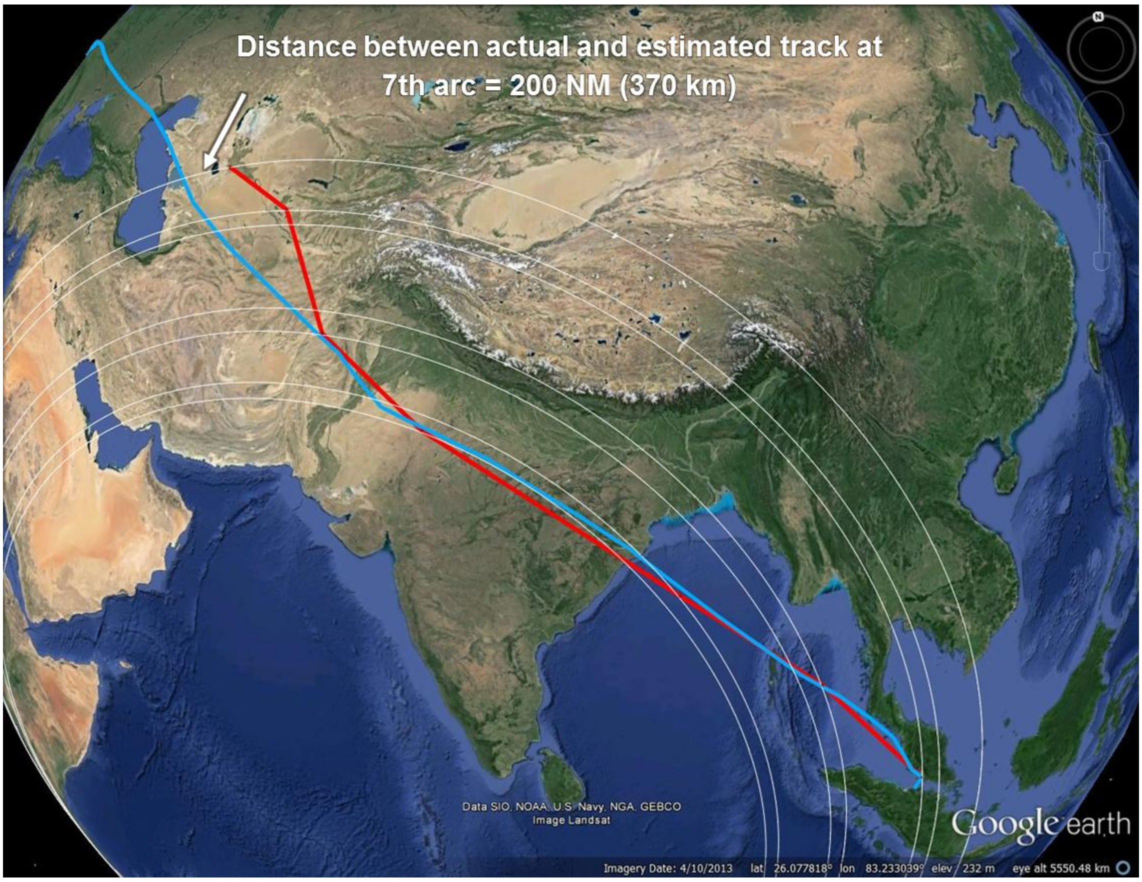
- Using nine previous flights of the accident aircraft (registered 9M-MRO) and 87 other aircraft with the same SATCOM terminal equipment in the air at the same time as MH370, some path prediction analysis techniques were verified. Shown below are two examples of comparative path estimations performed on sister ship flights departing Kuala Lumpur on the same day as MH370. Using only the starting location and an equivalent number, and approximate time spacing, of BFO and BTO values as the accident flight, predicted paths were created and compared against the actual flight paths (Figure 30 and Figure 31).

Figure 30: MH021 07 March 2014 - The red path is predicted path from BTO/BFO values; yellow track is the actual aircraft track



Source: Satellite Working Group

Figure 31: MH009 07 March 2014 - The red path is predicted path from BTO/BFO values; blue track is the actual aircraft track.

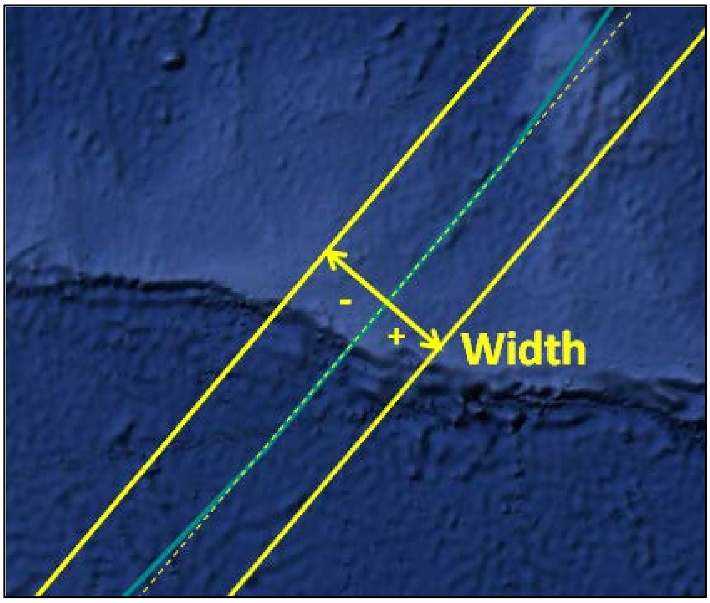


Source: Satellite Working Group

Determining the width of the search area

The width of the search area across the 7th arc is shown in Figure 32.

Figure 32: Description of the width of the search area



Source: ATSB

The final two SATCOM transmissions from the aircraft at 0019.29 (log on request) and 0019.37 (log on acknowledge) provided the last factual data related to the position of the aircraft. These transmissions placed the aircraft somewhere on the final arc but did not define a particular point on the arc.

There are several reasons why the aircraft satellite data unit (SDU) might generate a SATCOM log on request but an interruption to the aircraft electrical power supply was considered to be the most likely reason.

Aircraft electrical system

The electrical system on the B777 supplies 115 V AC and 28 V DC power. The main power sources are a left integrated drive generator (IDG) and a right IDG, powered by the left and right engines respectively. An auxiliary power unit (APU) can supply power if either or both of the IDGs are unavailable. The SDU was powered by 115 V AC from the left AC bus which was normally supplied by the left IDG. If power from the left IDG was lost, then a bus tie breaker would close and power would be automatically transferred from the right AC bus. Similarly, if power was lost from the right AC bus, power would be automatically transferred from the left AC bus. This power switching is brief and the SDU was designed to 'hold-up' during such power interruptions. To experience a power interruption sufficiently long to generate a log on request, it was considered that a loss of both AC buses or, a disabling of the automatic switching, would be required.

At 00:19, the aircraft had been airborne for 7 hours and 38 minutes[18] and fuel exhaustion was a distinct possibility. When a fuel tank was 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. Accident investigations show that when fuel exhaustion has occurred, typically one engine will flame-out before the other. In the case of MH370 it is likely that one engine has flamed-out followed, within minutes, by the other engine.

SDU power-up

Following the loss of AC power on both buses[19], the SDU would have experienced a power interruption sufficiently long to force a shut-down, the aircraft's ram air turbine[20] (RAT) would deploy from the fuselage into the aircraft's slipstream and the APU would auto-start. The APU would take approximately one minute to start-up and come 'on-line' after which time it could have provided electrical power[21] to the SDU. After power became available, the SDU would take approximately 2 minutes and 40 seconds to reach the log on stage evidenced in the SATCOM log at 0019.29.

If engaged, the autopilot could have remained engaged following the first engine flame-out but would have disengaged after the second engine flamed-out. By the time of the SATCOM log on message, the autopilot would have been disengaged for approximately 3 minutes and 40 seconds. If there were no control inputs then it would be expected that eventually a spiral descent would develop. In the event of control inputs, it is possible that, depending on altitude, the aircraft could glide for 100+ NM.

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

19 The earlier SDU log on request at 18:25 UTC was also considered likely to have been due to a power interruption. As this power interruption was not due to engine-flame outs, it is possible that it was due to manual switching of the electrical system. Therefore it is possible that the aircraft's electrical configuration was not in the normal state (i.e. the left IDG powering the left AC bus and the right IDG powering the right AC bus) at the time that the first engine flamed-out.

20 The RAT provides limited hydraulic and electrical power for instrumentation and flight controls.

21 The APU is supplied with fuel from the same tank as the left engine. Operation of the APU, after the left engine flamed-out, would be unreliable and would be of short duration before it too flamed-out.

Review of previous accidents

To assist in determining what may have occurred at the end of the flight, a review was performed by the ATSB of a sample of previous accidents. This review included the results of an analysis[22] by the BEA.

The ATSB reviewed three general classes of accidents that were relevant to the cruise phase of flight:

- An in-flight upset generally characterised by:
  - normal radio communications
  - normal en route manoeuvring of the aircraft
  - upset event such as a stall due to icing, thunderstorm, system failure etc
  - pilot control inputs
  - rapid loss of control
- An unresponsive crew/ hypoxia event generally characterised by:
  - failure of the aircraft to pressurise during initial climb
  - loss of radio communications
  - long period without any en route manoeuvring of the aircraft
  - a steadily maintained cruise altitude
  - fuel exhaustion and descent
  - no pilot intervention
  - loss of control
- A glide event generally characterised by:
  - normal radio communications
  - normal en route manoeuvring of the aircraft
  - engine failure/fuel exhaustion event(s)
  - pilot-controlled glide

Examples of these accident types are listed in Appendices C – E.

End of flight scenario

Note: Given the imprecise nature of the SATCOM data, it was necessary to make some assumptions regarding pilot control inputs in order to define a search area of a practical size. These assumptions were only made for the purposes of defining a search area and there is no suggestion that the investigation authority will make similar assumptions.

The limited evidence available for MH370 was compared with the accident classes listed previously.

In the case of MH370, there were multiple redundant communications systems fitted to the aircraft (3 x VHF radios, 2 x HF radios, SATCOM system, 2 x ATC transponders). However, no radio communications were received from the aircraft after 1719.29, 7 hours prior to the last SATCOM handshake at 00:19. Analysis of the SATCOM data also showed that there were probably no large changes to the aircraft's track after approximately 1915, about 5 hours prior to the last SATCOM handshake.

Given these observations, the final stages of the unresponsive crew/ hypoxia event type appeared to best fit the available evidence for the final period of MH370's flight when it was heading in a generally southerly direction:

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

- loss of radio communications
- long period without any en route manoeuvring of the aircraft
- a steadily maintained cruise altitude
- fuel exhaustion and descent

This suggested that, for MH370, it was possible that after a long period of flight under autopilot control, fuel exhaustion would occur followed by a loss of control without any control inputs.

Note: This suggestion is made for the sole purpose of assisting to define a search area. The determination of the actual factors involved in the loss of MH370 are the responsibility of the accident investigation authority and not the SSWG.

Also allowing for the fact that a maximum glide distance of 100+ NM would result in an impractically large search area, the search team considered that it was reasonable to assume that there were no control inputs following the flame-out of the second engine. Accordingly the aircraft would descend and, as there would be some asymmetry due to uneven engine thrust/drag or external forces e.g. wind, the descent would develop into a spiral.

As the BEA found in their study, in the case of an upset followed by a loss of control, all the impact points occurred within 20 NM from the point at which the emergency began and, in the majority of cases, within 10 NM.

For the small number of hypoxia cases that were available for review, the starting time of the loss of control was not always as well defined as for the upset cases, so the 20 NM range might not be as applicable. Balancing this was the consideration that, by the time of the final SATCOM log on message, the autopilot could have been disengaged for approximately 3 minutes and 40 seconds and the aircraft would have been descending during that period.

Width of the search area - summary

The position of the aircraft along the final arc was relatively inaccurately known due to the many combinations of starting position, heading, altitude and ground speed that could be matched to the BTO and BFO data.

The search strategy needed to take into account these relative accuracies and minimise the width of the search area as far as practicable to allow a longer search distance along the arc. The uncertainty in the width of the search area should be in balance with the uncertainty in the length of the search area.

The BFO data showed that the aircraft track at the time of final arc was approximately across the arc from North-West to South-East. As a consequence, the search distance to the East (right) of the arc should be larger than the search distance to the West (left) of the arc.

Based on all the above, it seems reasonable to propose a search width of 50 NM (20 NM to the left of the arc and 30 NM to the right of the arc). A 50 NM (93 km) search width would allow a search distance of about 350 NM (650 km) along the arc.

A summary of assumptions to define the width is shown at Table 1.

Table 1: Defining the search width

Probability of including the wreckage site:	Assumptions: (Add ±5 NM to all the distances due to the tolerance in the position of the arc)	Dimensions:	Resultant search length along the arc:	Comments:
Higher	Max. distance unpowered glide B777 from FL350 (120 NM).	± 125 NM (250 NM)	70 NM 130 km	Given the uncertainty of where the aircraft crossed the arc, these search widths give impractically small search lengths along the arc.
	Max. distance unpowered glide from OEI altitude of FL290 (90 NM).	± 95 NM (190 NM)	103 NM 191 km	
	Realistic distance unpowered glide (60 NM) from FL290 to extend range but no turn back.	+ 65 NM - 20 NM (85 NM)	206 NM 381 km	
	• No pilot or autopilot inputs • Use distances from BEA/ATSB study of loss of control accidents (20 NM) plus 5 NM	± 30 NM (60 NM)	292 NM 540 km	Reasonable search width.
	• No pilot or autopilot inputs • Use distances from BEA/ATSB study plus 5 NM • Moving in direction of previous track i.e. reduce '–' direction by 10 NM	+ 30 NM - 20 NM (50 NM)	350 NM 648 km	Reasonable search width.
	• No pilot or autopilot inputs • Use distances from BEA/ATSB study • Moving in direction of previous track i.e. reduce '–' direction by 5 NM	+ 25 NM -15 NM (40 NM)	437 NM 810 km	The BEA/ATSB case studies generally involve rapidly developing descents and short total upset durations (most cases are < 2 minutes). MH370 may not correlate well with the case studies and the 20 NM distance suggested from the study might not be applicable. A buffer above the 20 NM distance is advisable.
Lower	• No pilot or autopilot inputs • Use distances from BEA/ATSB study • Moving in direction of previous track i.e. reduce '–' direction by 5 NM • Ignore ±5 NM arc tolerance	+ 20 NM -10 NM (30 NM)	583 NM 1,080 km	

Other information considered

Air routes

General

All modern transport category aircraft, such as the B777, have a Flight Management System (FMS). An FMS is an integrated suite of navigation sensors, receivers and computers, coupled with navigation and performance databases. These systems provide performance and guidance information to the cockpit displays and the autopilot. Among other functions, the FMS uses the navigation database for lateral (horizontal) navigation (LNAV) which includes airway[23] and waypoint information[24]. There are two different types of waypoints:

- navigation database waypoints
- pilot-defined waypoints

Before take-off, a flight-plan route will be entered into the FMS. The route typically consists of a standard instrument departure from the origin airport, a series of en-route waypoints, a standard arrival procedure at the destination airport and a missed approach procedure.

The flight-plan can be uploaded automatically using ACARS or manually entered by the crew. In either case, the flight-planned route will be cross-checked by the crew and then must be manually activated by the flight crew. Two routes can be stored in the FMS although only one can be active at any time.

The standard autopilot mode for en-route lateral navigation is LNAV, where the aircraft tracks directly between waypoints along a great circle[25] route and the aircraft heading will be automatically adjusted to allow for the wind (sensed by the inertial reference unit).

In-flight, the flight-planned route can be changed by the crew selecting a different lateral navigation mode or maintaining LNAV and changing the route entered in the FMS. Other lateral navigation modes include:

- heading hold (either a true or magnetic heading can be selected)
- track hold (either a true or magnetic heading can be selected)

With these modes the track or heading is manually selected on the mode control panel on the glare-shield. True or normal reference is selected by the crew using a switch located on the Captain's inboard display panel. Normal reference is the usual setting which references magnetic North, unless the aircraft is operating at high latitudes, in which case the reference will change to true North. True North reference can be manually selected by the crew using the switch[26].

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23 An airway is a navigation corridor along a standard air route.

24 A waypoint is a predetermined geographical position that is defined in terms of latitude/longitude coordinates. Waypoints may be a simple named point in space or associated with existing navigation aids, intersections or fixes.

25 A great circle is the shortest distance between two points on a sphere.

26 In the case of MH370, for any possible track, fuel exhaustion would have occurred prior to reaching a latitude at which the aircraft would have automatically selected a true North reference.

Figure 33: B777 LNAV mode and track/ heading hold selectors

Source: Boeing

If using LNAV, the crew can enter new waypoints or change/delete existing waypoints. There is complete flexibility in the waypoints that can be entered, for example pilot-defined waypoints can be defined by the following methods:

- place/bearing/distance
- place bearing/place bearing
- along track
- latitude/longitude
- course intersection

MH370

Radar data showed that after take-off MH370 tracked in accordance with its flight-planned route to waypoint IGARI and then turned right towards waypoint BITOD. Secondary radar data was lost shortly afterwards. Primary radar data then showed that MH370 deviated from its flight-planned route.

Primary radar data showed that the aircraft tracked along the Malacca Strait. During this time the aircraft passed close to waypoints VAMPI, MEKAR, NILAM and possibly IGOGU along a section of airway N571.

Southern air routes/waypoints

Air routes and waypoints were then examined to see if there was any correlation with the possible southern tracks for MH370 obtained from the analysis of the SATCOM data. Relevant southern air routes that MH370 may have intersected/traversed were N509, N640, L894 and M641. Waypoints associated with these air routes were also considered as possible points on the MH370 flight path.

N509 ELATI 0200.0S 08957.7E
PORT HEDLAND

N640 TRIVANDRUM
BIKOK 0817.0N 07836.0E
COLOMBO
LEARMONTH
MOUNT HOPE
ADELAIDE

L894 KITAL 2003.0N 06018.0E
MALE
SUNAN 0028.7S 07800.0E
DADAR 0200.0S 07927.1E
PERTH

M641 MADURAI
BIKOK 0817.0N 07836.0E
COLOMBO
COCOS IS

Figure 34: Southern Indian Ocean air routes and selected waypoints

The waypoints at MUTMI and RUNUT were also considered as possible points that MH370 may have crossed. However ground tracks through these points did not correlate well with the most favoured paths generated through the analysis of the BFO and BTO data.

Air routes/ waypoints summary

Although waypoints and air routes were examined and compared to possible tracks derived from analysis of the SATCOM data, there was insufficient evidence to positively determine whether MH370 intersected any waypoints associated with published air routes in the Southern Indian Ocean.

Hydrophones

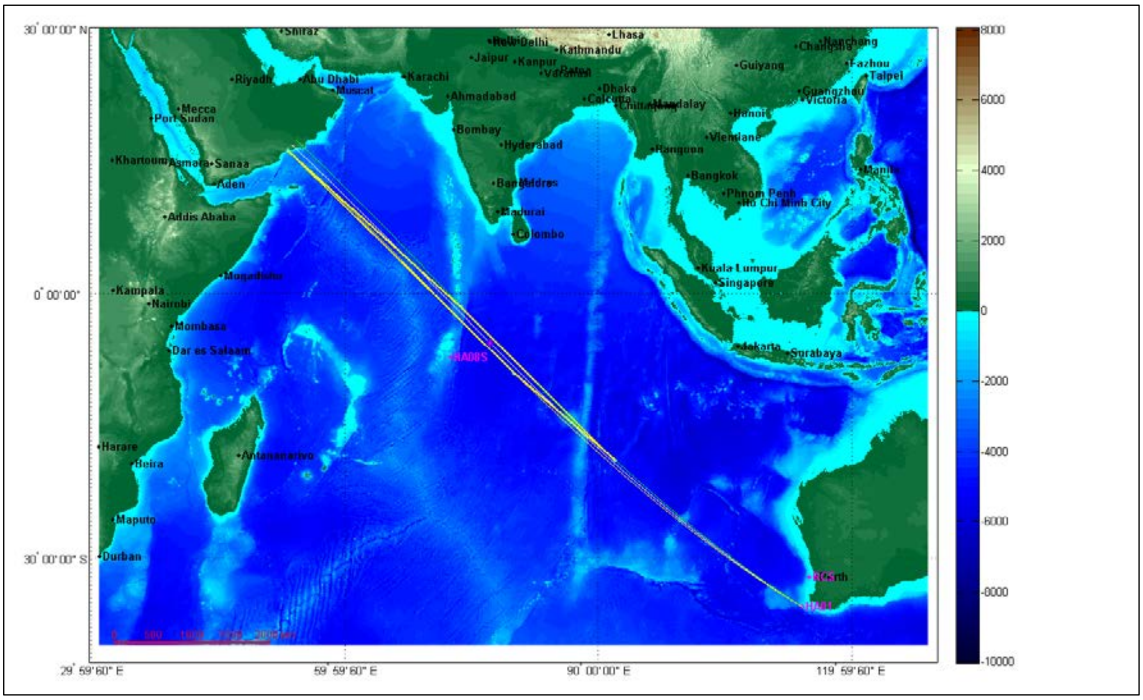
Low frequency hydro-acoustic signals present in the Indian Ocean were examined to determine whether they could provide any information to help define the search area. These signals were recorded by hydrophones as part of the United Nations Comprehensive Nuclear-Test-Ban-Treaty Organisation (CTBTO) or the Integrated Marine Observing System (IMOS).

Recordings of low-frequency underwater acoustic signals from data loggers and hydrophones off the WA coast were retrieved and analysed by Curtin University's Centre for Marine Science and Technology during the search for MH370.

The ATSB requested the Curtin University Centre for Marine Science and Technology (CMST) and DSTO analyse these signals in an attempt to detect and localise underwater sounds that could be associated with the impact of the aircraft on the water or with the implosion of wreckage as the aircraft sank.

One acoustic event of interest was identified that occurred at a time that may have potentially linked it to MH370. This event appeared to have been received on one of the IMOS recorders near the Perth Canyon (RCS) and at the CTBTO hydro-acoustic station at Cape Leeuwin (HA01). A detailed analysis of these signals has resulted in an approximate localisation for the source that was compatible with the time of the last satellite handshake with the aircraft, but incompatible with the satellite to aircraft range derived from this handshake.

Figure 35: Map showing most probable location for the source of the received sound signals (magenta asterisk) and the uncertainty region (yellow polygon) based on an uncertainty of +/- 0.75° in the bearing from HA01 and a +/- 4s uncertainty in the difference between signal arrival times at RCS and HA01



Source: Curtin University

The ATSB greatly appreciates the work and cooperation of Curtin University on this matter. More information regarding these signals can be found at http://news.curtin.edu.au/media-releases/curtin-researchers-search-acoustic-evidence-mh370/. A summary of Curtin University analysis is shown at Appendix B: Hydrophones – Curtin University Executive Summary. The ATSB will continue to discuss any further information with Curtin University for the purposes of the search.

Underwater search area

The ATSB defined underwater search areas using an aggregate of the results from five independent analyses. Individual solutions had provided either a preferred flight path or a range of candidate flight paths spanning a length along the seventh arc. The results showed a high degree of correlation between the preferred paths and the high ranking candidate paths.

The search strategy working group combined this analysis with the location of the 7th arc and width analysis discussed above to derive three search areas. These three search areas were designated wide, medium and priority. The location, size, derivation and position are shown in Table 2 and Figure 36.

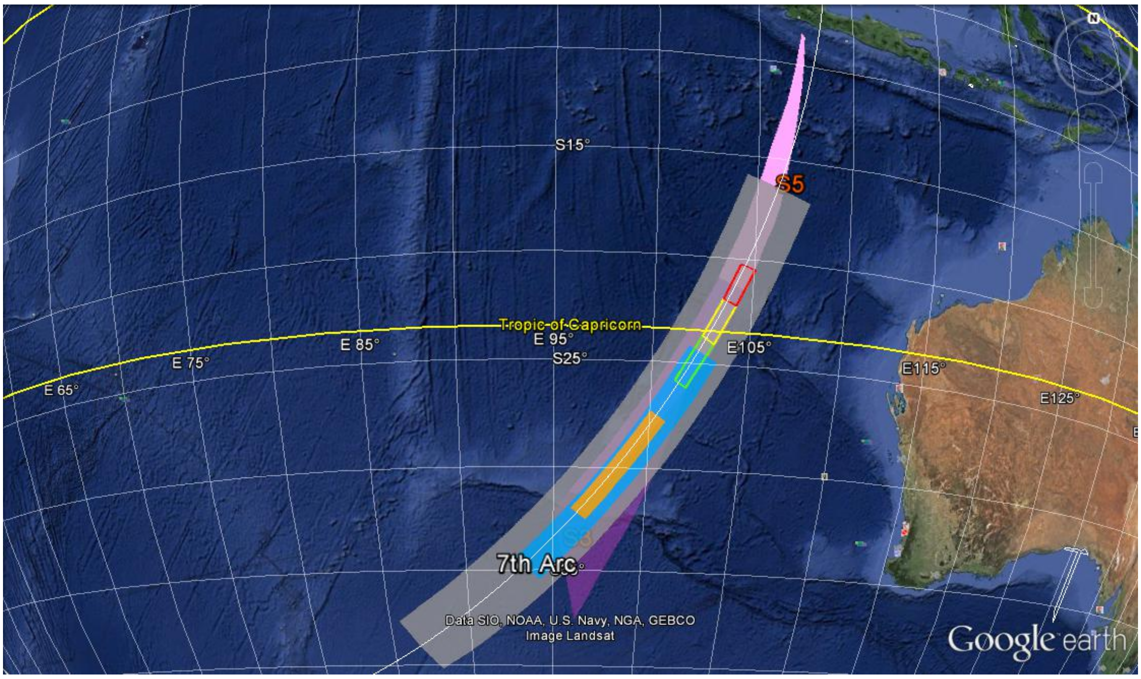
Table 2: Designated Underwater Search Areas

Area/ Size	Colour	Latitude lower bound on arc	Latitude upper bound on arc	Width across arc
1 - Priority area	Orange	Priority area definition for the RFT limited to 350 NM (650 km) covering the high probability area based on the ATSB evaluation of the working group results.	Priority area definition for the RFT limited to 350 NM (650 km) covering the high probability area based on the ATSB evaluation of the working group results.	Loss of control study, tolerance of the arc, balance of uncertainties and priority area for RFT of 60,000 km².
60,450 km²		**-32.1**	**-27.4**	**+30 NM, -20 NM**
2 - Medium area	Blue	Spans the highest correlation results from multiple analyses and error margin based on a fixed frequency bias tolerance of 5Hz (5Hz is equivalent to approximately 500 km variation at the 7th arc).	Spans the highest correlation results from multiple analyses and error margin based on a fixed frequency bias tolerance of 5 Hz (5 Hz is equivalent to approximately 500 km variation at the 7th arc).	**Forward of the arc** - Reasonable glide distance (performance of average pilot) starting from 3.5 minutes before final arc (approximately 30 NM) **Behind the arc** - loss of control limit. Both include the 5 NM tolerance of the arc.
240,000 km²		**-34.7**	**-24.4**	**+60 NM,-30 NM**
3 - Wide area	Grey	Southern range performance limit including a possible 100 NM along the arc.	Northern range performance limit including a possible 100 NM along the arc.	Maximum glide range from 30,000 ft including wind effects.
1,120,000 km²		**-39**	**-16.4**	**±100NM**

Source: ATSB

The limited data resulted in a large wide area (grey) needed to represent a high confidence in localising the aircraft. The medium area (blue) was calculated by using the ranking of candidate tracks contained within several of the analysis. Although still of reasonably high confidence, and relatively large, this reduced area does not contain all the possible derived paths.

Figure 36: Underwater Search Areas - Wide (Grey), Medium (Blue) and Priority (Orange) shown in comparison to S3/S5 and red, yellow, green search areas



Source: ATSB

Through consideration of the convergence of the preferred paths and highest ranked candidate paths a priority area (orange) was determined. This area is intended to be the priority area for deployment of the underwater search assets obtained through the RFT. Should additional assets become available, then underwater sections in the medium (blue) area may also be searched.

The potential aircraft location, where the derived flight paths cross the 7th arc, is very sensitive to variations in BFO frequency. A 10 Hz variation in the fixed frequency bias can result in the derived flight path at the arc moving 1,000 km.

Work is continuing by the group to define particular areas within the orange priority area in which to commence the underwater phase of the search.

Additionally, work is continuing with incremental refinements in the BFO characterisation in particular the EAFC .The ongoing refinement may result in search assets deployment outside the currently defined priority area (orange) into the medium (blue) area.

A map of the recommended underwater search areas is at Appendix F: Search Strategy Working Group underwater search areas.

Acronyms

AAIB	Air Accidents Investigation Branch (UK)
AC	Alternating Current
ACARS	Aircraft Communications Addressing and Reporting System
ADV	Australian Defence Vessel
AF447	Air France Flight 447
AH	Artificial Horizon
AMSA	Australian Maritime Safety Authority
APU	Auxiliary Power Unit
ATC	Air Traffic Control
ATSB	Australian Transport Safety Bureau
AUV	Autonomous Underwater Vehicle
BEA	Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile
BFO	Burst Frequency Offset
BTO	Burst Timing Offset
CMST	Curtin University Centre for Marine Science and Technology
CTBO	Comprehensive Nuclear-Test-Ban-Treaty Organisation
CVR	Cockpit Voice Recorder
DC	Direct Current
DSTO	Defence Science and Technology Organisation
EAFC	Enhanced Automatic Frequency Control
FDR	Flight Data Recorder
FFB	Fixed Frequency Bias
FL	Flight Level (altitude in units of 100 ft)
FMS	Flight Management System
FPM	Feet Per Minute
GES	Ground Earth Station
GHz	Gigahertz (1 x 10^9 cycles per second)
GMT	Greenwich Mean Time
HF	High Frequency
IDG	Integrated Drive Generator
IFE	In-flight Entertainment System
IMOS	Integrated Marine Observing System
IOR	Indian Ocean Region
IRS	Inertial Reference System
JACC	Joint Agency Coordination Centre
JIT	Joint Investigation Team
KHZ	Kilohertz (1 thousand cycles per second)
KM	Kilometre
KT	Knot (1 NM per hour)
LNAV	Lateral Navigation
LOC	Loss Of Control
MAS	Malaysian Airline System
MH370	Malaysia Airlines Flight 370

MV	Motor Vessel
NM	Nautical Mile (1.852 km)
NTSB	National Transportation Safety Board (USA)
OEI	One Engine Inoperative
RAT	Ram Air Turbine
SA	Situational Awareness
SATCOM	Satellite Communications
SDU	Satellite Data Unit
SITA	Société Internationale de Télécommunications Aéronautiques
SSWG	Search Strategy Working Group
SW	South West
TPL	Towed Pinger Locator
UK	United Kingdom
ULB	Underwater Locator Beacon
USA	United States of America
UTC	Coordinated Universal Time
V/S	Vertical Speed
VHF	Very High Frequency
Z	Zulu - a time zone reference (interchangeable with GMT & UTC)

List of Appendices

Appendix A: Information used in determining and refining search areas

Dates	17-27 March 2014	28 March – 01 April 2014	02 -28 April 2014	June 2014
Event	Initial Surface Search Area	Refined Surface Search Area	Second Refinement to Search	Proposed Underwater Search Area
Probable Impact area	S1/S2	S3/S4 starting from southerly region of S4	S4/S5 starting at S4/S5 boundary and defined by red/ yellow/green areas	Southerly region of S4
Data used in planning search area refinement	• Fixed satellite location • Turn south occurred at the northern tip of Sumatra • Performance predictions based on speed and range only with no wind consideration • Only positional information from Malaysian primary radar data • Length of arc to the south constrained by maximum aircraft groundspeed • Lateral navigation set to 'track' mode • Two speeds provided 'best fit` with longest and straightest tracks reaching the 6th arc. • Assumed speed/ altitude to last radar point was final ACARS values	• Greater confidence in increased speeds from primary radar thus increased fuel burn • More confidence that 7th arc was fuel exhaustion point	• Based on the satellite timing data, the aircraft will be located near the 7th arc. • The aircraft passed close to a NW point at 1912. • The measured Doppler profile closely matched that expected from an aircraft travelling in a southerly direction. • One analysis showed that the best fit for the Doppler frequency was at a ground speed of 400 kts, with slightly 'less' best fits at 375 and 425 kts. A Monte Carlo style analysis, using a number of different starting positions on the 2nd arc also gave a best fit at 400 kts. A most probable speed range of 375 to 425 kts was selected. • One analysis used a combination of aircraft performance and Doppler data, obtained from the satellite, to generate a range of probable best fit tracks. This work was supported by a Root Mean Square analysis that took account of a number of variables. • Flight planning carried out by MAS independently showed that there was sufficient fuel onboard the aircraft to reach the positions determine by the analysis. • The length of the arc that defined the most probable area was obtained from the overlay of the results of all approaches. • Given the probable battery life of the Dukane beacon, and the number of assets available to conduct the underwater search, it was decided to break the underwater search area into three smaller areas. • The width of the areas was defined by the probable position of the 7th arc, half of the glide range (40 NM) and the area the towed detector could cover before the Dukane battery expired. • The area that was crossed by air route M641 was classified as red (Priority 1), the next two priorities, yellow and green, were then defined moving south along the arc from this position.	• Effects of an eclipse on the satellite during a period of MH370 flight taken into consideration • Refined EAFC model • Flight path from 2nd arc at 1941 • Candidate paths with zero BTO tolerance • Candidate paths within BFO tolerance of 10Hz

Appendix B: Hydrophones – Curtin University Executive Summary

The Australian Transport Safety Bureau (ATSB) asked the Centre for Marine Science and Technology (CMST) to analyse signals received on underwater sound recorders operated by CMST that form part of the Australian Government funded Integrated Marine Observing System (IMOS), and on hydro-acoustic stations operated by the Comprehensive Nuclear Test Ban Treaty Organisation (CTBTO) in an attempt to detect and localise underwater sounds that could be associated with the impact of the aircraft on the water or with the implosion of wreckage as the aircraft sank.

One acoustic event of particular interest has been identified that occurred at a time that could potentially link it to MH370 and appears to have been received on one of the IMOS recorders near the Perth Canyon (RCS) and at the CTBTO hydro-acoustic station at Cape Leeuwin (HA01).

A detailed analysis of these signals has resulted in an approximate localisation for the source that is compatible with the time of the last satellite handshake with the aircraft, but incompatible with the satellite to aircraft range derived from this handshake. There appear to be three possible explanations for this discrepancy:

1. The signals received at HA01 and RCS are from the same acoustic event, but the source of the signals is unrelated to MH370.
2. The signals received at HA01 and RCS are from different acoustic events, which may or may not be related to MH370.
3. The signals received at HA01 and RCS are from the same acoustic event, and the source of the signals is related to MH370, but there is a problem with the position line determined from the satellite handshake data.

Of these, the first explanation seems the most likely as the characteristics of the signals are not unusual, it is only their arrival time and to some extent the direction from which they came that make them of interest.

If the second explanation was correct then there would still be some prospect that the signal received at HA01 could be related to the aircraft, in which case the combination of the HA01 bearing and the position arc derived from the satellite handshake data would provide an accurate location on which to base a search. However, the analysis carried out here indicates that, while not impossible, this explanation is unlikely.

The third explanation also seems unlikely because of the intense scrutiny the satellite handshake data has been subjected to, However, should the arc defined by the handshake data be called into question, the various timing and acoustic considerations discussed here would suggest that a reasonable place to look for the aircraft would be near where the position line defined by a bearing of 301.6° from HA01 crosses the Chagos-Laccadive Ridge, at approximately 2.3°S, 73.7°E. If the source of the detected signals was the aircraft impacting the sea surface then this would most likely have occurred in water depths less than 2000m and where the seabed slopes downwards towards the east or southeast. These considerations could be used to further refine the search area. If, instead, the received sounds were due to debris imploding at depth it is much less certain where along the position line from HA01 this would have occurred.

Appendix C: Accident case studies – loss of control accidents

Date:	Location:	Reg:	Type:	Operator:	Upset Duration (mm:ss):	Altitude Loss (ft):	Average V/S: (fpm)	Max. Distance from start of emergency (NM):	Type of Loss of Control:
23-May-06	Helendale,CA, USA	N600XJ	Lear 24B	Pavair Inc.	02:00	23,000	11,500	N/A	Undetermined LOC.
25-Oct-99	Aberdeen, SD, USA	N47BA	Lear 35	Sunjet Aviation	02:30	48,900 Planned: 39,000	> 30,000	N/A	Hypoxia, fuel exhaustion. 'Payne Stewart' flight. Spiral and 'severe' descent.
01-Jun-09	Atlantic Ocean (500 NM from shore)	F-GZCP	A330-203	Air France	03:18	37,924	11,500	5	Stall.
22-Mar-94	Near Novosibirsk, Russia	F-OGQS	A310-308	Aeroflot	02:36	33,100	12,000	3	Roll upset, spiral and spin. Child at controls.
03-Mar-91	Colorado Springs, CO, USA	N999UA	B737-291	United Airlines	00:10	1,000	6,000	1	Rudder hard-over.
03-Mar-74	Near Paris, France	TC-JAV	DC-10-10	Turkish Airlines	01:12	9,000	7,500	11	Control damage. Cargo door failure.
12-Feb-63	Near Miami, FL, USA	N724US	B720B	Northwest Airlines	00:30	19,000	> 30,000	< 10	Extreme turbulence, overspeed.

Date:	Location:	Reg:	Type:	Operator:	Upset Duration (mm:ss):	Altitude Loss (ft):	Average V/S: (fpm)	Max. Distance from start of emergency (NM):	Type of Loss of Control:
01-Dec-74	Near JFK airport, NJ, USA	N247US	B727-251	Northwest Orient	01:23	24,800	16,500	< 20	Pitots blocked, stall and spiral dive.
26-May-91	Near Bangkok, Thailand	OE-LAV	B767-329ER	Lauda Air	00:29 (inflight break-up ~10,000 ft)	24,700	> 30,000	N/A	Asymmetric thrust. Thrust reverser deployed in flight.
07-Dec-95	Near Grossevichi, Russia	RA-85164	TU-154B	Aeroflot	00:57	31,000	32,000	8	Roll upset, spiral. Fuel imbalance.
19-Nov-01	Near Kalyazin, Russia	RA-75840	IL-18V	IRS Aero	00:59	26,000	26,000	4	Dive from cruise and spiral.
21-Dec-02	Near Penghu Islands, Taiwan	B-22708	ATR72	Trans Asia	00:40	18,000	27,000	2	Icing and stall.
16-Aug-05	Near Machiques, Venezuela	HK-4374X	MD-82	West Caribbean	03:30	31,000	12,000	17	Stall during cruise.
22-Aug-06	Near Donetsk, Ukraine	RA-85185	TU-154M	Pulkovo	02:46	39,000	14,000	3	Stall during cruise and spin.

Date:	Location:	Reg:	Type:	Operator:	Upset Duration (mm:ss):	Altitude Loss (ft):	Average V/S: (fpm)	Max. Distance from start of emergency (NM):	Type of Loss of Control:
01-Jan-07	Makassar Strait, Indonesia	PK-KKW	B737	Adam Air	01:45	35,000	20,000	9	Roll upset. IRS malfunction.
15-Jul-09	Near Qazvin, Iran	EP-CPG	TU-154M	Caspian Airlines	01:30	24,000	16,000	5	Roll upset and spiral.
12-Nov-01	New York, USA	N14053	A300-605R	American Airlines	00:24	2,300	5,750	1.5	Vertical stabiliser failure.
10-Oct-85	Near Sydney, Australia	VH-IWJ	IAI 1124	Pel-Air Aviation	00:25	5,000	20,000 (last 9 seconds)	< 5	Simulated emergency instrument flight conditions check at night. Loss of SA.
09-Apr-08	Near Sydney, Australia	VH-OZA	SA227-AC	Airtex	00:30	4,340	10,400	< 2	Spatial disorientation at night. AH unpowered.
03-May-05	Near Stratford, New Zealand	ZK-POA	SA227-AC	Airwork (NZ)	~ 01:20	22,000	15,000	< 2	Steep spiral descent, overstress and break-up. Fuel trimming using rudder.
26-Jan-90	Near Meekatharra, Australia	VH-MUA	MU-2B-60	Great Western Aviation	~ 02:00	21,000	10,500	< 5	Icing & stall. Aircraft entered a spin. Steep, near vertical, descent.
07-Oct-07	Near Nanches, WA, USA	N430A	C208A	Kapowsin Air Sports	~ 02:00	15,000	8,000	3	Hypoxia and stall. Pilot conscious but hypoxic.

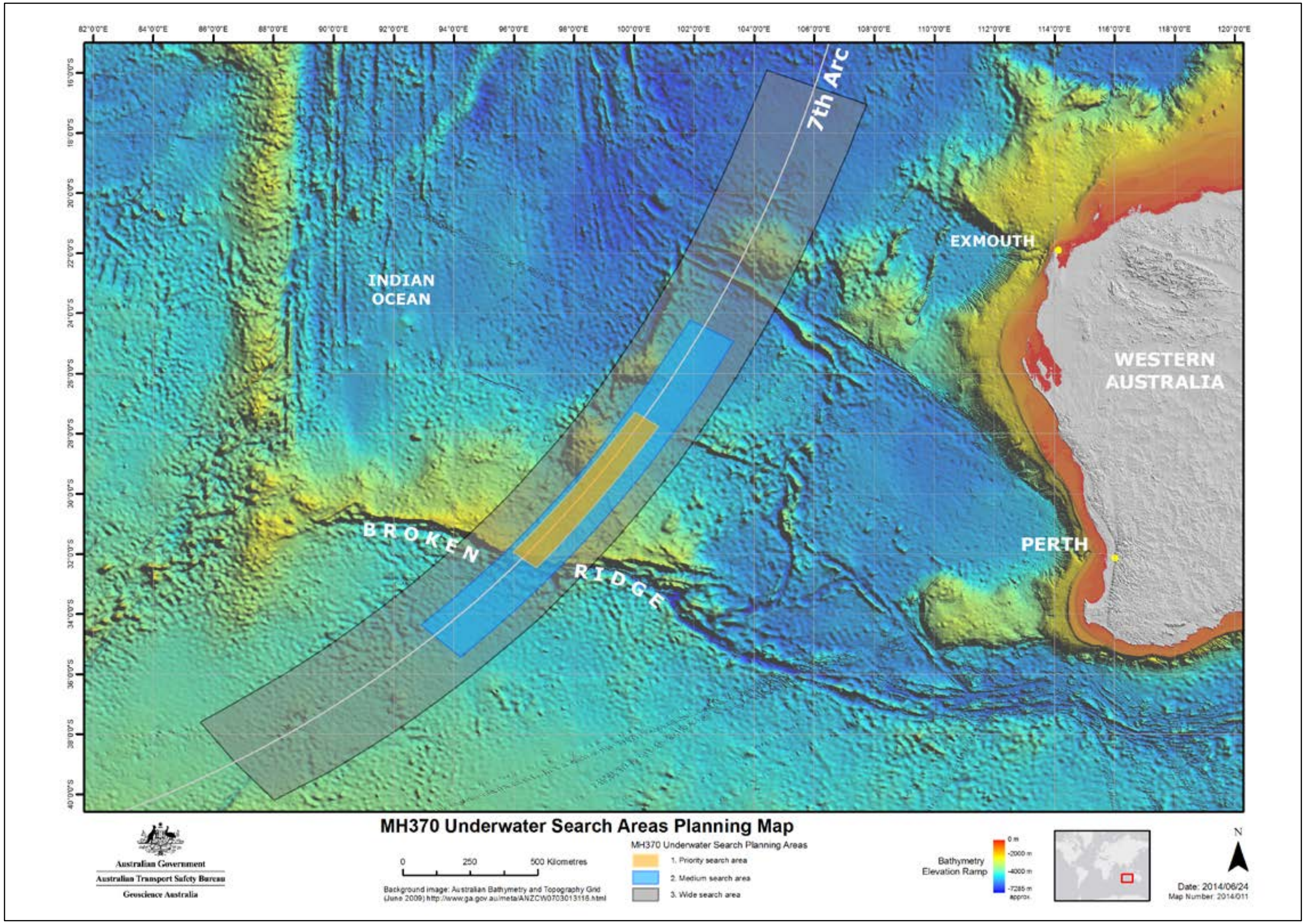
Appendix D: Accident case studies – unresponsive crew/ hypoxia accidents

Date:	Location:	Reg:	Type:	Operator:	Upset Duration (mm:ss):	Altitude Loss (ft):	Av. V/S: (fpm)	Max. Distance from start of emergency (NM):	Loss of Control:
25-Oct-99	Aberdeen, SD, USA	N47BA	Lear 35	Sunjet Aviation	02:30	48,900 Planned: 39,000	> 30,000	Unavailable.	Hypoxia, fuel exhaustion. Loss of control. 'Payne Stewart' flight. Spiral and 'severe' descent.
14-Aug-05	33 km NW Athens, Greece	5B-DBY	B737-31S	Helios Airways	11:52	N/A	No LOC	0849:50 FL340 left engine flame-out. 0851:40 Start of descent. 0859:47 7,000 ft right engine flame-out. 0903:32 Impact.	Hypoxia, fuel exhaustion. Under the partial control of a cabin crew member.
04-Sep-00	Qld, Australia	VH-SKC	Beech 200	Mining Charter Flight	Unavailable	5,000	Unavailable	Unavailable. Gradual steady descent over a period of hours.	Planned cruise level was FL250. Observed at FL343. Hypoxia, fuel exhaustion. Low level loss of control. No CVR or FDR.
07-Oct-07	Near Nanches, WA, USA	N430A	C208A	Kapowsin Air Sports	~ 02:00	15,000	8,000	3	Hypoxia and stall. Pilot conscious but hypoxic.

Appendix E: Accident case studies – a sample of accidents involving a glide

Date:	Location:	Reg:	Type:	Operator:	Duration (mm:ss):	Altitude Loss (ft):	Av. V/S: (fpm)	Max. Distance from start of emergency (NM):	Comments:
14-Oct-04	Jefferson City, MO, USA	N8396A	CL-600	Pinnacle Airlines	20:30	41,000	2,000	81	Dual engine flame-out. 2154:36 Stick-shaker. 2215:06 Impact.
23-Jul-83	Gimli, Canada	C-GAUN	B767-233	Air Canada	17:00	28,500	1,700	39	'Gimli Glider'. Fuel exhaustion. High for landing and side-slipped.
24-Aug-01	Azores, Portugal	C-GITS	A330-243	Air Transat	19:00	34,500	1,800	65	Fuel leak, fuel exhaustion.
16-Jan-02	Serenan, Indonesia	PK-GWA	B737-300	Garuda Indonesia	~ 4:00	18,500	4,600	~ 35	Dual engine flame-out due to water/hail ingestion.

Appendix F: Search Strategy Working Group underwater search areas



Appendix G: Explanatory notes on BTO and BFO analysis

This appendix provides some explanatory notes on the BTO and BFO calculations used by the satellite communications group. The organisations within the group worked independently using different techniques but collaboratively came to a consensus on the results of their analysis.

BTO Analysis

The BTO measurement comprises two components: a bias component caused by fixed delays in the system, plus a variable component caused by the time taken for the outbound radio wave to pass from the GES to the aircraft and the inbound radio wave to make the return journey. This allows a simple equation to be developed relating satellite to aircraft distance to timing delay.

$$Range_{(satellite\ to\ aircraft)} = \frac{c.(BTO - bias)}{2} - Range_{(satellite\ to\ Perth\ GES)} \quad (1)$$

where

bias is a fixed (and constant) delay due to GES and AES processing
c is the speed of light

To determine the bias value, and to get an indication of the accuracy of the technique, signals exchanged between the GES and aircraft, historical values were analysed with the known aircraft location.

BTO Example

An example of this would be to use the values in the 30 minutes prior to take off. During this 30 minute period the satellite moved 122 km. Table 1 shows the location of the satellite, aircraft and GES during this period, expressed in an Earth Centred Earth Fixed (ECEF) coordinate system where the centre of the earth is the origin, the z-axis is due North and the x and y axes are in the equatorial plane with 0° and 90° longitude respectively. Note: this example uses a simplified ellipsoid Earth model.

Table 1: BTO Calibration Geometry

Terminal	Location (km)			Lat	Lon
	X	Y	Z	°N	°E
GES (Perth)	-2368.8	4881.1	-3342.0	-31.8	115.9
AES (KLIA)	-1293.0	6238.3	303.5	2.7	101.7

Time	Satellite Location (km)			Dist to Satellite	
(UTC)	X	Y	Z	GES (km)	AES (km)
16:00:00	18118.9	38081.8	706.7	39222.7	37296.0
16:05:00	18119.6	38081.5	727.9	39225.0	37296.4
16:10:00	18120.3	38081.2	748.7	39227.3	37296.7
16:15:00	18120.9	38080.9	769.2	39229.6	37297.1
16:20:00	18121.6	38080.6	789.4	39231.8	37297.4
16:25:00	18122.2	38080.3	809.1	39233.9	37297.8
16:30:00	18122.9	38080.0	828.5	39236.1	37298.1

17 measurements taken during this 30 minute period can be processed to estimate the fixed timing bias. The mean bias of -495,679 µs is then used to predict the path length from the measured data (Table 2 right hand columns), showing a high degree of consistency. The peak error out of all 17 measurements is 17.7 km in the distance from GES to AES and back, equivalent to less than 9 km in the distance between the satellite and the AES.

Table 2: BTO Calibration (Kuala Lumpur International Airport)						
Time (UTC)	BTO (µS)	Path (km)	Transmission Delay (µs)	Bias (µs)	Predicted Path (km)	Error (km)
16:00:13	14820	153037	510478	-495658	153044	-6.3
16:00:17	14740	153037	510478	-495738	153020	17.7
16:00:18	14780	153037	510478	-495698	153032	5.7
16:00:18	14820	153037	510478	-495658	153044	-6.3
16:00:23	14740	153037	510478	-495738	153020	17.7
16:00:23	14820	153037	510478	-495658	153044	-6.3
16:00:32	14820	153037	510478	-495658	153044	-6.3
16:09:37	14840	153048	510514	-495674	153050	-1.7
16:09:47	14840	153048	510514	-495674	153050	-1.7
16:11:04	14840	153048	510514	-495674	153050	-1.7
16:11:13	14860	153048	510514	-495654	153056	-7.7
16:27:59	14920	153068	510581	-495661	153074	-5.5
16:28:16	14860	153068	510581	-495721	153056	12.5
16:29:17	14860	153068	510581	-495721	153056	12.5
16:29:42	14920	153068	510581	-495661	153074	-5.5
16:29:50	14940	153068	510581	-495641	153080	-11.5
16:29:52	14920	153068	510581	-495661	153074	-5.5
			Average:	-495679		

With the bias value determined from the ground measurements the in-flight measurements can be processed to determine the satellite to aircraft distance at each measurement point.

Additional information

The signals at 18:25:27 and 00:19:37 were both generated as part of a Log-on sequence after the terminal has likely been power cycled, contrasting with the other messages which were generated as part of a standard ‘Log-on/Log-off Acknowledgement’ (LLA) exchange. Each power up sequence starts with a Log-on Request message which has been found to have a fixed offset of 4600 µs relative to the LLA message exchange by inspecting historical data for this aircraft terminal. The subsequent messages during the Log-on sequence have variable delay, and so are not helpful in this analysis. This means that the BTO data for 18:25:34 and 00:19:37 should be ignored, but that corrected BTO values of 12520 and 18400 µs may be derived from the Log-on Request messages at 18:25:27 and 00:19:29 respectively.

BFO Analysis

Unlike the timing calculation, which predicts the location of the aircraft relative to the satellite from the BTO measurement, the frequency calculation works backwards, taking the aircraft location and velocity at a given time and calculating the BFO that this would generate. This enables the likelihood of potential flight paths to be evaluated, depending on how well the projected BFO values align with the measured values during the flight.

The BFO may be calculated by combining the contributions of several factors:

$$BFO = \Delta F_{up} + \Delta F_{down} + \delta f_{comp} + \delta f_{sat} + \delta f_{AFC} + \delta f_{bias} \quad (2)$$

where

ΔFup	is the Doppler on the signal passing from the aircraft to the satellite
ΔFdown	is the Doppler on the signal passing from the satellite to the GES
δf comp	is the frequency compensation applied by the aircraft
δf sat	is the variation in satellite translation frequency
δf AFC	is the frequency compensation applied by the GES receive chain
δf_{bias}	is a fixed offset due to errors in the aircraft and satellite oscillators

BFO Example

The uplink and downlink Doppler may be calculated from the relative movement of the aircraft, satellite and GES using the signal frequencies of 1646.6525 MHz (uplink) and 3615.1525 MHz (downlink). The satellite location and velocity are accurately documented by Inmarsat for satellite station keeping and collision avoidance activities and a selection are shown in Table 3 for the key times used in the analysis.

Table 3: Satellite Location and Velocity (ECEF)

Time	Satellite Location (km)			Satellite Velocity (km/s)		
(UTC)	x	y	z	x'	y'	z'
16:30:00	18122.9	38080.0	828.5	0.00216	-0.00107	0.06390
16:45:00	18124.8	38079.0	884.2	0.00212	-0.00114	0.05980
16:55:00	18126.1	38078.3	919.2	0.00209	-0.00118	0.05693
17:05:00	18127.3	38077.6	952.5	0.00206	-0.00120	0.05395
18:25:00	18136.7	38071.8	1148.5	0.00188	-0.00117	0.02690
19:40:00	18145.1	38067.0	1206.3	0.00189	-0.00092	-0.00148
20:40:00	18152.1	38064.0	1159.7	0.00200	-0.00077	-0.02422
21:40:00	18159.5	38061.3	1033.8	0.00212	-0.00076	-0.04531
22:40:00	18167.2	38058.3	837.2	0.00211	-0.00096	-0.06331
00:10:00	18177.5	38051.7	440.0	0.00160	-0.00151	-0.08188
00:20:00	18178.4	38050.8	390.5	0.00150	-0.00158	-0.08321

The aircraft terminal adjusts its' transmit frequency to compensate for the Doppler induced on the uplink signals by the aircraft velocity. Aircraft heading and ground speed are used to calculate the Doppler shift the signal would experience if the satellite was at its nominal location over the equator. This only partially compensates for the Doppler associated with aircraft velocity as it does not allow for vertical movement (which introduces discrepancies when the aircraft is climbing/ descending) and the satellite is rarely at its nominal location: these small errors are immaterial to the communications performance, but do affect the BFO. This is δf_{comp} in equation 2.

Signals received by the satellite are translated in frequency, amplified and relayed to the GES. The satellite translation frequency is derived from an ultra-stable oscillator which is maintained in a temperature controlled enclosure to improve its stability, nevertheless its temperature (and hence frequency translation) varies throughout the day. During eclipse periods when the satellite passes through the earth's shadow, the satellite temperature drops significantly resulting in a further variation in translation frequency. Such an eclipse occurred during the flight of MH370 starting at 19:19 and ending at 20:26. The changes of satellite oscillator frequency with time are represented by δf_{sat} in equation 2.

The GES translates the frequencies it receives from the satellite to an Intermediate Frequency (IF) before passing them to the equipment that demodulates and processes them. The translation frequency it applies is controlled by an Automatic Frequency Control (AFC) loop to compensate for the downlink Doppler. The AFC loop works by monitoring the absolute frequency of a reference signal transmitted through the satellite, and using these measurements to determine the appropriate translation frequency to apply over a 24 hour period. The hardware used to implement this AFC loop in the Perth GES only partially compensates for the downlink Doppler, and the translation frequency cannot readily be deduced by arithmetic calculation, however its effects can be measured. This is δf_{AFC} in equation 2.

The reason for the partial compensation is that the Perth EAFC receiver was not designed to handle the case where the reference Pilot signal is transmitted from a different hemisphere to that in which it is received. In the MH370 situation the reference Pilot signal was transmitted from the Burum GES in the Netherlands, and received at Perth, resulting in the equipment only being able to partially remove the C Band Doppler component.

The EAFC receiver at Perth is an old unit that is unable to accept negative latitude values to service southern hemisphere locations as described. Inmarsat operates the unit in such a manner that it reduces the effect of the C Band Doppler rather than removing it completely. Such an approach is perfectly serviceable for communications use.

An algorithm was used which enabled determination of the frequency translation variations applied in the GES due to the EAFC receiver. However this is of limited utility to the analysis as there is still the uncertainty related to the translation frequency applied by the satellite.

Inmarsat compared the measured frequency of the Burum LC Pilot signal received at the Perth GES (after passing through the satellite and the Perth receive chain) with the frequency that would have been expected due to the effect of Doppler shift due to satellite movement. This determined the combined effect of satellite translation frequency and GES EAFC frequency variation. This combined factor was used to determine the 'Satellite and EAFC Effect' in the BFO calculations.

The final component in the frequency calculation is a fixed bias component related to the aircraft and satellite oscillator errors. Whilst manufactured to high tolerances, the oscillators on the aircraft and the satellite exhibit small fixed frequency errors which result in a bias value appearing in the BFO associated with any particular terminal. As the value is constant it can be determined through calibration measurements when the aircraft location and velocity are known. This is δf_{bias} in equation 2.

A key problem in solving equation 2 is determining the values of δf_{sat} and δf_{AFC} at the arc crossing times. This was resolved by measurements taken on a fixed frequency L Band reference signal that was transmitted from Inmarsat's GES in Burum (Netherlands) through the 3F1 satellite and received in the Perth GES, where its final frequency was recorded after passing through the EAFC controlled down conversion chain. These measurements allowed the combined value of δf_{sat} and δf_{AFC} to be determined at the appropriate times, as documented in Table 4.

Table 4: Satellite and AFC values

Time UTC	(δf sat + δf AFC) Hz
16:30:00	29.1
16:42:00	27.6
16:55:00	25.8
17:07:00	24.1
18:25:00	10.7
19:41:00	-0.5
20:41:00	-1.5
21:41:00	-18.0
22:41:00	-28.5
00:11:00	-37.7
00:19:00	-37.8

Tables 5 and 6 present an example BFO calculation during the early phase of flight MH370 when the aircraft location, ground speed and heading are known. They illustrate the sensitivity of the BFO frequency calculation to heading and latitude errors, showing that the calculation works and that it is reasonably sensitive to errors in aircraft location and heading.

Table 5: BFO Sensitivity to Aircraft Heading Errors

Measurement		Heading			
Parameter	-25°	True	+25°	Unit	Notes
Time	17:07	17:07	17:07	UTC	
Aircraft Latitude	5.27	5.27	5.27	°N	
Aircraft Longitude	102.79	102.79	102.79	°E	
Aircraft Ground Speed	867	867	867	kph	
Aircraft Heading	0	25	50	°ETN	
Bias Component	152.5	152.5	152.5	Hz	From Calibration
Aircraft Freq. Compensation	108.9	489.5	777.8	Hz	Calculated (for 64.5°E satellite)
Aircraft Doppler (uplink)	-75.3	-459.4	-756.8	Hz	Aircraft velocity towards satellite
Satellite Doppler (uplink)	-3.2	-3.2	-3.2	Hz	Satellite velocity towards aircraft
Satellite Doppler (downlink)	-71.9	-71.9	-71.9	Hz	Satellite velocity towards Perth GES
Satellite and EAFC Effect	24.1	24.1	24.1	Hz	Measured
Predicted BFO	135.1	131.7	122.5	Hz	
Measured BFO	132.0	132.0	132.0	Hz	Measured
Error	3.1	-0.3	-9.5	Hz	Close match at true heading

Table 6: BFO Sensitivity to Aircraft Latitude Errors

Measurement		Latitude			
Parameter	-5°	True	+5°	Unit	Notes
Time	17:07	17:07	17:07	UTC	
Aircraft Latitude	0.27	5.27	10.27	°N	
Aircraft Longitude	102.79	102.79	102.79	°E	
Aircraft Ground Speed	867	867	867	kph	
Aircraft Heading	25	25	25	°ETN	
Bias Component	152.5	152.5	152.5	Hz	From Calibration
Aircraft Freq. Compensation	398.3	489.5	577.1	Hz	Calculated (for 64.5°E satellite)
Aircraft Doppler (uplink)	-367.9	-459.4	-547.5	Hz	Aircraft velocity towards satellite
Satellite Doppler (uplink)	-7.6	-3.2	+1.1	Hz	Satellite velocity towards aircraft
Satellite Doppler (downlink)	-71.9	-71.9	-71.9	Hz	Satellite velocity towards Perth GES
Satellite and EAFC Effect	24.1	24.1	24.1	Hz	Measured
Predicted BFO	127.5	131.7	135.5	Hz	
Measured BFO	132.0	132.0	132.0	Hz	Measured
Error	-4.5	-0.3	3.5	Hz	Close match at true latitude

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Investigation

ATSB Transport Safety Report
MH370 - Definition of Underwater Search Area

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