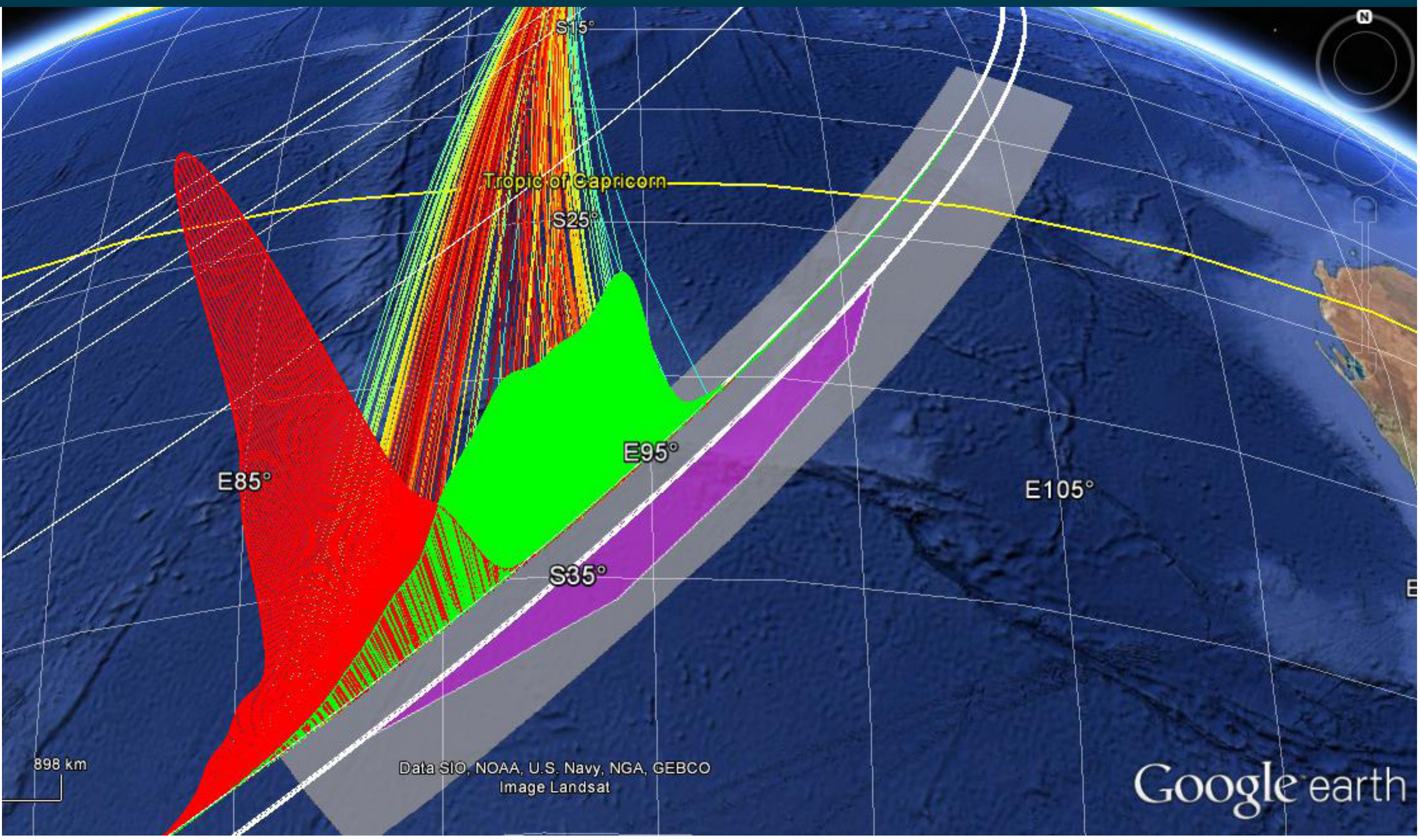
Australian Government

Australian Transport Safety Bureau

# MH370 – Flight Path Analysis Update




Investigation

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**Addendum**

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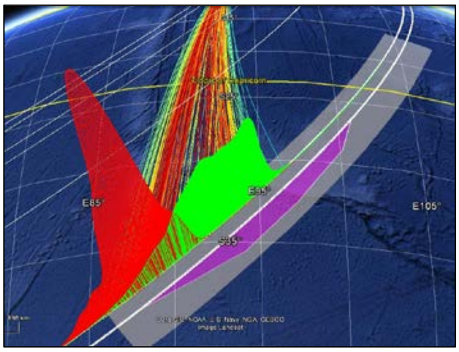
# Executive summary




On 8 March 2014, flight MH370, a Boeing 777-200ER registered 9M-MRO, lost contact with Air Traffic Control during a transition between Malaysian and Vietnamese airspace. 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 close to where the aircraft's fuel was exhausted.

Refinements to the analysis of both the satellite and flight data have been continuing since the loss of MH370. The analysis has been undertaken by a team from the UK, US, Australia and Malaysia working both independently and collaboratively. Priority, medium and wide search areas were provided in the ATSB's MH370 – Definition of Underwater Search Areas (June report).

The latest analyses indicate that the next, underwater, phase of the search should be prioritised further south within the wide search area.

Work is continuing with refinements to the analysis of the SATCOM data. This ongoing work may result in changes to the prioritisation and locale of search activity over the period of the underwater search.

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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 between Malaysian and Vietnamese airspace. 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.

The ATSB is responsible for leading the search for MH370 and therefore directing search activities to areas that represent the best prospects of locating MH370. A search strategy group, coordinated by the ATSB, has been working towards defining the most probable position of MH370 at the time of the last aircraft-to-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 from the time of the its last radar contact. Information recorded by a satellite ground station at the time of handshakes (log-on request from aircraft or log-on interrogation[2] from the ground station) with MH370 was used to estimate the track of the aircraft. Satellite communications information from two unanswered ground to air telephone calls was also available.

| | |
|---|---|
| • 1st handshake (log-on request) initiated by the aircraft | 1825.27[3] |
| • Unanswered ground to air telephone call | 1839.52[4] |
| • 2nd handshake (log-on interrogation) initiated by the ground station | 1941.00 |
| • 3rd handshake (log-on interrogation) initiated by the ground station | 2041.02 |
| • 4th handshake (log-on interrogation) initiated by the ground station | 2141.24 |
| • 5th handshake (log-on interrogation) initiated by the ground station | 2241.19 |
| • Unanswered ground to air telephone call | 2313.58 |
| • 6th handshake (log-on interrogation) initiated by the ground station | 0010.58 |
| • 7th handshake (log-on request) initiated by the aircraft | 0019.29 |
| • Failed handshake (log-on interrogation) initiated by the ground station - aircraft did not respond | 0115.56 |

On 26 June 2014, an ATSB report[5] presented the results of analysis conducted by the group. The report noted that prioritisation within the search area would change as refinements in the analysis of the SATCOM data occurred.

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1 All times used in this report are referenced to Coordinated Universal Time (UTC) using the format hhmm or hhmm.ss
2 The time of the log-on interrogation is determined by an inactivity timer of approximately 60 minutes.
3 Associated log-on request transmissions with R-channel BTO/BFO continued to 1828.15
4 Unanswered telephone call at approximately 1840 and therefore referred to as 1840 in this update

This update presents recent results from analysis of SATCOM data and information from an unanswered ground-to-air telephone call 17 minutes after the last radar information. The update provides a key input to the ATSB's planning and direction of current underwater search activities to locate MH370 in the Southern Indian Ocean. This update should be read in conjunction with the June report.

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[5] ATSB Transport Safety Report, External Aviation Investigation, AE-2014-054, MH370 – Definition of Underwater Search Areas (June report)

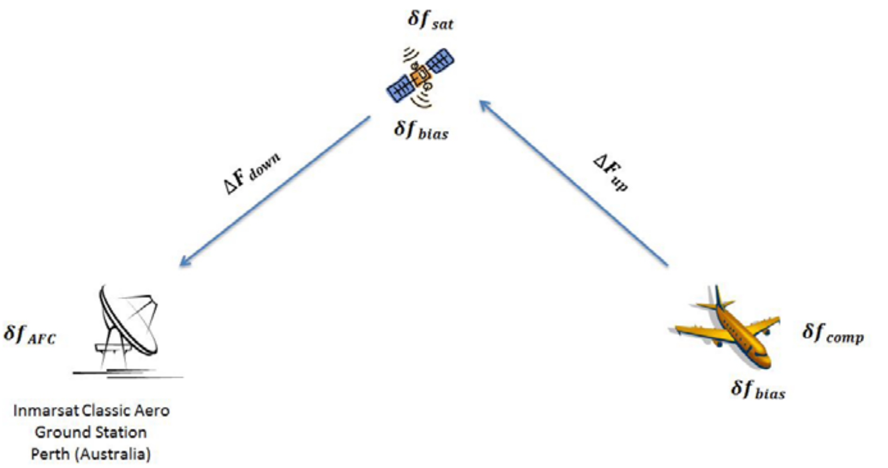
# Refining the probable location of MH370

## Refinements to satellite communications (SATCOM) system model

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 total contributions to the BFO of the transmissions from MH370 are shown in Figure 1.

**Figure 1: Total of BFO contributions**




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

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

Source: SATCOM Working Group

Once the other contributions to the BFO had been determined and removed, the remainder represented the Doppler Effect associated with the relative motion of the aircraft with respect to the satellite ($\Delta F_{up}$). For a given relative motion, there were many combinations of aircraft speed and heading that would produce the correct frequency change (BFO). The refinements to this system model applied to flight path analysis since the release of the June report can be summarised as follows:

- An improved Enhanced Automatic Frequency Control (EAFC) and satellite translation frequency measurement approach was implemented with a smoothed transfer function.
    - The mathematical model of EAFC behaviour was refined with increasing accuracy. The satellite frequency translation component correlated well with the recorded satellite oscillator temperature. The June model assumed the EAFC receiver fitted a 24 hour sinusoidal correction to the data, while the receiver actually applied a correction from a 24-hour moving average of the deviation from a pilot signal.

- The output of the EAFC was sampled and recorded in real-time every 10 seconds by a separate measurement system, which has its own ground oscillator reference. This allowed the frequency of the Burum[6] L band-to-C band pilot signal received at the Perth Ground Earth Station (GES) (after passing through the satellite and the Perth receive chain) to be accurately measured and compared with the frequency that would have been expected due to the effect of the Doppler shift due to the 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 (Table 1). This improved approach had the advantage of removing any dependencies on assumptions about how either system behaves.

**Table 1: Updated Satellite and AFC values[7]**

| Time UTC | ($\delta$f sat + $\delta$f AFC) Hz |
|---|---|
| 16:30:00 | 29.1 |
| 16:42:00 | 26.7 |
| 16:55:00 | 25.9 |
| 17:07:00 | 24.2 |
| 18:25:00 | 10.8 |
| 19:41:00 | -1.2 |
| 20:41:00 | -1.3 |
| 21:41:00 | -17.9 |
| 22:41:00 | -28.5 |
| 00:11:00 | -37.7 |
| 00:19:00 | -38.0 |

Source: SATCOM working group

- The precise location of the Perth GES was updated to match that used in the EAFC software. The aircraft velocity vector was corrected for latitude (minor issue only relevant when aircraft was at low latitude).

As a result, a new model has been developed and confidence in the model by the group has increased through correlation with previous flights.

## Refinement of southern turn location using ground initiated phone call data

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 the aircraft had approximately continued on that track. However, by the time of the ground initiated telephone call at 1840, analysis of the BFO data associated with the telephone call indicated that the aircraft was travelling approximately south. This analysis was based on the assumption that the aircraft had maintained a relatively constant altitude during the time of the telephone call.

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6 Burum GES - Inmarsat Ground Earth Station located at Burum, Netherlands

7 A description and initial version of the 'Unified' model was presented in Appendix G of the June report (updated in August). The flight path reconstruction in the June report was based mainly on the previous 'Eclipse 2' model as shown in Appendix A of the June report. Probable paths using the initial Unified model did not affect the definition of the priority search area at that time.

As a result of this analysis, there is greater confidence that a turn to the south occurred before the unanswered telephone call at 1840.

Examination of the second telephone call BFO at about 2314 did not narrow the range of predicted latitudes at the 7th arc intercept.

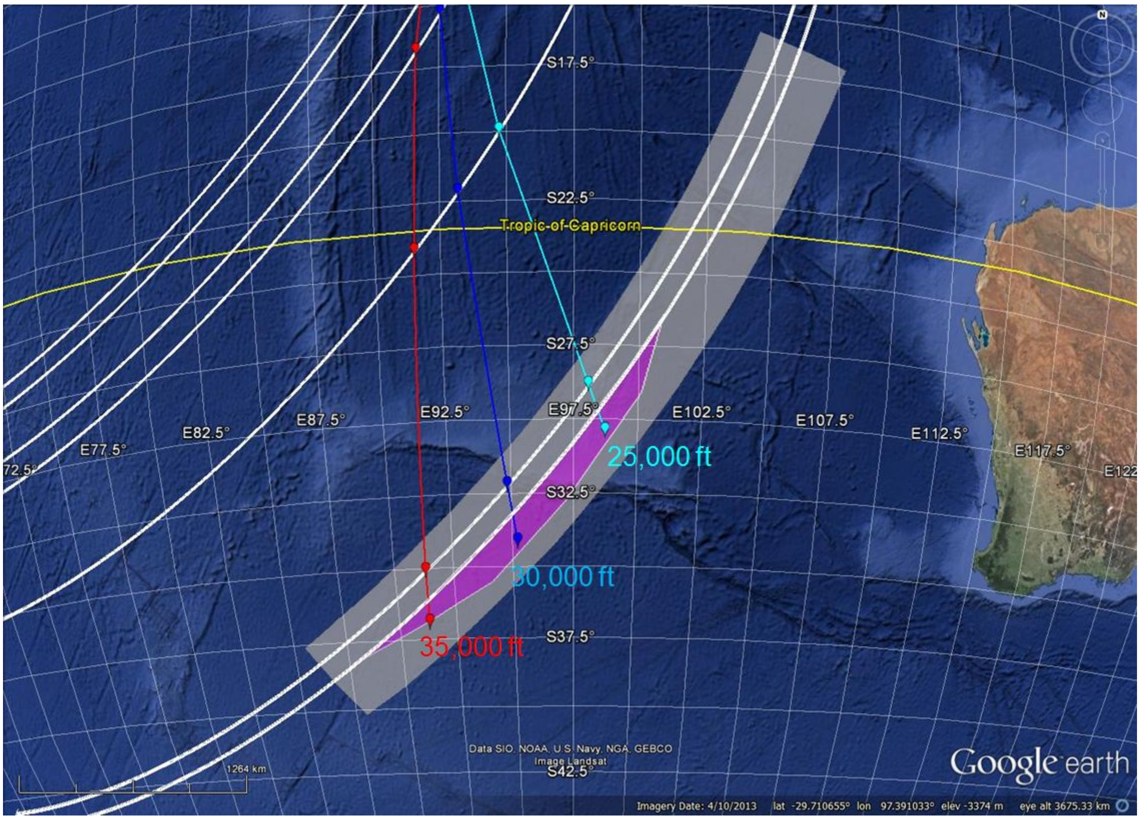
## Aircraft performance boundaries for southern turn prior to 1840

At 1707, the last ACARS transmission from the aircraft provided the total weight of the fuel remaining on board at 43,800 kg. Between that time and 1822, while the aircraft was being tracked by primary radar, the aircraft's speed and consequently fuel burn was estimated.

The MRC (maximum range cruise) performance was calculated for a turn shortly after the last radar contact near the 1st arc (1828) and at the time of the 1st telephone call (1840). These scenarios were used to estimate the MRC boundary as they represented an early turn and a late turn.

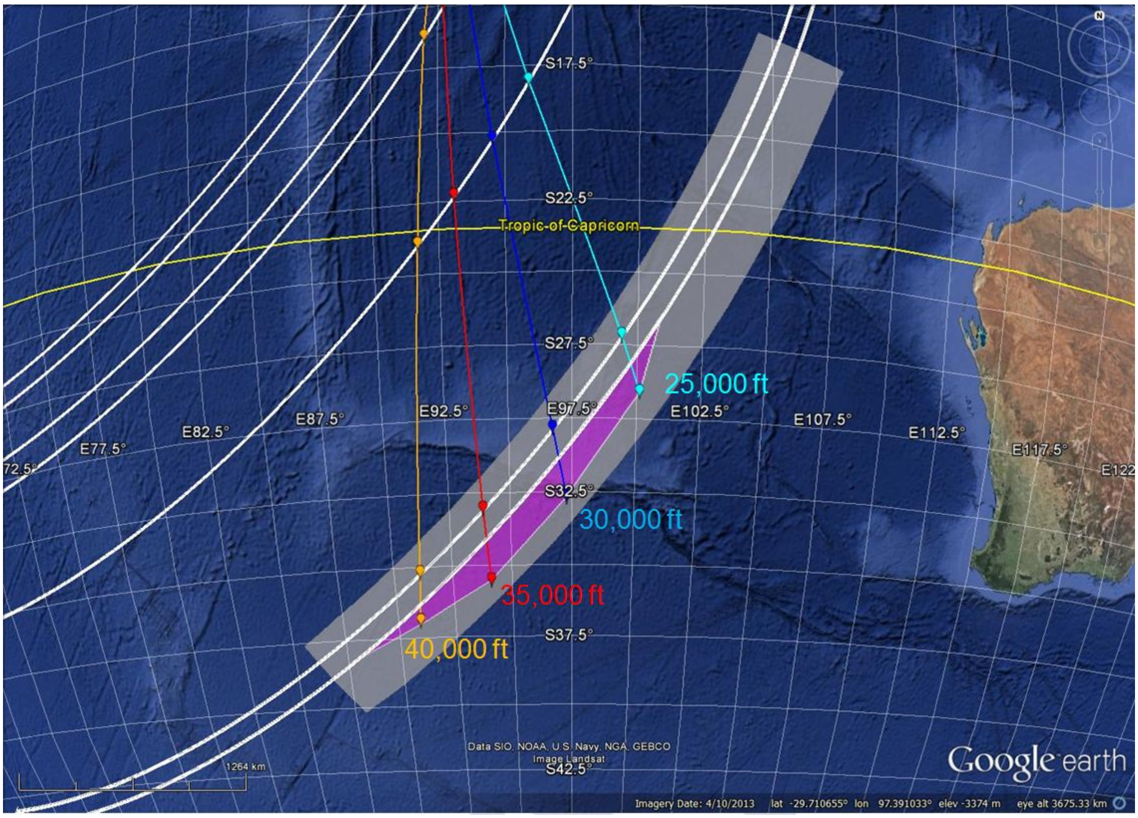
- The heading and speed were constrained so that all paths intersected the BTO arcs at the times of the handshakes.
- Winds were incorporated into the calculations: true airspeed remained constant and ground speed varied due to the winds.
- The paths that defined, and were within, the MRC boundary beyond the 7th arc were the paths for a turn near the 1st arc - 1828 (35,000 ft, 30,000 ft and 25,000 ft) (Figure 2) and for 1840 (40,000 ft, 35,000 ft, 30,000 ft, and 25,000 ft) (Figure 3).
- The end points of the MRC boundary are associated with the paths that terminated very near the 7th arc. To the south (1828 – 40,000ft) and to the north (1840 – 20,000ft).

**Figure 2: MRC boundary based on turn near the 1st arc - 1828**




**Source: Google Earth/ Flight path reconstruction group**

**Figure 3: MRC boundary based on turn at time of telephone call - 1840**




**Source: Google Earth / Flight path reconstruction group**

## Effect of the latest refinements on flight path reconstruction

### *Southern turn*

The June report avoided discussion of possible manoeuvres between the 1822 last radar point and the 1941 arc, except for range estimates, due to the large number of possible scenarios. The analysis instead used starting locations on the 1941 arc which were able to be reached from the last radar fix using reasonable flight speeds.

A turn southwards before 1840 increases the probability of more southerly intersections with the 1941 arc and consequently solutions which are further south at the 6$^{th}$ (0011) and 7$^{th}$ arc (0019). The southern performance boundary at 0019 remained unchanged from that defined in the June report for a turn south shortly after the last radar point at the 1$^{st}$ arc (see Figure 2).

### *SATCOM System Model*

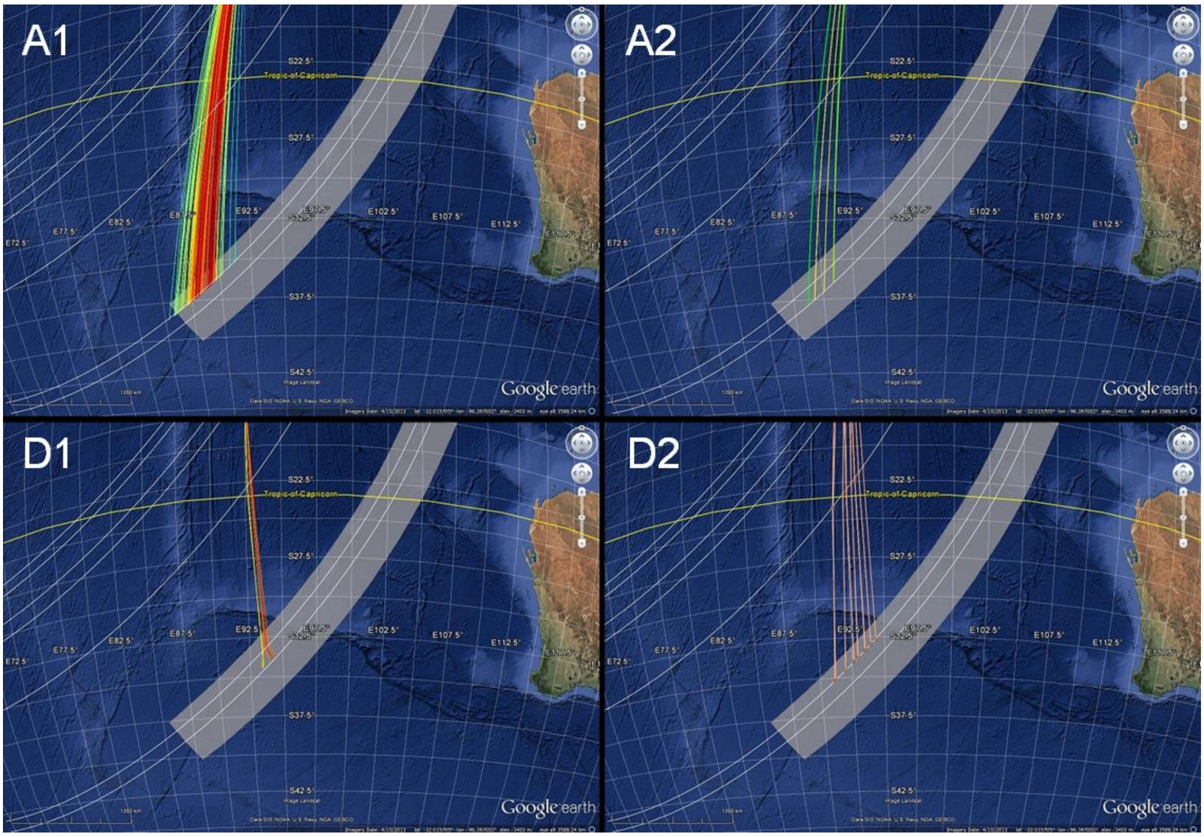
Using various assumptions, the flight path reconstruction group used combinations of aircraft altitudes, speeds and headings to generate candidate paths and calculated the BFO values at the arc crossings for these paths. These values, compared with the recorded BFO values, provided a measure of statistical consistency. The latest refinements to the SATCOM system model affected the calculations of the BFO, therefore the various analyses were required to be repeated. The analysis methods, as per the June report, were categorised into two classes:

- Constrained autopilot dynamics - The aircraft was assumed to have been flown using one of the autpilot modes. Each of these modes is modelled to generate candidate paths. The satellite data (BFO, BTO) values were then calculated for these flight paths and compared against the recorded values.
- Data error optimisation - The candidate path was broken up into steps using successive recorded BTO/BFO values. At each step, speed and/or heading values were varied to

minimise the error between the calculated BFO of the path and the recorded value. Paths were not constrained by the aircraft autopilot behaviour.

The following figure shows graphical representations of results from the various analyses.

**Figure 4: Analysis results – A1 and A2 are two results from the constrained autopilot dynamics method. D1 and D2 are two results from the data error optimisation method.**




**Source: Google Earth / Flight path reconstruction group**

To reconcile some of the differences between the two classes of analysis, a probability distribution of the intersection with the $6^{th}$ arc was prepared.

For the analysis using constrained autopilot dynamics, the top 100 paths were selected on the basis of the match with the satellite data and the consistency with the autopilot behaviour. The paths were coloured according to the probability on the arc at 0011[8]. The distribution driven by autopilot dynamics is the red area in Figure 4. Some southern paths from this analysis were beyond the estimated performance limits (grey area including tolerance for the MRC performance limit estimation) of the aircraft. The performance limits were comparatively certain and therefore results south of the southern performance limit were not considered valid.

For the data error optimisation method, the paths were weighted according to the root-mean-square (RMS) error of the BFO values at each arc crossing. The best 100 paths selected were coloured by probability at 0011. The distribution in the RMS values is the green area in Figure 5.

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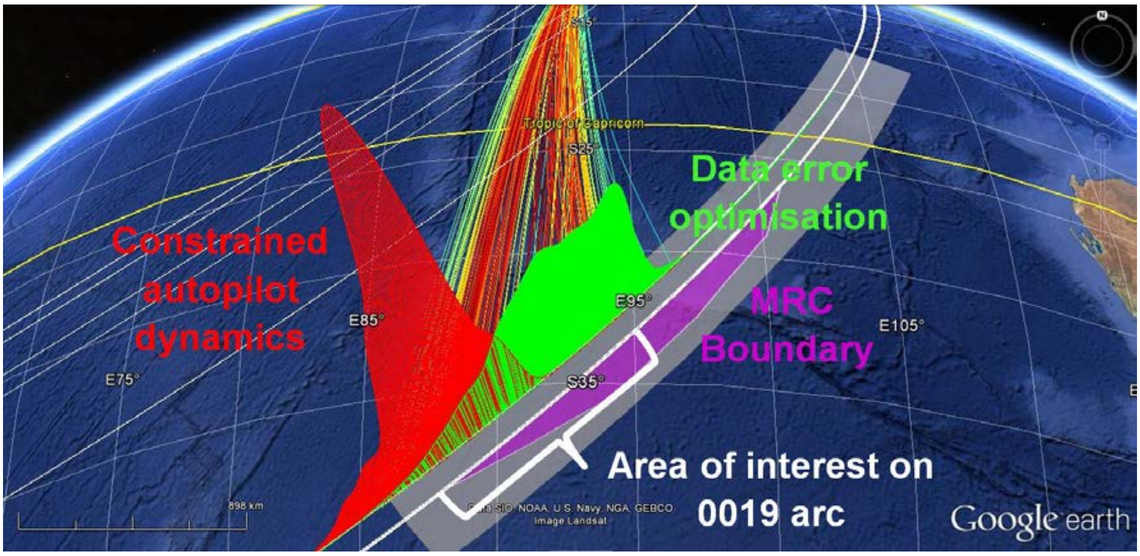
[8] Analyses varied with their consideration of BTO/ BFO at 0011 and 0019. The last time associated with a log-on interrogation request was at the 0011 arc whilst the 0019 arc was a log-on request initiated by the aircraft which had an effect on the BFO.

**Figure 5: Representation of probability distribution at 0011 arc for constrained autopilot dynamics (red) and data error optimization (green). Red flight paths are most probable paths from the two types of analysis. Area of interest on 0019 arc covers 80% of probable paths from the two analyses at 0011 and consideration of the MRC approximate southern boundary**




**Source: Google Earth/ Flight path reconstruction group**

This analysis indicates that the total probability areas overlap between approximately 35°S and 39°S at 0011. The 6th arc between latitudes 32.5°S and 38.1°S covers 80% of the highest probability paths for both analyses. Extrapolating paths and limiting the southern boundary by the MRC intersection with the 7th arc provides an area between approximately 33.5°S and 38.3°S at 0019 (7th arc).

## Update on factors relating to likely MH370 proximity to the 7th arc

### *End-of-flight scenarios*

To estimate and have confidence in a reasonable search area width, it is important to understand the aircraft system status at the time of the SATCOM transmission from the aircraft at 0019.29 (log-on request), and the variations in aircraft behaviour and trajectory that were possible from that time.

The log-on request recorded at the final arc occurred very near the estimated time of fuel exhaustion. The recorded BFO values indicated that the aircraft could have been descending at that time. Aircraft systems analysis, in particular the electrical system and autoflight system, has been ongoing. In support of the systems analysis, the aircraft manufacturer and the operator have observed and documented various end-of-flight scenarios in their B777 simulators.

The simulator activities involved fuel exhaustion of the right engine followed by flameout of the left engine with no control inputs. This scenario resulted in the aircraft entering a descending spiralling low bank angle left turn and the aircraft entering the water in a relatively short distance after the last engine flameout. However when consideration of the arc tolerances, log on messages and simulator activities are combined, it indicates that the aircraft may be located within relatively close proximity to the arc. Whilst the systems analysis and simulation activities are ongoing, based on the analysis to date, the search area width described in the June report remains reasonable with the underwater search to commence at the 7th arc and progress outwards both easterly and westerly.

# Summary

Following the release of the June report, MH370 – Definition of Underwater Search Areas, further refinement of the satellite communications (SATCOM) data and analysis has been ongoing. A combination of a better understanding of the ground initiated telephone call messages and a refined SATCOM system model both indicate that an area further south on the 7th arc search should be prioritised.

Although of reasonably high confidence, and relatively large, this area does not contain all the possible derived paths.

This area is intended to be the focus of activities for the initial deployment of the underwater search assets.

Additionally, work is continuing with ongoing examination and analysis of the SATCOM data and end-of-flight scenarios or simulations which may affect the dimensions or flight path probabilities within the search area. The ongoing refinement may result in changes to search asset deployment.

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