Blowin' in the Wind
Scanning the Southern Indian Ocean for MH370
by Richard Godfrey, Bobby Ulich and Victor Iannello

24th June 2019

Introduction

Following on from Richard Godfrey's earlier paper entitled "How to play Russian Roulette and Win" published on 13th February 2019, which covered the first part of the flight and diversion of MH370 into the Straits of Malacca, Richard was contacted by Bobby Ulich, who asked the question "where do we go from here?" Richard Godfrey, Bobby Ulich and Victor Iannello came up with the idea to scan the Southern Indian Ocean (SIO) for possible flight paths of MH370 using a degree of precision, that we believe has not been previously applied and to use certain statistical checks on the presence or absence of correlations in the data. Each of us had independently developed a MH370 flight model using the Boeing 777-200ER aircraft performance data, Rolls Royce Trent 892 fuel range and endurance data, Inmarsat satellite data and the GDAS weather data. The goal was to find all possible MH370 flight routes that fit the data within appropriate tolerances. Additionally, the data would be checked using a set of correlations.

Background

It is generally accepted that the last known position of MH370 is somewhere near flight route N571 between waypoint MEKAR and waypoint NILAM, as inferred by the Malaysian military radar trace and Inmarsat satellite data between 18:25:27.421 UTC and 18:28:14.904 UTC. It is also generally accepted that the MH370 end point is somewhere in the SIO, based on the Inmarsat satellite data between 19:41:02.960 UTC and 00:10:59.928 UTC and the discovery of 20 items of debris, which are either confirmed or likely from MH370. The measured satellite data after 19:41 until 00:11 show that the timing data (Figure 1) follows a smooth curve and the frequency data (Figure 2) follows a straight line. Based on the regular sequence of the satellite data, we make the key assumption that during this time interval, the aircraft was flying with autopilot and autothrottle engaged and with no pilot inputs.

On the other hand, the wind speed and direction as well as the magnetic variation were far from constant for MH370. For example at waypoint BEDAX (5.364328°N 93.787575°E) off the tip of Sumatra at 19:21 UTC, the wind speed was 16.2 knots and the wind direction was easterly from 105.5°T. The average winds were from the East at 17 knots and wind direction from 84°T between the satellite handshakes at 19:41:03 UTC and 20:41:05 UTC. Later, the average winds were from the West at 55 knots and wind direction from 271°T between the satellite handshakes at 22:41:22 UTC and 00:11:00 UTC. Depending on flight path, there is a point midway where the wind direction turns around. Similarly, the magnetic variation (MV) at waypoint BEDAX is 1.21°W, but at 35°S on the same longitude the MV is 21.08°W.

The LNAV lateral navigation mode follows a great circle using waypoint(s) and is only affected in time by the Along-Track Wind (ATW) and Cross-Track Wind (XTW); Constant True Track (CTT) follows a rhumb line (or loxodrome) and is affected by the ATW and XTW; Constant True Heading (CTH) follows a rhumb line and is affected by the ATW and more significantly by the XTW than CTT; Constant Magnetic Track (CMT) and Constant Magnetic Heading (CMH) are additionally affected by the magnetic variation. To misquote Bob Dylan, "the answer to MH370, my friend, is blowin' in the wind".

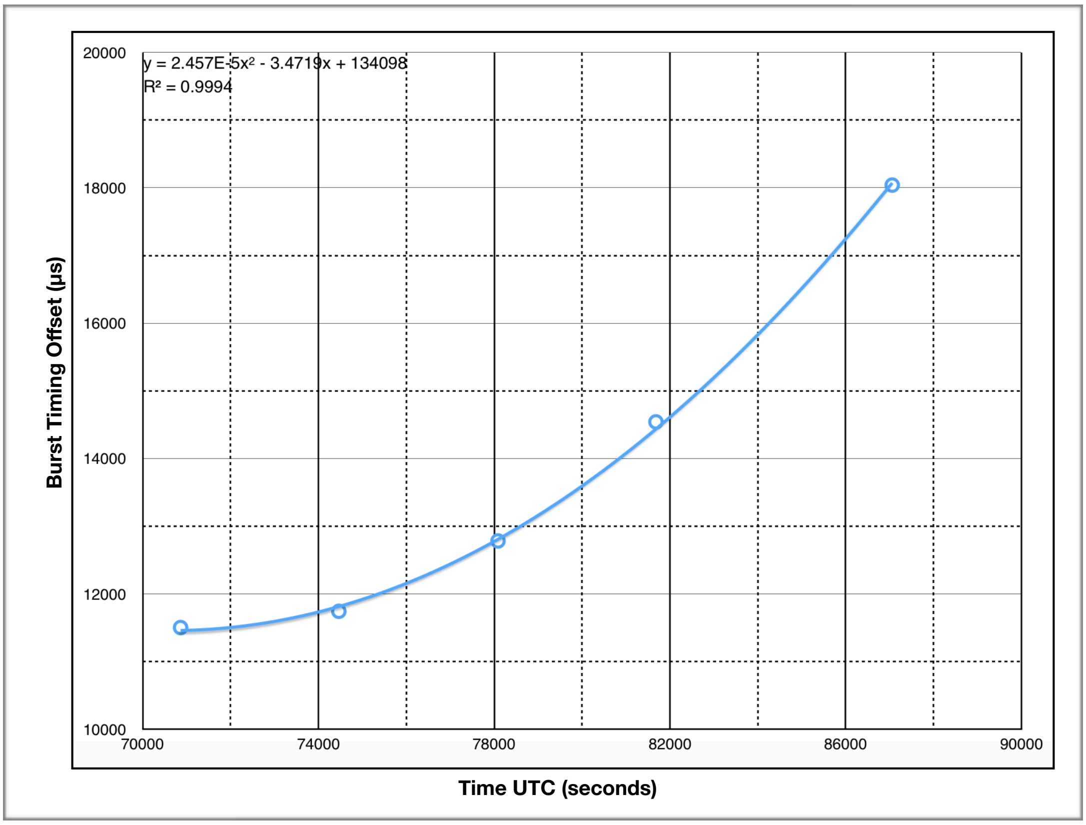


Figure 1: BTO (μs) vs Time (Seconds) from 19:41:03 UTC to 00:11:00 UTC.

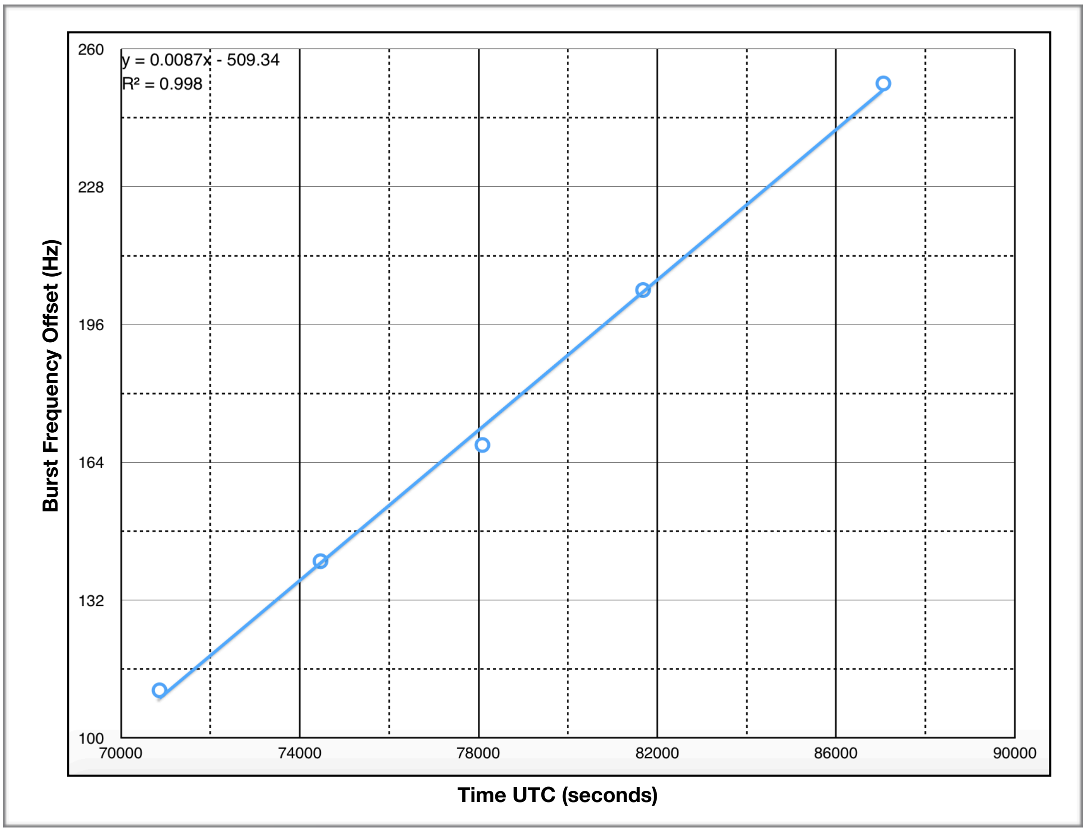


Figure 2: BFO (Hz) vs Time (Seconds) from 19:41:03 UTC to 00:11:00 UTC.

Method

Our assumptions about the automated flight after 19:41 are that there are 7 parameters that determine a possible MH370 flight path:

1. Start Time.
2. Start Latitude.
3. Start Longitude.
4. Flight Level.
5. Lateral Navigation Method.
6. Initial Bearing.
7. Speed Control Mode.

If you draw an arbitrary line of latitude between the area of the last known point and the SIO, MH370 must have crossed this line at a certain time, longitude, flight level and initial bearing using a particular lateral navigation method and speed control mode. Figure 3 below depicts such an arbitrary starting line of latitude.

Last Known Position and Arbitrary Starting Line

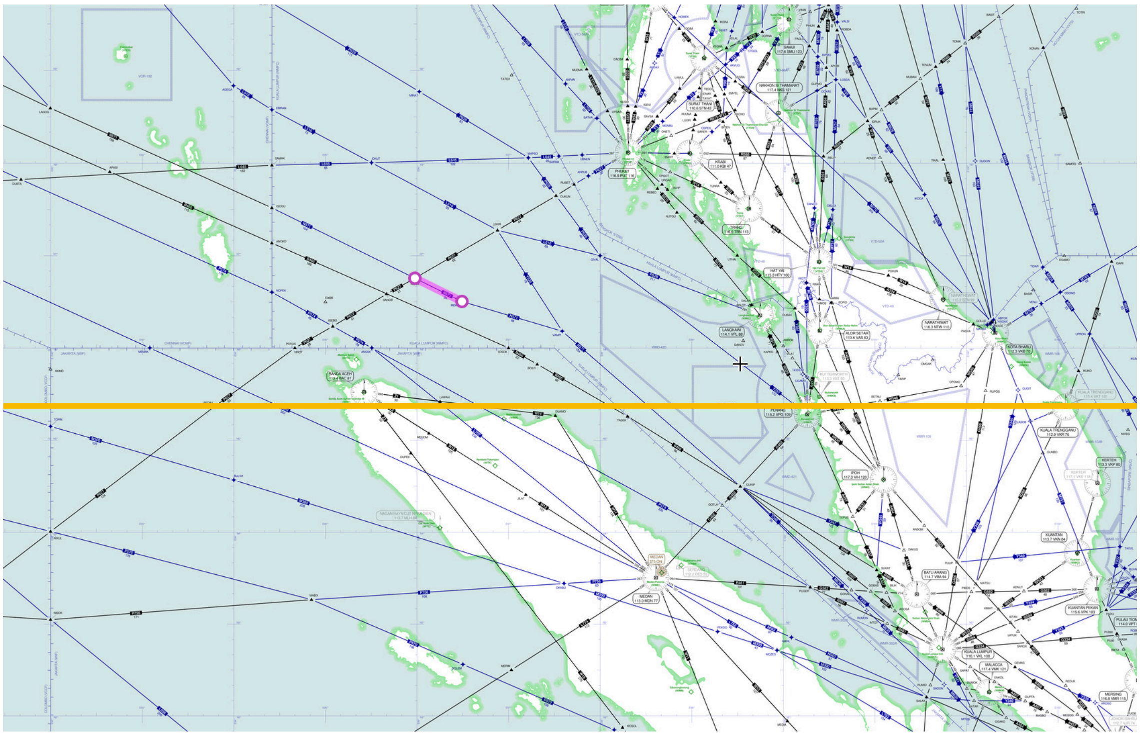


Figure 3: Flight Route N571 from waypoint MEKAR to NILAM

Having fixed the start latitude, the start time and start longitude can be varied for any given flight level, lateral navigation mode, initial bearing and speed control mode and the fit to the aircraft performance data, satellite data and weather data ascertained. The flight model used in the wide area scan was developed by Richard Godfrey. First the altitude and air pressure at the selected flight level is approximated. The GDAS weather data provides the actual surface air pressure and surface air temperature for a given position and time by interpolation. The air pressure for a given flight level is calculated based on the ISA standard surface pressure of 1013.25 hPa and standard surface temperature of 15.0°C. The geometric altitude for a given flight level is then approximated using the actual surface pressure and actual surface temperature. The altitude is used in the satellite data calculations, assuming the flight level is maintained between 19:41:03 UTC and 00:11:00 UTC.

Similarly, the GDAS weather data is interpolated for the exact latitude, longitude and time to find the Outside Air Temperature (OAT) at the given flight level. The GDAS data is available for every degree of latitude and longitude every 3 hours. For example, for a position at 4.688407°N 93.801983°E at 19:39:00 UTC and FL408 (41,047 feet), the GDAS data is retrieved at 4°N 93°E, 5°N 93°E, 4°N 94°E, 5°N 94°E at both 18:00 UTC and 21:00 UTC and at both 200 hPa and 150 hPa and interpolated. The ∂latitude at 0.688407, the ∂longitude at 0.801983, ∂time at 0.450000 and finally the air pressure at the given flight level, which in this example is 180.461 hPa, are used to determine the OAT. The speed of sound is then determined at the resulting OAT and the True Air Speed (TAS) determined for the Mach value for the given Speed Control Mode. Using the same procedure, the GDAS weather data is interpolated for the wind speed and wind direction for the exact latitude, longitude and time at the given flight level.

The Aviation Formulary by Ed Williams (V1.46) and Thaddeus Vincenty (1975a) are used to determine the aircraft's Ground Speed and Track based on the resulting wind speed and wind direction. A new position is then calculated every minute from the start time. The step time is adjusted at each arc crossing to match the Inmarsat data at the 5 points between 19:41:03 UTC and 00:11:00 UTC at the precise times. The ATW and XTW is calculated for each step. The step distance is calculated from the Ground Speed and step time. The whole procedure repeated around 300 times until the MH370 end point is reached. Separately, the fuel endurance and fuel range are checked at various levels of the engines' Performance Degradation Allowance (PDA) to match a fuel exhaustion time of 00:17:30 UTC.

One concern was the accuracy of the GDAS data, so a comparison was made using the GDAS data following the above methodology compared with the ACARS data from flight MH371. The aircraft transmits the Outside Air Temperature (OAT), Wind Speed (WSPD) and Wind Direction (WDIR) normally every 30 minutes in the cruise. However, during the MH371 flight, there were a lot of changes of Flight Level and Track, as well as a lot of changing between the Pacific Ocean Region (POR) and Indian Ocean Region (IOR) Inmarsat satellites. During one stable part of the cruise, the differences between the GDAS model and the actual ACARS data are as follows:

The OAT Actual - Predicted had a Mean Error of -1.0 °C and Standard Deviation of 2.5 °C.
The WSPD Actual - Predicted had a Mean Error of -0.8 knots and Standard Deviation of 1.3 knots.
The WDIR Actual - Predicted had a Mean Error of +1.6 degT and Standard Deviation of 6.8 degT.

The accuracy of the aircraft performance data, satellite data and weather data will be taken into account when determining the width of any search area proposal.

The scan method for each Lateral Navigation Method (LNAV, CTT, CTH, CMT and CMH) and for each Speed Control Mode (Constant Mach and Long Range Cruise) requires stepping through each possible Initial Bearing (initially from 155°T to 195°T) in steps of 1°T. In Constant Mach (CM) the value was set initially at 0.85 and decremented in steps of 0.1 Mach.

Once the Initial Bearing and (if relevant) the Mach has been set, the Start Time or Start Latitude is adjusted to minimise the RMS BTO Residual (BTOR) across the 5 satellite handshake points between 19:41:03 UTC and 00:11:00 UTC. The BTOR is the difference between the predicted BTO and the observed BTO. Then the Start Longitude is varied to minimise the RMS BTOR. Finally the Flight Level is adjusted in steps of 1 (standard altitude steps of 100 feet) to minimise the RMS BTOR. A full report is then produced for each scan and an example is shown in Figure 5 on the page 6 below. A sample start data sheet is shown in Figure 4 below. The definition of GSE is found later in the paper, and the significance of the correlation coefficients is based on the work of Bobby Ulich and will be presented in a future paper.

Figure 4: Example start data sheet.

Item	Value
Start Time (UTC)	19:23:20.000
Start Time (secs)	69,800.000
Start Latitude	5.3643000
Start Longitude	93.7875000
Lateral Navigation Mode	LNAV
Initial Bearing (degT)	180.0000000
Air Speed Mode	LRC
Mach	0.8399 to 0.8343
Flight Level	390
Altitude (feet)	39,300
19:41:03 UTC Latitude	2.9906000
19:41:03 UTC Longitude	93.7875000
19:41:03 UTC Track	180.0000000
00:11:00 UTC Latitude	-33.3652000
00:11:00 UTC Longitude	93.7875000
00:11:00 UTC Track	180.0000000
MEAN BTOR	9.8133
MIN BTOR	-53.8163
MAX BTOR	40.6507
RMS BTOR	34.8928
STDEV BTOR	37.4367
MEAN BFOR	-3.3516
STDEV BFOR	2.5944
RMS GSE	2.09
PDA for MEFE at 00:17:30 UTC	0.9780
CC BTOR Leg Start vs End	-0.3345
CC BTOR vs Time	-0.1502
CC ∂BTOR vs DW GSE + ATW	-0.6149
CC BFOR vs Time	0.6277
CC BFOR vs BTOR	0.4310

Handshake Time (UTC)	Hours (UTC)	At Handshake Time Latitude (°)	Longitude (°)	Altitude MSL (feet)	Flight Level	Observed BTO (µs)	Predicted BTO (µs)	BTO Residual (µs)	∂BTO Residuals = End - Start (µs)	Observed BFO (Hz)	Predicted BFO (Hz)	BFO Error (Hz)	Predicted GDAS SAT (°C)	Predicted Local Sound Speed (knots)	Predicted Mach	Predicted TAS (knots)	Track (degT)	Predicted GDAS Wind Speed (knots)	Predicted GDAS Wind From (degT)
19:23:20.000		5.3643000	93.7875000	39,300	390								-53.906	575.999	0.8397	483.685	180.0000	15.362	104.393
19:41:03	19.6842	2.990600	93.787500	39,300	390	11,500	11,509.4	9.4		111.0	103.50	-7.50	-54.046	575.816	0.8399	483.628	180.0000	23.206	97.090
									31.2										
20:41:05	20.6847	-5.141600	93.787500	39,300	390	11,740	11,780.7	40.7		141.0	139.41	-1.59	-54.321	575.454	0.8405	483.669	180.0000	6.106	95.134
									-19.5										
21:41:27	21.6908	-13.337500	93.787500	39,300	390	12,780	12,801.1	21.1		168.0	165.57	-2.43	-54.431	575.309	0.8408	483.720	180.0000	11.347	62.747
									-74.9										
22:41:22	22.6894	-21.425100	93.787500	39,300	390	14,540	14,486.2	-53.8		204.0	199.84	-4.16	-54.811	574.810	0.8396	482.610	180.0000	26.602	259.749
									85.5										
24:11:00	24.1833	-33.365200	93.787500	39,300	390	18,040	18,071.7	31.7		252.0	250.91	-1.09	-52.717	577.558	0.8348	482.145	180.0000	48.364	260.519
24:19:37		-34.287700	93.787500	23,658		18,410	18,404.8	-5.2		-2.0	-1.99	0.01	-41.117	592.557	0.8341	494.274		0.810	234.707
Richard Godfrey 21st June 2019						19:41:03 to 24:11:00	Mean	9.8			Mean	-3.35							
							STDEV	37.4			STDEV	2.59							
							RMS	34.9			Slope	0.93	Hz/hour						
Correlation Coefficients						BTOR Start vs End -0.3345		BTOR vs Time -0.1502		∂BTOR vs ATW + GSE -0.6149		BFOR vs Time 0.6277			BFOR vs BTOR 0.4310				

Handshake Time (UTC)	ROI Scan Trial # 671 Curved Path Length Lat/Lon (NM)	Average Ground Speed Lat/Lon (knots)	1-Min Leg Average Predicted Mach	LNAV 1-Min Leg Average GDAS SAT (°C)	1-Min Leg Average TAS (knots)	Track 180° 1-Min Leg Average Heading (degT)	1-Min Leg Average GDAS Wind Speed (knots)	Speed Mode LRC 1-Min Leg Average GDAS Wind From (degT)	1-Min Leg Average Along-Track Wind Speed (knots)	FL390 1-Min Leg Average Ground Speed (knots)	Ground Speed Error (knots)	Flight Model V19.7 Average Track (degT)	Lateral Error (degT)
19:23:20.000													
	141.9965	480.9337	0.8398	-54.113	483.524	177.717	19.641	103.154	-4.294	479.231	1.703	180.000	0.000
19:41:03													
	486.4575	486.1876	0.8402	-54.129	483.708	177.957	17.662	84.903	1.197	484.905	1.283	180.000	0.000
20:41:05													
	490.3927	487.4139	0.8406	-54.319	483.757	178.897	10.060	76.041	1.728	485.486	1.928	180.000	0.000
21:41:27													
	484.2198	484.8931	0.8402	-54.248	483.577	180.045	11.843	154.592	-0.357	483.220	1.673	180.000	0.000
22:41:22													
	715.7614	479.1243	0.8372	-54.258	481.833	186.513	55.250	269.800	0.333	482.166	-3.042	180.000	0.000
24:11:00													
	55.3537	391.1244	0.8344	-50.244	484.619	184.537	39.077	251.852	-10.664	473.955	-82.830	180.000	0.000
24:19:37													
	Mean								0.73		0.46		
	RMS								1.08		2.09		
	MEFE 00:17:30 UTC PDA 0.9780%												

Figure 5: Example Full Report of a single scan.

The only constraint placed on the start point of the track into the SIO was that the Final Major Turn (FMT) had to be completed by the time MH370 reached the 2nd Arc at 19:41:03 UTC (depicted in orange in Figure 6 below). The maximum range of MH370 from the Malaysian military radar end point to the 2nd Arc at 19:41:03 UTC reaches from 16.0°N to 4.3°S along the 2nd Arc (depicted in red in Figure 6 below). The maximum range is based on an average Ground Speed of 506 knots.

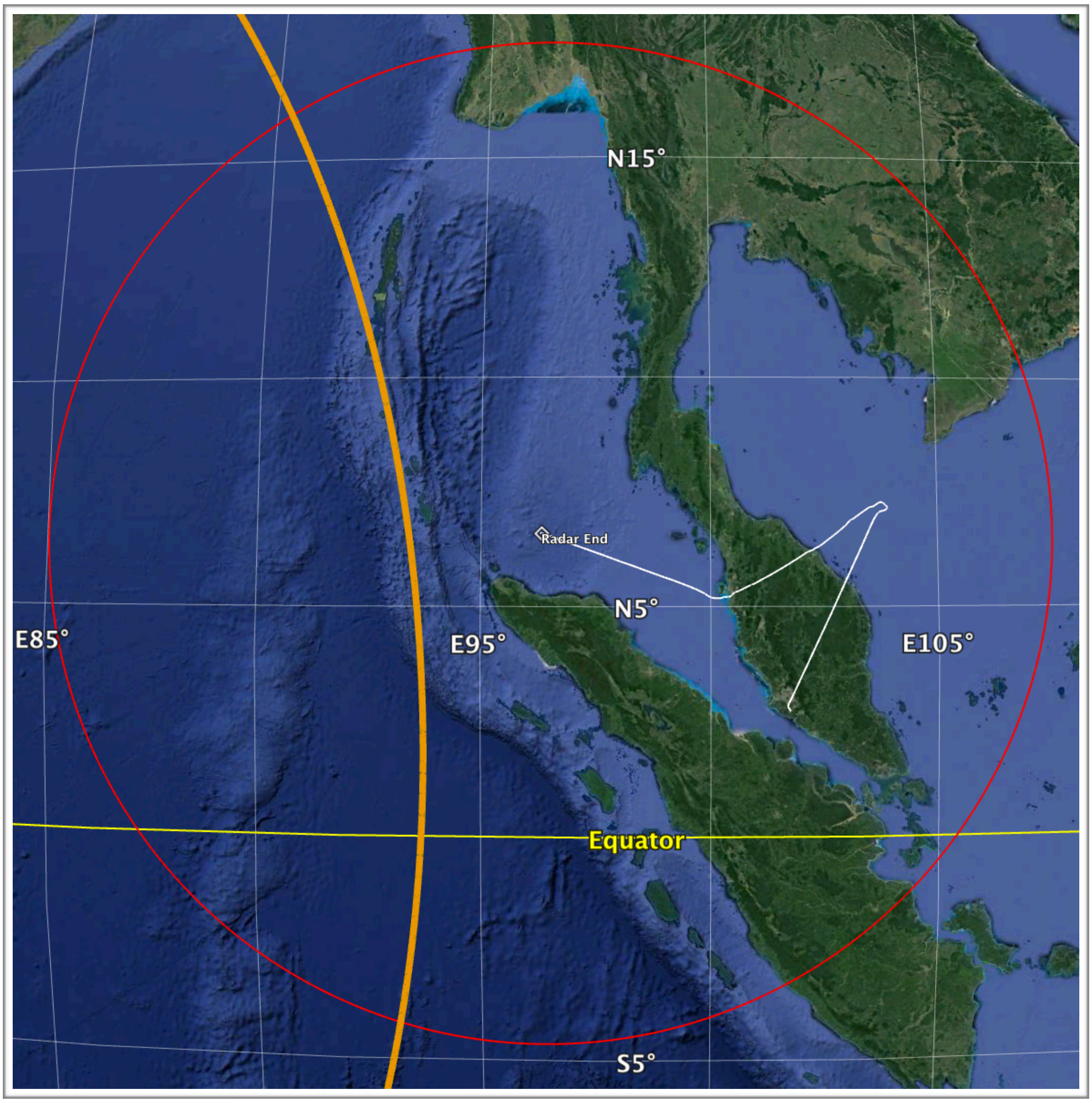


Figure 6: Maximum range of MH370 from the Radar end point by 19:41:03 UTC.

There is a large range of possible flight paths into the SIO, limited by the available fuel and the requirement to fit the satellite and weather data. The range of MH370 end point latitudes on the 7th Arc, which have been considered in the wide area scan, is from 17.6°S to 40.3°S. A flight path in LNAV navigation mode on an initial bearing of 155°T in Long Range Cruise speed mode at flight level 290 ends at 17.6°S. A flight path in LNAV navigation mode on an initial bearing of 190°T in Constant Mach 0.84 speed mode at flight level 403 ends at 39.3°S. Both these flight paths are depicted in light blue in Figure 7 below. For reference, a flight path in LNAV navigation mode on an initial bearing of 180°T in Constant Mach 0.84 speed mode at flight level 403 ends at 34.5°S (depicted in green in Figure 7 below).

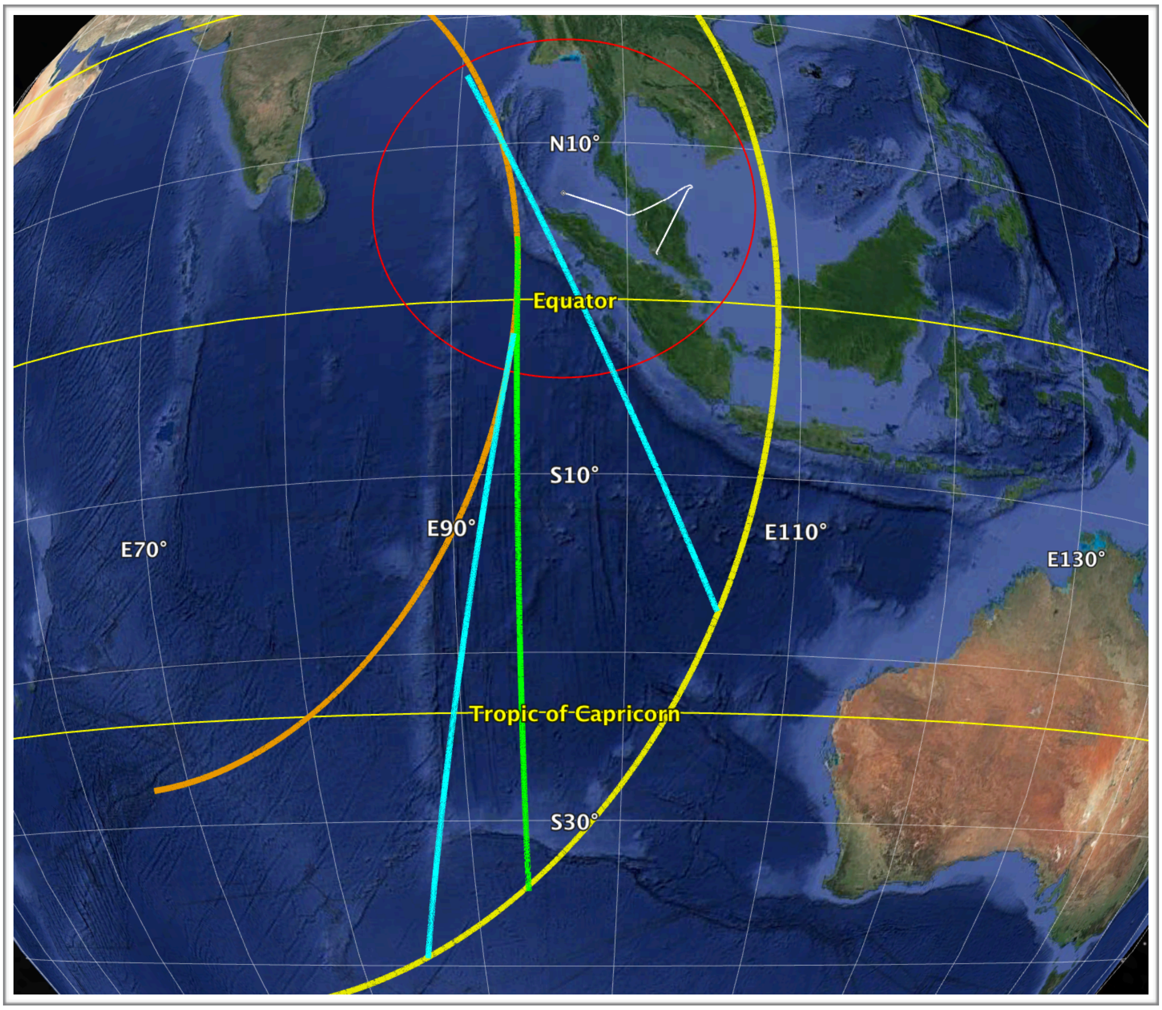


Figure 7: Range of possible flight paths into the SIO.

Results

A number of MH370 candidate flight paths have been found over the years by various analysts resulting in Regions of Interest (ROIs) that have either already been searched or have been proposed for a further search. The table in Figure 8 below lists some of the ROIs. The table includes some new ROIs which have been found as a result of the current systematic search. Some of the ROIs can be readily dismissed as the standard deviation BTO residual ("<47 μs"), standard deviation BFO residual ("<4.3 Hz") or the calculated PDA ("<1.5%") is too high.

Flight Route	Speed Mode	Flight Level	Latitude 00:19:37 UTC	Average GS (knots)	Average A-T Wind (knots)	PDA (%)	Mean BTOR (μs)	STDEV BTOR (μs)	STDEV BFOR (Hz)	RMS GSE (knots)
LNAV192	CM 0.838	FL355	-40.30	478.39	-8.8630	1.2835	-2.2783	40.0161	6.1431	1.7284
LNAV190	CM 0.84	FL403	-39.33	478.39	-3.2423	1.3848	-6.2559	57.3962	5.3093	1.2018
CTT183	CI52	FL400	-36.12	480.89	-0.1100	1.6111	0.2513	45.5468	3.6789	1.3431
LNAV180	LRC	FL385	-34.40	482.54	-0.1149	1.0006	0.3971	47.0368	2.8341	1.5098
LNAV180	CM 0.84	FL403	-34.58	483.56	2.2422	1.3691	0.6135	56.2870	2.5570	2.4878
LNAV178	CM 0.836	FL405	-33.21	480.61	2.2015	1.9127	-0.2808	56.3785	2.4263	1.3008
CMT181	MRC	FL330	-32.29	502.02	-1.5916	1.5827	4.4111	265.3137	2.0587	1.4695
LNAV170	LRC	FL350	-28.18	475.11	-0.5252	1.1693	-2.1716	45.1963	3.0637	2.5586
CTH170	LRC	FL290	-28.89	446.90	3.4664	2.7953	-1.2023	88.9579	2.9538	3.5273
CTT160	CM 0.84	FL403	-20.91	474.36	-5.8060	1.3923	0.2636	37.9687	7.9940	0.7159
CTT158	CM 0.84	FL403	-19.30	473.45	-6.8256	1.3953	0.0788	42.0023	9.0142	0.6249
LNAV155	LRC	FL290	-17.58	450.69	-0.1253	2.7253	-3.2182	119.6363	9.1699	0.2038

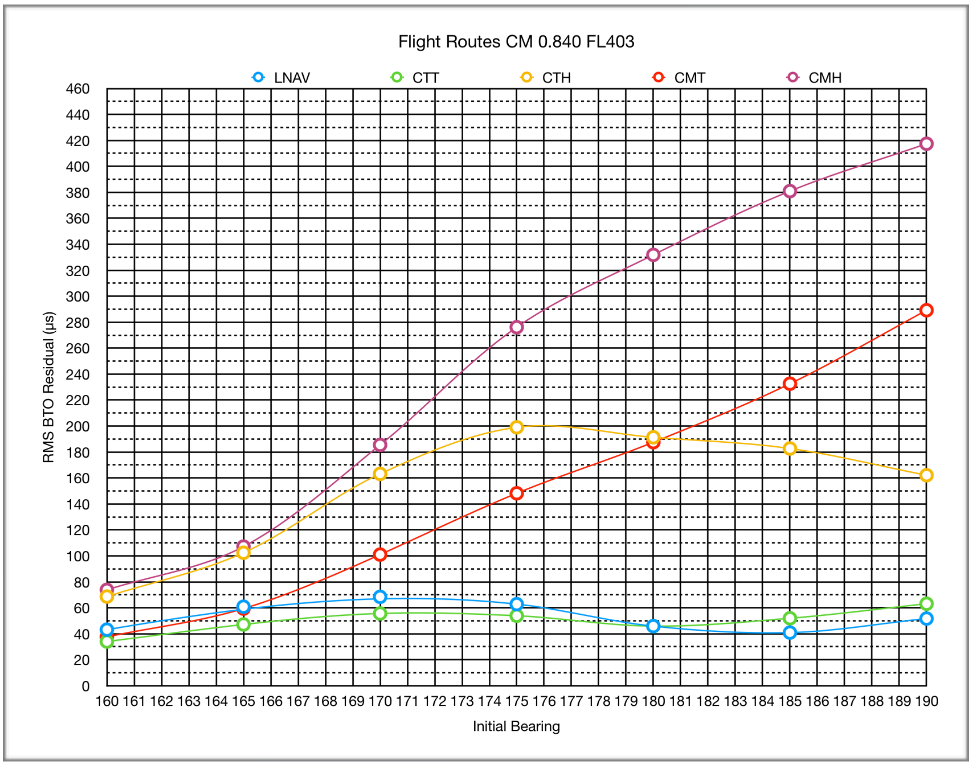
Figure 8: Table of possible MH370 flight paths resulting in a candidate Region of Interest

The aircraft performance of a Boeing 777-200ER in Long Range Cruise (LRC) speed mode determines the Mach speed at a given flight level and weight. The results shown on subsequent pages are grouped into 3 categories, a high and fast flight route (Constant Mach 0.84, FL403), medium flight route (LRC, FL350) and a low and slow flight route (LRC, FL290).

Time (UTC)	Aircraft Weight (kg)	FL290	FL310	FL330	FL350	FL370	FL390	FL410	FL430
19:20:00	203,164	0.7493	0.7764	0.8031	0.8274	0.8400	0.8398	0.8390	0.8390
19:41:03	200,973	0.7463	0.7734	0.8003	0.8257	0.8400	0.8400	0.8390	0.8390
20:41:05	194,844	0.7370	0.7638	0.7910	0.8175	0.8354	0.8397	0.8393	0.8390
21:41:27	188,850	0.7277	0.7542	0.7817	0.8088	0.8300	0.8394	0.8396	0.8390
22:41:22	183,102	0.7188	0.7450	0.7728	0.8005	0.8248	0.8392	0.8398	0.8390
00:11:00	174,765	0.7056	0.7314	0.7588	0.7868	0.8136	0.8332	0.8392	0.8395
00:17:30	174,166	0.7047	0.7304	0.7578	0.7858	0.8127	0.8326	0.8391	0.8396

Figure 9: Long Range Cruise (LRC) Mach vs Flight Level

At high speed (Constant Mach 0.84) and high altitude (FL403 40,517 feet), the RMS BTOR is below 47 μs in CTT navigation mode for an initial bearing from 160°T to 165°T as well as from 178°T to 184°T and in LNAV mode from 179°T to 188°T. The STDEV BFOR is below 4.3 Hz in CTT and LNAV mode from 168°T to 183°T. Combining both the BTOR and BFOR criteria, there is a Region of Interest (ROI) in LNAV or CTT mode between 178°T and 183°T.



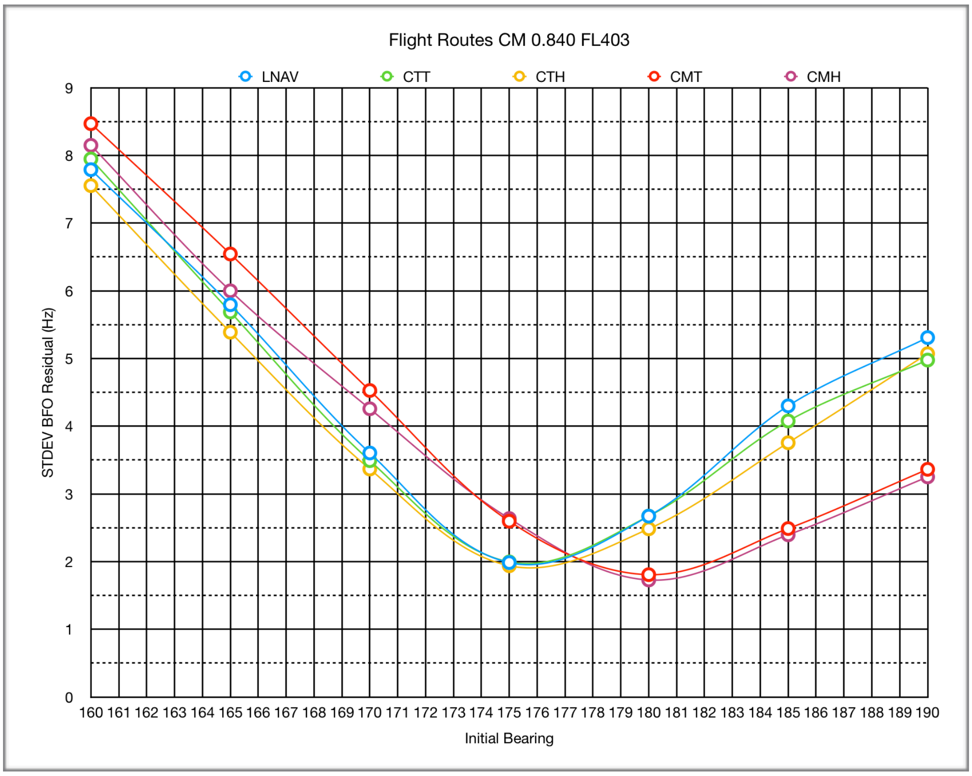
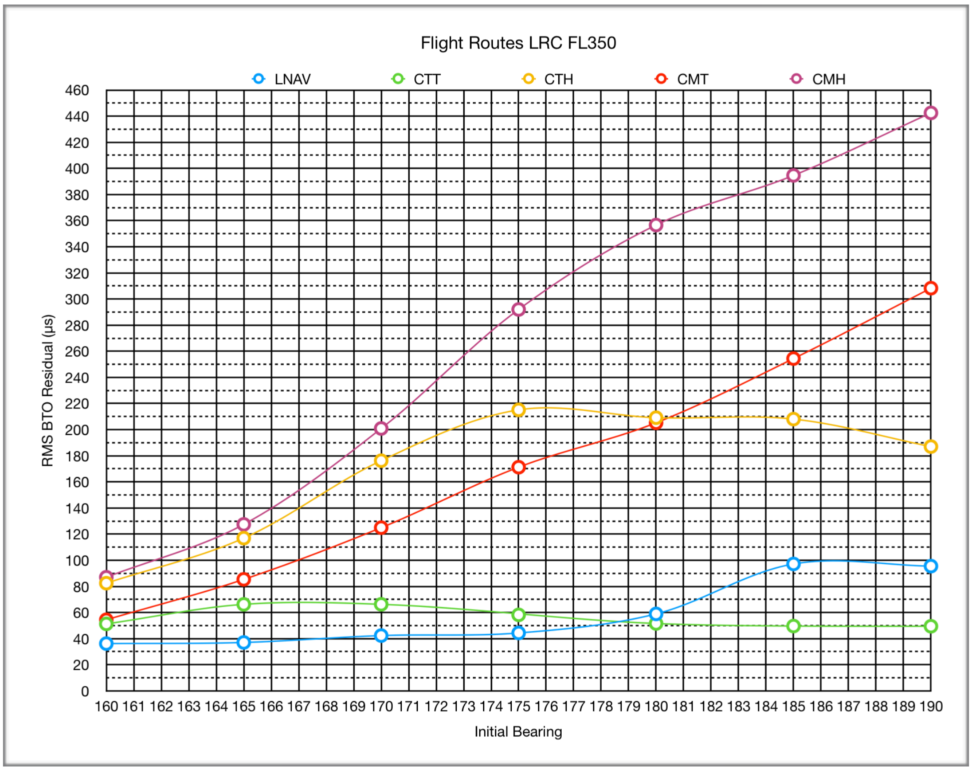


Figure 10 and 11: RMS BTOR and STDEV BFOR at CM 0.84 and FL403.

At medium speed (Long Range Cruise Mach 0.8257 to 0.7868) and medium altitude (FL350 36,503 feet), the RMS BTOR is below 47 μs in LNAV navigation mode for an initial bearing below 178°T. The STDEV BFOR is below 4.3 Hz in LNAV mode from 168°T to 183°T and in CTT mode from 168°T to 184°T. Combining both the BTOR and BFOR criteria, there is a ROI in LNAV mode between 168°T and 178°T.



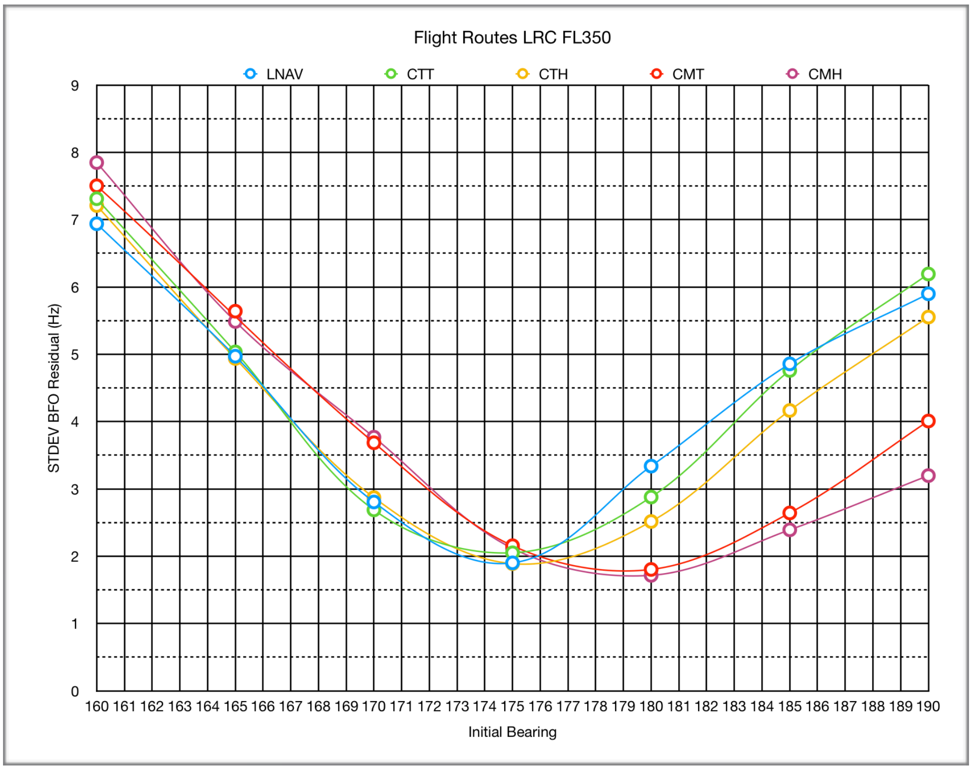
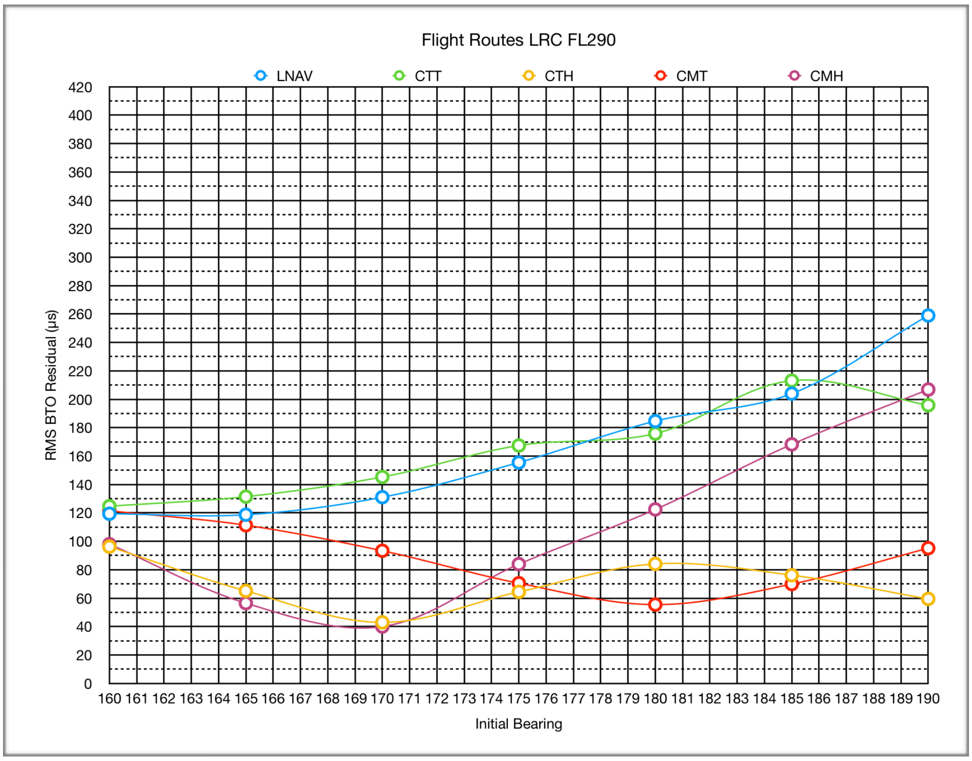


Figure 12 and 13: RMS BTOR and STDEV BFOR at LRC and FL350.

At low speed (Long Range Cruise Mach 0.7475 to 0.7056) and low altitude (FL290 30,240 feet), the RMS BTOR is below 47 μs in CTH navigation mode for an initial bearing from 168°T to 172°T and in CMH mode from 167°T to 172°T. The STDEV BFOR is below 4.3 Hz in CTH and CMH mode above 169°T. Combining both the BTOR and BFOR criteria, there is a ROI in CTH and CMH mode between 169°T and 172°T.



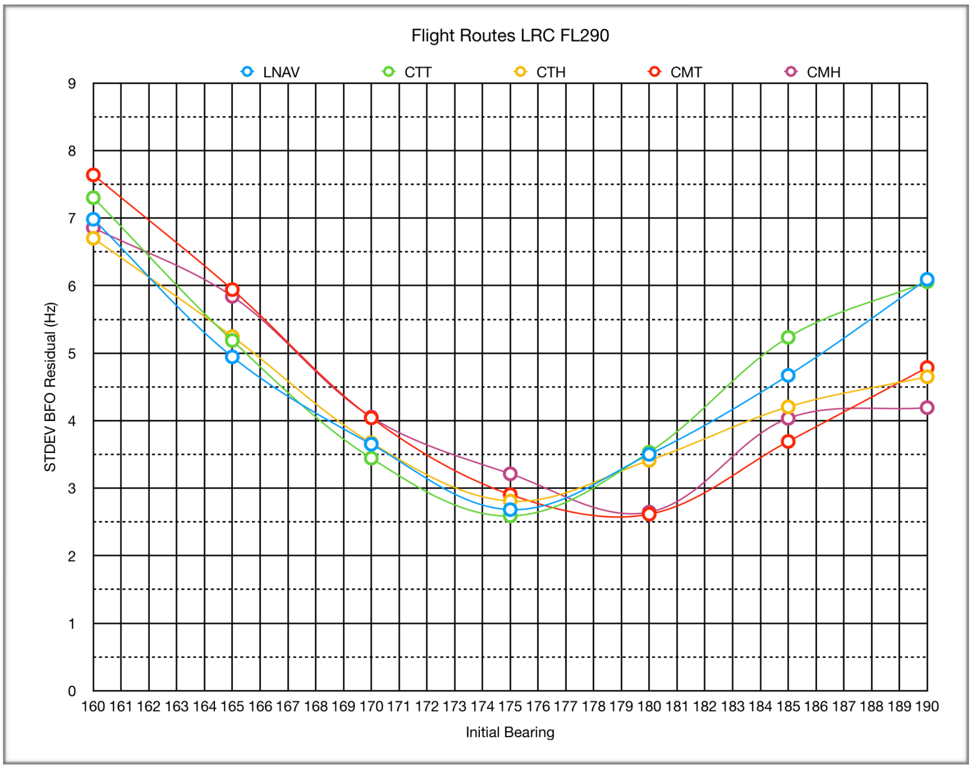
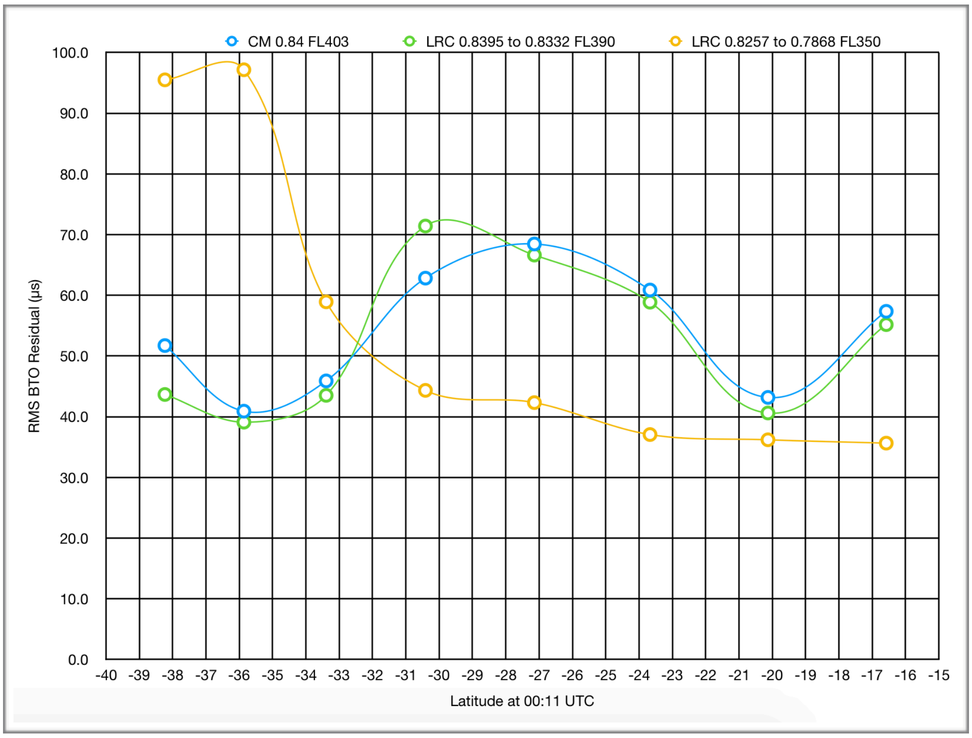


Figure 14 and 15: RMS BTOR and STDEV BFOR at LRC and FL290.

A closer analysis of the RMS BTORs vs latitude at 00:11:00 UTC shows that south of around 32.5°S CM 0.84 speed mode was more likely and north of around 32.5° LRC speed mode is more likely. More importantly, the STDEV BFORs show that only latitudes from around 25°S to 36°S are below 4.3 Hz.



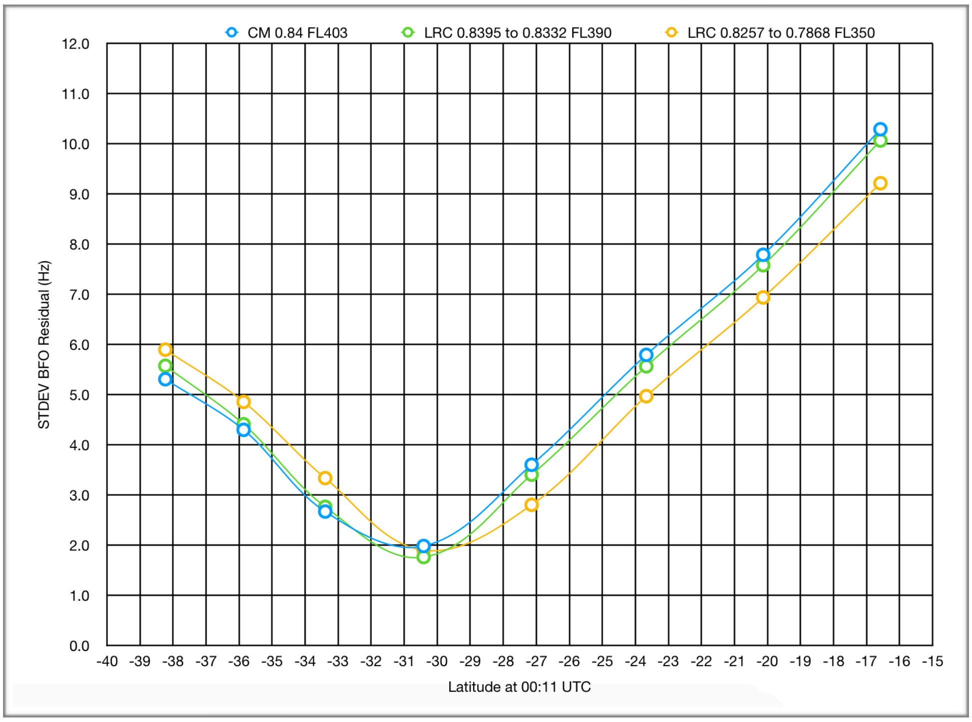
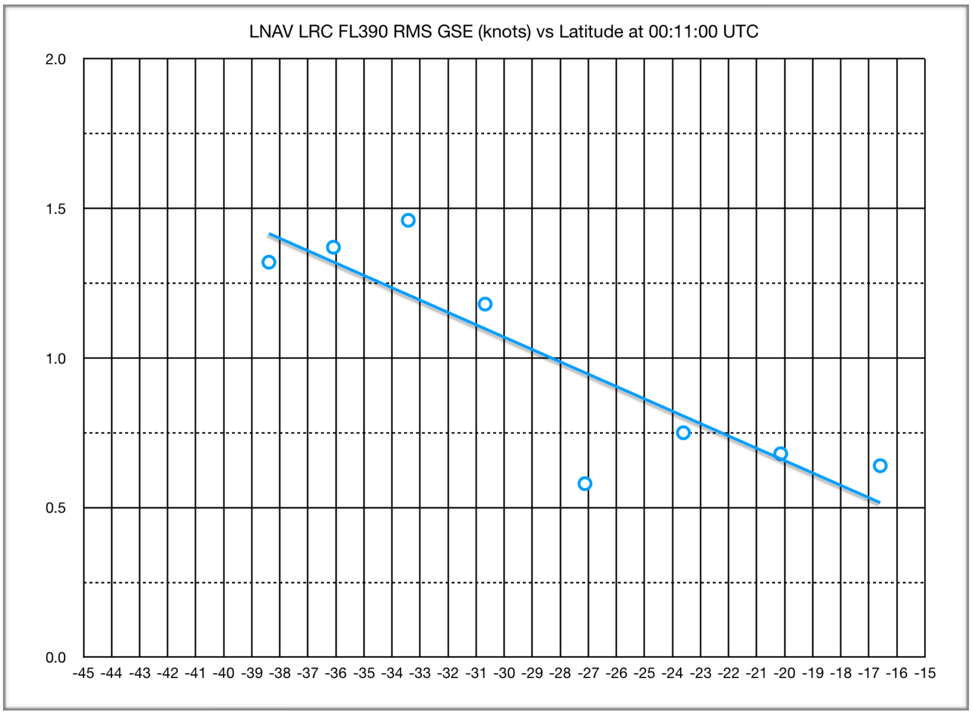


Figure 16 and 17: RMS BTOR and STDEV BFOR vs Latitude at 00:11:00 UTC.

The along-track Ground Speed Error (GSE) is the difference between the leg average Ground Speed calculated from the Latitude and Longitude of the leg start and end points at each satellite handshake compared with the average Ground Speed predicted by the model every minute during the leg. The RMS GSE is expected to be between 1.0 and 3.0 knots. The RMS for all LNAV180 LRC FL390 flight paths show that the expected value greater than 1.0 is only achieved for solutions south of 30°S (Figure 18). The ROI candidates in the table in Figure 8 show a similar result (Figure 19).



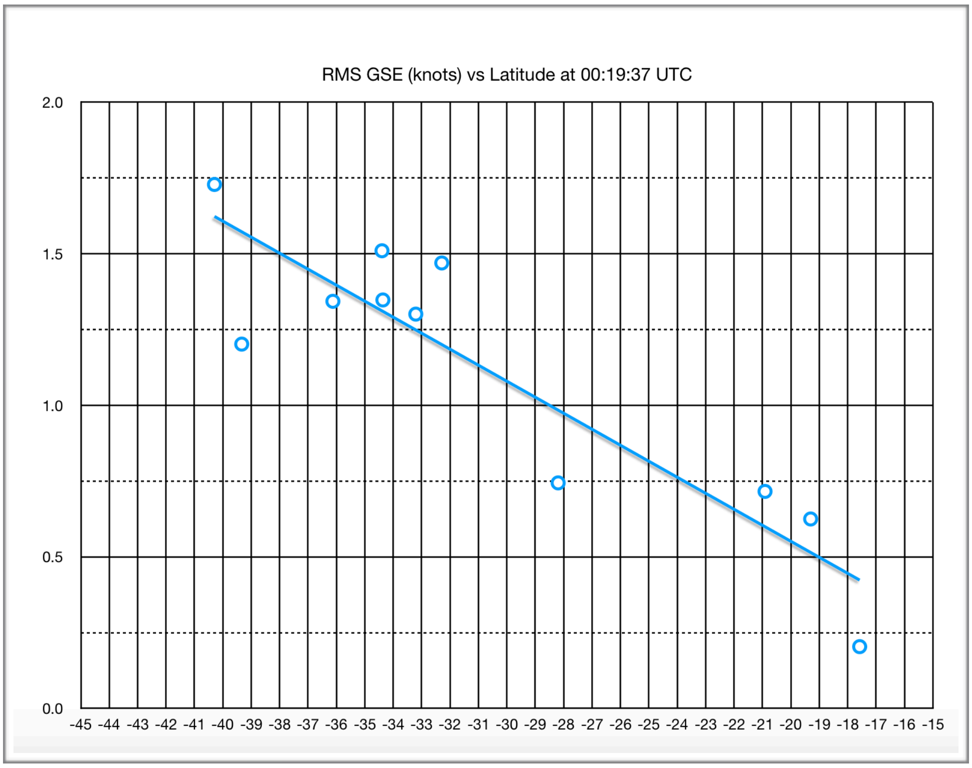


Figure 18 and 19: RMS GSE vs Latitude at 00:11:00 UTC.

DISCUSSION

A more detailed analysis reveals 3 candidate ROIs for further investigation: ROI 1 - LNAV180 CM 0.84 FL403, ROI 2 - LNAV 170 LRC FL350 and ROI3 - CTH170 LRC FL290.

From a pilot's point of view, a LNAV path on a bearing of 180°T would require setting a final waypoint as the South Pole. This flight path passes close to waypoint BEDAX. The overall fuel endurance and range fits and for a Main Engine Fuel Exhaustion (MEFE) at 00:17:30 UTC, a PDA of 1.37% is calculated (the nominal PDA is 1.5%). The RMS GSE is 2.49, which fits the expected range between 1.0 and 3.0 knots. This flight path ends at 00:19:37 UTC at around 34.5°S near the 7th Arc. This area was originally searched by Go Phoenix but all possible sightings were re-examined and discounted. The search area was widened in later search by Ocean Infinity, but again nothing was found.

A LNAV path on an initial bearing of 170°T starts close to Car Nicobar Airport (VOCX) and passes close to Cocos Island before ending at 00:19:37 UTC at around 28.9°S near the 7th Arc. The overall fuel endurance and range fits and for a MEFE at 00:17:30 UTC, with a calculated PDA of 1.17%. Notably, the Mean BFOR for this flight path is low at -6.87 Hz and is out of the expected range. The area around 28.9°S was searched by Ocean Infinity, but nothing was found.

The CTH path on an initial bearing of 170°T is unlikely as the fuel endurance and range does not fit well. The RMS BTOR is high at 79.6 μs and individual BTOR values are out of normal range. It is also unlikely that a pilot would switch to a True Heading mode. Normal operation is Magnetic Track and this mode is only used for short flight paths, such as during an approach or deviating to avoid bad weather. Switching from Magnetic to True compass mode is only normally done in the region of the north or south poles.

LNAV180 CM 0.84 FL403

Item	Value
Start Time (UTC)	19:32:00.000
Start Time (secs)	70,320.000
Start Latitude	3.8710000
Start Longitude	93.7490000
Lateral Navigation Mode	LNAV
Initial Bearing (degT)	180.0000000
Air Speed Mode	CM
Mach	0.840000
Flight Level	403
Altitude (feet)	40,517
19:41:03 UTC Latitude	2.6776205
19:41:03 UTC Longitude	93.7490000
19:41:03 UTC Track	180.0000000
00:11:00 UTC Latitude	-33.4610949
00:11:00 UTC Longitude	93.7490000
00:11:00 UTC Track	180.0000000
MEAN BTOR	0.6135
MIN BTOR	-88.6776
MAX BTOR	55.7643
RMS BTOR	50.3484
STDEV BTOR	56.2870
MEAN BFOR	-3.2088
STDEV BFOR	2.5570
RMS GSE	2.49
PDA for MEFE at 00:17:30 UTC	1.3691
CC BTOR Leg Start vs End	-0.5476
CC BTOR vs Time	0.0946
CC ∂BTOR vs DW GSE + ATW	0.7242
CC BFOR vs Time	0.5586
CC BFOR vs BTOR	0.6121

LNAV170 LRC FL350

Item	Value
Start Time (UTC)	19:32:00.000
Start Time (secs)	70,320.000
Start Latitude	9.0460000
Start Longitude	92.8790000
Lateral Navigation Mode	LNAV
Initial Bearing (degT)	170.0000000
Air Speed Mode	LRC
Mach	0.8259 to 0.7871
Flight Level	350
Altitude (feet)	36,503
19:41:03 UTC Latitude	7.8624525
19:41:03 UTC Longitude	93.0896466
19:41:03 UTC Track	170.0309708
00:11:00 UTC Latitude	-27.0517840
00:11:00 UTC Longitude	99.5667720
00:11:00 UTC Track	168.8980887
MEAN BTOR	-2.1716
MIN BTOR	-48.5880
MAX BTOR	50.4881
RMS BTOR	40.4831
STDEV BTOR	45.1963
MEAN BFOR	-6.8720
STDEV BFOR	3.0637
RMS GSE	2.56
PDA for MEFE at 00:17:30 UTC	1.1693
CC BTOR Leg Start vs End	-0.1664
CC BTOR vs Time	-0.0814
CC ∂BTOR vs DW GSE + ATW	-0.5635
CC BFOR vs Time	-0.7047
CC BFOR vs BTOR	0.6810

CTH170 LRC FL290

Item	Value
Start Time (UTC)	19:32:00.000
Start Time (secs)	70,320.000
Start Latitude	6.1610000
Start Longitude	93.1600000
Lateral Navigation Mode	CTH
Initial Bearing (degT)	170.0000000
Air Speed Mode	LRC
Mach	0.7463 to 0.7056
Flight Level	290
Altitude (feet)	30,240
19:41:03 UTC Latitude	5.0338472
19:41:03 UTC Longitude	93.3379656
19:41:03 UTC Track	171.7505049
00:11:00 UTC Latitude	-27.8630280
00:11:00 UTC Longitude	98.9479993
00:11:00 UTC Track	163.6497879
MEAN BTOR	-1.2023
MIN BTOR	-104.7490
MAX BTOR	114.5698
RMS BTOR	79.5754
STDEV BTOR	88.9579
MEAN BFOR	-4.2696
STDEV BFOR	2.9538
RMS GSE	3.53
PDA for MEFE at 00:17:30 UTC	2.7953
CC BTOR Leg Start vs End	-0.2520
CC BTOR vs Time	0.0959
CC ∂BTOR vs DW GSE + ATW	-0.0805
CC BFOR vs Time	-0.6276
CC BFOR vs BTOR	0.6931

Conclusion

In total 1,372 flight paths have been analysed, of which 828 flight paths since the start of this systematic study on 17th February 2019. Start latitudes from 16.0°N to 4.3°S have been covered and the start longitudes were unconstrained. Start times from 18:41:00 UTC to 19:32:00 UTC, but the final major turn had to be completed before the 2nd Arc at 19:41:03 UTC was reached.

Systematic initial bearings from 155°T to 195°T in steps of 1°T were analysed, plus some exotic cases in steps of 0.1°T. All navigation methods were covered: LNAV, CTT, CTH, CMT and CMH, all speed modes: Constant Mach 0.80 to 0.85, LRC 0.7047 to 0.8408, MRC, ECON CI52 and all flight levels: from FL290 to FL430. The fuel endurance was allowed to vary around 00:17:30 UTC and the resulting PDA was noted. The PDA was allowed to vary from the nominal 1.5% and the possibility that the bleed air was shut off for part or all of the time was considered.

All possible MH370 end points of flight routes in any navigation mode and any speed mode have already been searched, within at least ± 25 NM of the 7th Arc (partially ± 40 NM). This means that MH370 has either been missed in a previous search or recovered from a steep descent of around 15,000 fpm and glided out to an end point outside the previously searched area.

There is only one Region of Interest, where we recommended a further analysis and search at around 34.4 °S near the 7th Arc, following a flight route from close to waypoint BEDAX using the LNAV lateral navigation mode with an ultimate waypoint of the South Pole on a track of 180°T due south, in Long Range Cruise speed mode and at a flight level between FL390 and FL403.

This Region of Interest will be analysed in more depth in the next paper in this series.

Acknowledgements

Richard Godfrey as lead author would like to thank Bobby Ulich and Victor Iannello for their many contributions, comments and corrections in the course of this study. Richard says "I would not have been able to complete the analysis without Bobby and Victor". The value of having 3 independent flight models was proven in that Bobby and Victor were able to provide confirmation of Richard's results or an alert when Richard's model showed a different result.

Richard would also like to thank the members of the Independent Group, in particular Duncan Steel, Mike Exner, Don Thompson and Barry Martin, for being able to benefit from the many contributions they have made in the search for MH370 over the last 5 years.

Many thanks to Victor Iannello for providing the forum to be able to discuss the disappearance of MH370 and the many contributors to that forum, who are helping to solve the world's greatest aviation mystery.