Analysis of the trajectory of Flight MH370

Technical and Aeronautical analysis from take-off

to the end of the flight

by

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To the families of the victims …

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[1] *The authors are grateful to Peter Hotham (BSc(Hons), PgDip, FRAeS) for his review*

Executive Summary:

The known part and the recalculated unknown part of the trajectory

Reconstructing the proposed probable trajectory took four years and was made possible thanks to publicly available material and information. The main findings of this study and some complementary aspects have been recently published in a book [1]. This paper presents the methods used, the computations with their justification as well as the results in more details.

The following elements have been addressed:

1. The known trajectory from waypoint IGARI until the last radar contact in the north of Sumatra has been analysed in detail. It is shown that the U-turn during the rerouting of the aircraft was most likely performed manually. After a short descent, the aircraft flew at FL300 at a constant IAS of 310kt and slightly accelerated after 18h21’ UTC. This matches the timing from the official Exit point after the U-Turn to the last radar contact.

2. The reconstructed unknown trajectory using proven aeronautical computations is based on:
    a. Our estimation of the fuel quantity at 18h28 UTC using weather data on that day.
    b. The Inmarsat satellite arcs which are considered trustworthy.
    c. Meteorological information of the day used by pilots and data collected a posteriori by satellites (wind maps, temperature reports, Global Data Assimilation System-GDAS, etc.)
    d. “In Flight Performance” tables for the B777-200ER powered by Rolls-Royce Trent 892 engines.
    e. 9M-MRO Specific technical data like the fuel consumption performance factor

3. BTO and BFO[2] values computed along our recalculated trajectory match the official measured values since they are within Inmarsat defined margins of +/-50 µs and +/- 7 Hz respectively.

The following conclusions were drawn:

1. The reconstructed trajectory is a quasi-straight continuous track, initially a magnetic track at 188° then true at 178°. It is somehow similar to Inmarsat’s example published in the report “the Search for MH370” [3]. Figure 1 below allows comparing the reconstructed trajectory in yellow with Inmarsat’s example in red.

2. Thus, Inmarsat “loss of contact point” is very close to the reconstructed unknown trajectory path and it coincides well with our estimated location where the second engine was voluntarily shut down (c.f. Figure 3).

3. The northernmost probable point of impact (POI) identified in this study is located at approximately [35°31’S ; 93°02’E]. It is also very close to the POI computed by CSIRO forward drift analysis reported in their report n°III of 26 June 2017. In addition, potential debris have been photographed by the French CNES Pléiades 1A satellite in this area.

[2] *BTO: Burst Time Offset; BFO: Burst Frequency Offset*

4. Concerning the end of the flight, two slightly different possible scenarios have been elaborated. Both include a gliding phase with a final controlled ditching producing little debris. Scenario 1 is illustrated in Figure 2.
5. From these scenarios, a zone for a new search of the wreckage is proposed (Green area in Figure 3) which extends the already searched area in 2018 to the south by about 25Nm. Its width is ~15Nm. The estimated duration to scan this area of ~350Nm^2 is approximately 5 days according to recent information provided by Ocean Infinity which was the last company searching in the field in 2018.

All of this forms a coherent and realistic piloted trajectory.

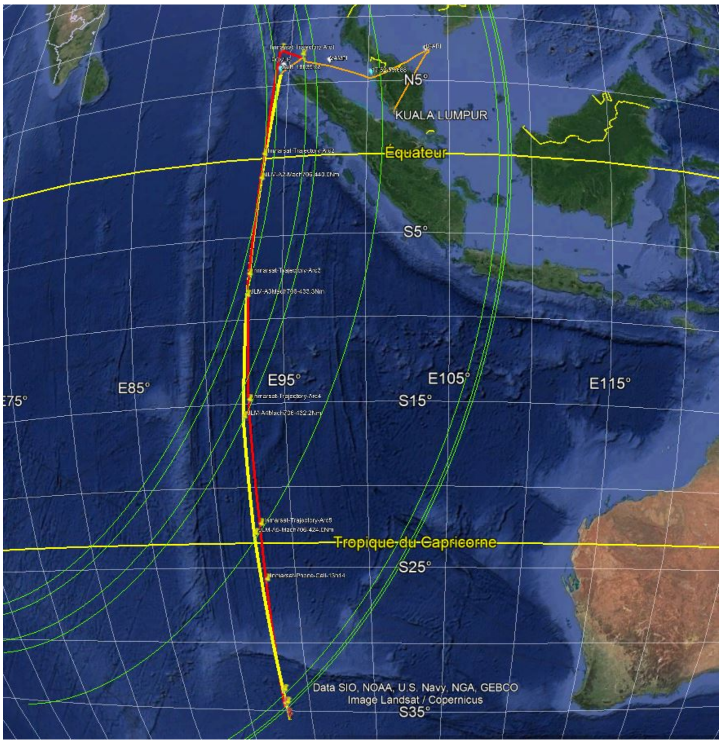

Figure 1: Reconstructed trajectory (Yellow) and Inmarsat example (Red)

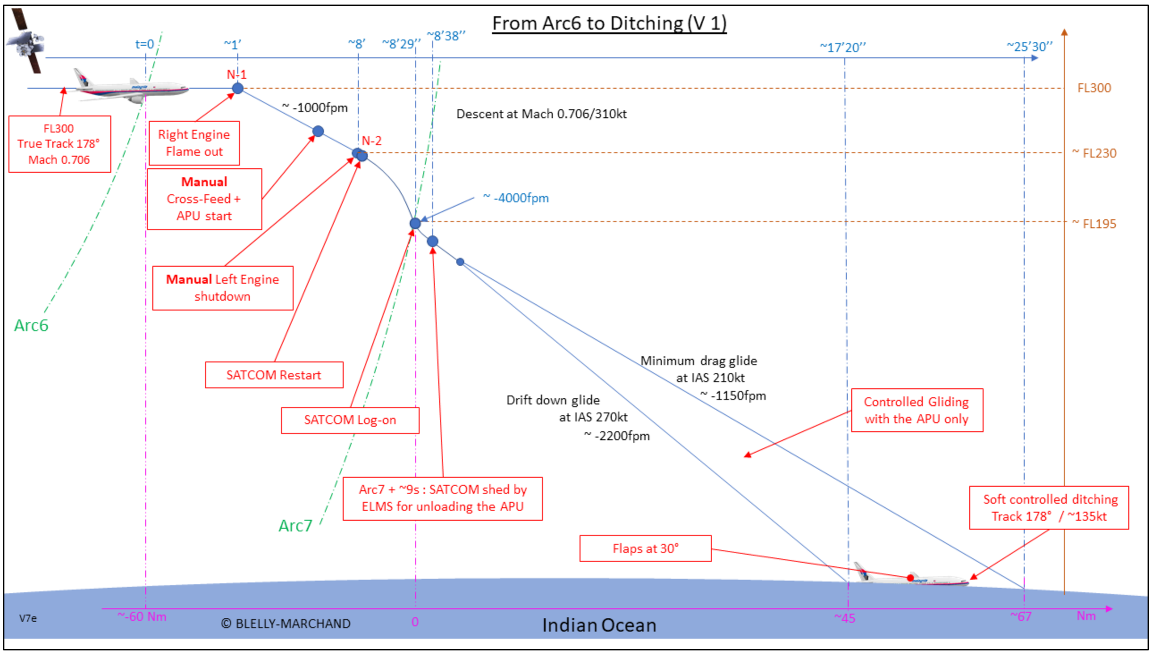

Figure 2: Scenario 1 of the probable final descent of MH370 with a glide

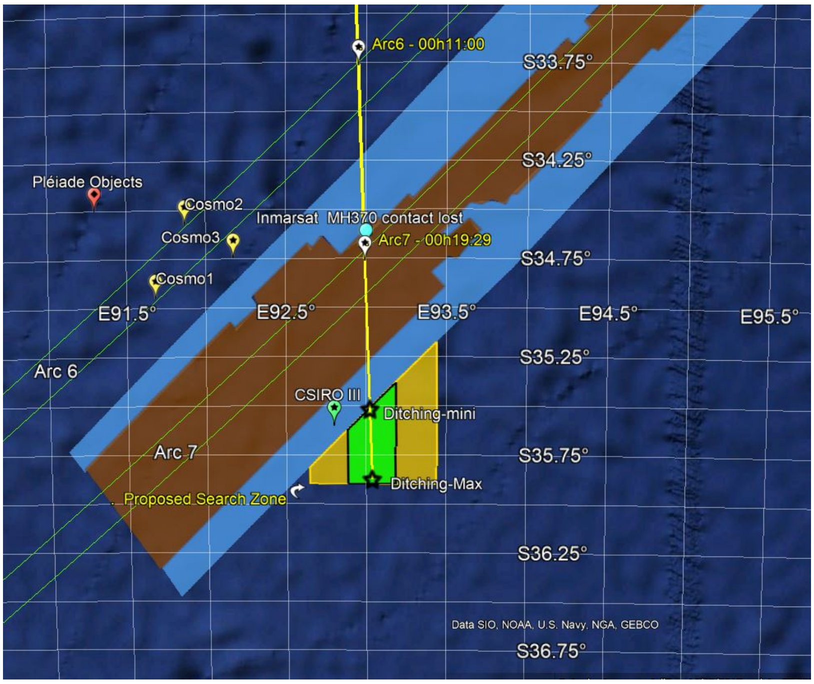

Figure 3: Proposed search zone (Green, ~300Nm2) and CSIRO III estimated Point of Impact Contact

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1 Introduction

This paper presents the results of a study by Captain Patrick Blelly and Jean-Luc Marchand, MSc, performed during several years.

The aim is to demonstrate that a probable cause of flight MH370's disappearance was a well-prepared hijacking by a highly skilled aeronautical person and most probably a professional pilot. The main driving hypothesis is this person in command went for a nefarious one-way journey with the aim to make the plane disappear without any trace in the South of the Indian Ocean.

Our approach is humble and based on realistic hypotheses with an attempt to unify and consolidate aeronautical operational elements. We used all available officially published technical satellite data within a demonstrable scenario with no identified flaw to our knowledge, as explained in Chapter 2.

It was found important to provide our findings not only for the unknown part of the flight but also for the known part as both form a coherent scenario.

Thus, the trajectory includes two major parts:

- The verified known trajectory segment

  This part of the flight begins at Kuala Lumpur and lasts until the last recorded radar plot as known thanks to published official radar data. It is addressed in Chapter 3.

- The recalculated unknown trajectory

  Chapter 4 explains the unknown trajectory reconstruction mainly based on aeronautical data validated by the published Inmarsat satellite data. It begins at the exit of the radar coverage in the northwest of the Malacca Straight and ends by a ditching in the south of the Indian Ocean.

In addition, Chapter 5 details the new zone proposed for future search of the wreck.

Some additional elements of interest are also provided in Chapter 7.

This contribution is to be considered as a working hypothesis to support any future search for the wreck. Our hope is to provide solid elements to help manifesting the truth about this disappearance.

2 Overview of the flight

Our reading of the events is that the person in command followed a well thought, well-prepared diverted flight as analysed in Captain Blelly's book [1].

The main driving hypothesis is made that the person in command went for a nefarious one-way journey with the aim to make the plane disappear without any trace.

This work represents some years of work still it does not pretend to be the truth. We have reconstructed the first part of the MH370 flight by using the published radar tracks, by re-computing the aeronautical parameters of the aircraft as well as by taking into account the airspace structure. For the "unknown" second part of the trajectory, we have computed a path until the end of the flight and ensured that all Inmarsat data were matched. This was done to help potential future search for the wreck and also for the families of the victims. It is our humble contribution.

The key elements of this flight are presented below as numbered bullets points for the sake of simplicity:

1. The leg from take-off at Kuala Lumpur to abeam waypoint IGARI was flown, according to the filed flight plan, as shown in Figure 4. Some additional clearances were given to the pilot like a more direct route to waypoint IGARI or a final flight level at FL350, above the one originally requested.

2. Abeam waypoint IGARI, the transponder was manually switched to stand-by making the aircraft disappear from the screens of the civil air traffic controllers. In addition, the right turn towards waypoint BITOD was interrupted and was shortly followed by a U-turn to the left.

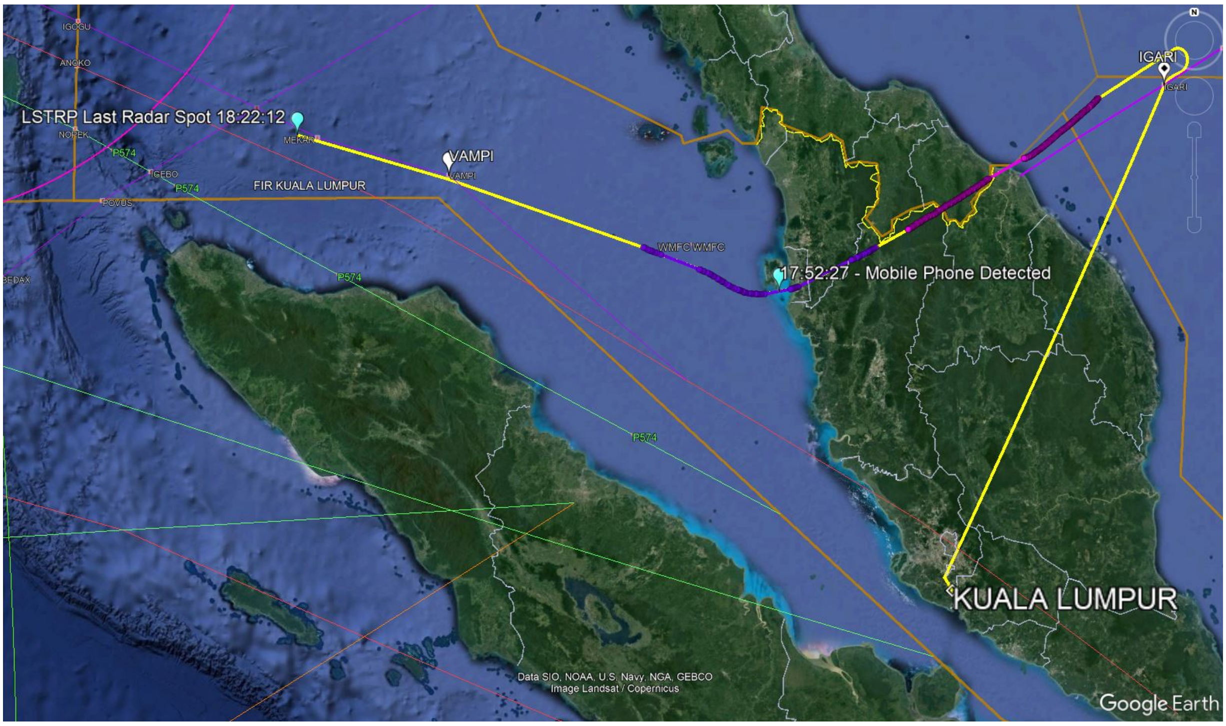


Figure 4: Known trajectory of Flight MH370 from Kuala Lumpur till the last radar plot

3. This U-turn is considered to have started earlier than the “official” entry point defined in the Malaysian official report [2]. Most likely, it started just after the overshoot of waypoint IGARI. The turn was performed manually as the military radar track shows a geometrical shape of a turn with a banking up to its maximum i.e. ~38°. This is incompatible with a standard LNAV (with the auto-pilot) manoeuvre which limits the banking to 25°. In fact, the presence of the Thai Air Defence Identification Zone (Thai ADIZ) in the vicinity is a clear constraint for the turn and explains why the person in command avoided trespassing it and performed a very sharp manual turn. The turn finished at the “official” exit point when the aircraft was on direct track to Kota Bharu. We supposed the flight maintained a constant flight level FL350 (i.e. ~35000ft) during the U-turn.

4. After having overflown the official “exit” point and because of the high banking turn the aircraft speed had probably dropped down to M0.787.

5. Most likely, it was then the time when the person in command carried out a series of technical actions: total power outage by disconnecting the two main generators control push-buttons and the two back-up generators control push-buttons. In addition, he prevented the auto start of the auxiliary power unit (APU) by turning its knob to On and Off successively. The electrical outage would have triggered the Ram Air Turbine (RAT) automatic deployment. The RAT is a small windmill generator used as last resort. Flying with the electricity power provided by the RAT only and with the full hydraulic power from the main engines is manageable for an experienced pilot. Carrying out these actions before the turn is unlikely as performing this high banking U-turn without electricity in a degraded control mode would have been difficult. Additionally, depressurising the aircraft before the turn would have required the person in command to wear his full-face oxygen mask and reducing his flying capabilities. Thus, we believe these actions were performed after the U-turn.

6. The way-out trajectory began at the official exit point and the aircraft approximately overflew waypoint GOLUD and continued towards the south of Penang Island. Because the aircraft was being depressurised after the U-Turn at waypoint IGARI, the person in command probably started descending to FL300 (~30000ft approx.).

7. From the beginning of the descent, the A/P was disconnected due to the electrical power outage and subsequently the throttle was probably in a steady state. Thus, the aircraft accelerated up to about ~M0.85 most likely and reached the IAS (Indicated Air Speed) speed of 310kt which was further manually maintained steadily as the reference speed until waypoint VAMPI.

8. But rate of descent must have been low between 300fpm and 500fpm for two reasons: a sustainable pain in the ears of the person in command due to the change of pressure and also to avoid that passengers’ mobile phones could get connected to a terrestrial telecom network close to Kota Bharu revealing his presence and possibly placing calls to alert third parties. The bottom of the descent is probably in the vicinity of Kota Bharu.

9. The chosen flight level FL300 (30000ft with altimeter reference at 1013.25hpa) is in the low-level part of the airways followed by long haul flights reducing the probability of conflicts.

10. Also, this allowed a better ground speed for a given Mach with the best specific fuel consumption.

11. In addition, as the meteorological conditions were excellent at that time, Kota Bharu city lights might have been a landmark in the first place and allowed the person in command to fly visually just above the Thai boundary. Later, a more precise navigation was required to stay within the boundary area without trespassing the Thailand airspace and the most likely, efficient means is to use Penang radial VOR (VPG) which also explains the small path deviations mentioned in the Malaysian report [2] as the aircraft did not follow specific routes.

12. Still manually piloted, the aircraft circumvented Penang Island to the south. Then it took a heading at 301° intercepting the VPG outbound radial at ~291°/292°. At that moment, it was away from any IFR[3] airway. During the leg Penang to waypoint VAMPI, the latter could have been targeted thanks to its icon visible on the navigational display (ND), consolidating the manual flight path using the VPG 291° radial outbound. The flight level was still maintained at FL300 and the IAS was maintained at ~310kt. Waypoint VAMPI is 170Nm away from Penang and thus is well within VPG range. Thus, overflying waypoint VAMPI was an easy task.

15. Shortly after waypoint VAMPI, the aircraft exited the VPG range making the radio navigation impossible for the intended flight path any more. Thus, the person in command was left with the MEKAR icon on the ND screen with the inertial navigation function due to the RAT. Subsequently, his route was less precise considering also the potential inertial drifting (triple mixing) affecting the actual position of the MEKAR icon in particular. This is why the aircraft flew a little south of MEKAR as shown on the Lido hotel official image shown to the Next of Kin (cf Figure 23).

16. It is our understanding that the person in command's intent was to overfly waypoints VAMPI, MEKAR, NILAM (all on route N571), SANOB, IGEBO, POVUS (all on route P627) and then a constant track to the south of the Indian Ocean after passing Banda Aceh (Sumatra) as illustrated in Figure 4 and in Figure 5. The selected magnetic track was most probably at ~188° to avoid adverse meteorological conditions reported in the southwest of Banda Aceh. Following route P627 from waypoint NILAM would ensure not to enter the South-India ADIZ and also to only cross one FIR boundary i.e. the one between FIR Kuala Lumpur and FIR Jakarta

[3] IFR: Instrument Flight Rules

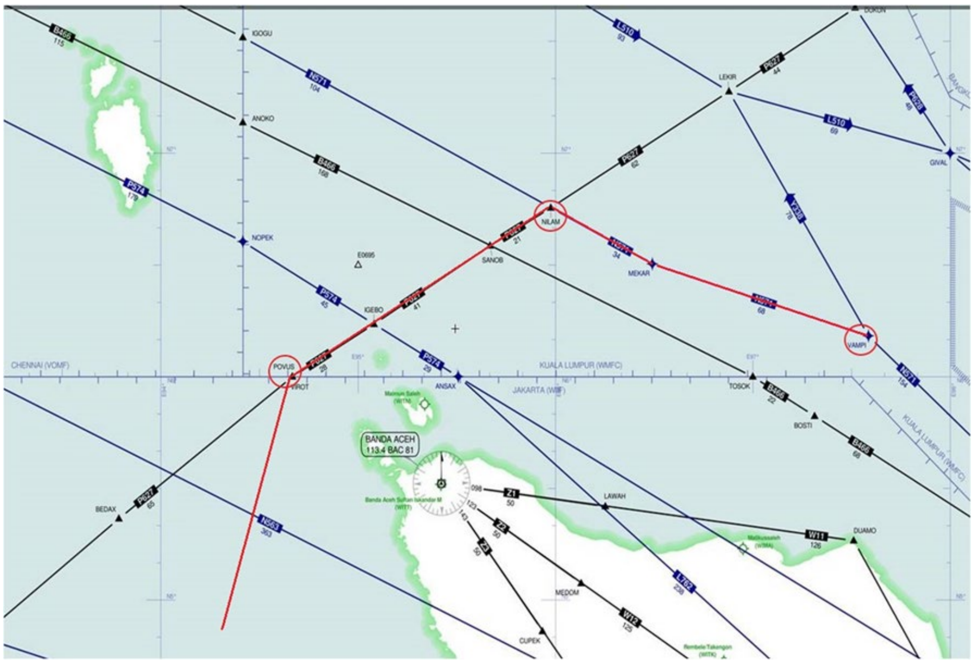


Figure 5: Flight intent after waypoint VAMPI to get around Sumatra without ATC drawing attention

17. To stay on his intended path, the person in command had to reactivate the LNAV function at some point after having restored the full electrical power. The Inmarsat data records show that it was decided to do so at about 18h23 UTC after having passed abeam waypoint MEKAR and being out of range of Butterworth military radar (Penang Island). It is also noticeable that this is basically one hour after exiting the U-turn at IGARI.

18. From waypoint VAMPI, the flown path appears to indicate that the aircraft flew the intended path like any commercial airliner would do in this region respecting the airmen rules to avoid drawing military controller's attention by an abnormal behaviour. The transponder is meant to be on standby still and thus was not responding to any civil SSR (secondary Surveillance Radar) interrogation leading to the absence of tag on the Indonesian civilian ATC controller's screen. Furthermore, staying on airways N571 and then on P627 would ensure that the aircraft would not enter in the range of Car Nicobar military radar or trespass the Indian ADIZ.

19. As soon as the electrical power was restored, a kind of countdown was triggered for the person in command to react in a minimum time and quickly configure and engage the autopilot for safely managing the aircraft trajectory. This was needed to create an opportunity for disabling as soon as possible all communication systems before they could broadcast any message, and therefore stay undetected. The intent was to make the aircraft follow published local airways with the LNAV function. In addition, also restoring the pressure was most probably on its way at this time (automatically or manually). Blocking the communications before the Satellite Data Communication Unit (SDU) became operational was probably done thanks to a data link reset via the Communication Manager page on the MFD (Multi Function Display) which, in flight, has a side effect of erasing the flight and company information and in particular the flight identification (Flight ID). It should be noted that this is the unique way to have the Flight ID erased and missing in the SDU signal units as reported in the Malaysian report [2].

20. In our opinion, the Inmarsat BFO for Arc-1 at 18h25:27 can be used and provides a trustful indication on the potential trajectory. Therefore, we included it in our recalculation of the flight path at that time.

21. Thus, in the rush for completing these tasks, the person in command is likely to have had difficulty to properly control the trajectory during two minutes approximately and probably did not pay attention to the actual position of the aircraft relative to Route N571. We make this hypothesis because we think that the person in command had to look down to complete his tasks on the MFD and FMC and did not pay sufficient attention to the evolution of the aircraft track.

22. When the FMC was fully operational, the most logical first waypoint entered was probably NILAM. Thus, the person in command had sequentially keyed NILAM in, then pressed "Execute" on the MCDU and pressed the "LNAV" button on the MCP commanding the aircraft to pass by waypoint NILAM automatically. Thus, being in the south of the route, the aircraft had to turn right to the north in direction to NILAM as revealed by the Inmarsat BFO value at Arc-1 time. We don't think it is a coincidence that waypoint NILAM was basically overflown, it was a properly executed route. In addition, as the reference IAS is reset to 200kt at power-up on the MCP, the person in command had to manually increase the requested speed to a much more adequate value. Thanks to Inmarsat data, we estimate this value to be close to 325kt and surely below the maximum operating speed of VMO 330kt up to flight level FL300. This is in line with the behaviour of someone keen to escape quickly, but things did not go exactly as planned.

23. A second hitch comes from the fact that, at power-up, the FMC grasps the instantaneous rate of descent (or climb) and keeps it as the reference value on the MCP. At that time, it was around -1000fpm in descent as indicated by Inmarsat data. The descent lasted around 2.5 minutes leading the aircraft to ~FL270 (~27000ft). This could be explained by one of these following reasons:

- Either the person in command voluntarily triggered a descent when he saw the lights of the Indigo traffic coming ahead. As he thought he was on Route N571, as MH370 was not detectable by the other aircraft due to the TCAS standby state and lights off and as he could not know what was the Indigo's flight level, a potential collision was possible. Descending was safe and would be seen by ATC as a normal behaviour.
- Or, in the rush and with the oxygen mask on, the person in command did not pay attention or was focused on the MFD and MCDU displays while the aircraft was descending as mentioned above.

Figure 6: Heading to waypoint NILAM after electrical power restoration

24. A few minutes after the electrical power was restored and after having completed the urgent actions with head down, the person in command likely realised the aircraft was heading north while descending and reaching ~FL270. Immediately, the auto-pilot was disengaged and a manual left turn was started with a high banking along with a climb to get back to FL300. The Inmarsat BTOs indicate that the turn had to be sharp especially towards the end, probably to stay as close as possible to route P627 by a direct to waypoint POVUS. Doing so put him close to his intended path at the planned flight level in quasi-normal flight conditions.

25. After this first part of the FMT, the time tags show that the aircraft strongly accelerated probably to cross the straight between Andaman Islands and Sumatra Island and get out as quickly as possible of this area where its recovered awkward manoeuvre took place. Our analysis shows that the reference IAS was ~325kt which is close to Mach 0.850. Let's remember that the LNAV function became operational again. The person in command keyed in "direct to waypoint POVUS" on the MCDU followed by "Execute" and then engaged the LNAV function of the A/P.

26. After the first part of the FMT, the aircraft made a speedy direct to waypoint POVUS.

27. Then, it is most probable that at waypoint POVUS, the aircraft started the second part of the FMT by turning left to a southerly direction. Several studies suggested that its heading was established at 180°. But to avoid encountering dangerous meteorological phenomena developing around [4.25N;95.5E] in the south/southwest of Banda Aceh in the form of a cumulonimbus, the person in command probably selected at different track at ~188°. In addition, this was a safe way to avoid detection by the military radars located on Sumatra west coast in particular Sibolga radar.

28. Shortly after overflying waypoint POVUS, and en-route on track ~188°, the person in command kept this magnetic track constant until crossing about 25° South parallel. At this latitude, the strong increase in magnetic declination forced him to switch to true (track/heading) function. Thus, the aircraft followed an almost-linear southern trajectory from 18h40 UTC onwards.

29. As reported in the Malaysian report [2], the right engine consumed more fuel than the left one leading to the right engine starvation in the first place. We think that according to Captain

Blelly's book [1] the APU was then started manually before voluntarily shutting down the left engine. Thus, the APU had enough fuel to power all systems allowing a fully controlled final ditching i.e. probably about 200kg.

30. Based on the Inmarsat data between Arc6 and Arc7, two possible piloted trajectories of descent could be envisaged including a low speed or a high-speed segment. In fact, the last BFO (-2Hz) at 0h19:37 reported in Inmarsat report [3] raises questions and appears to indicate that aircraft was in a high diving for few seconds followed by a safe aircraft recovery by the person in command.

The major events of the recalculated trajectory are summarised in Table 1.

Table 1: Synopsis of the recalculated trajectory

Time UTC	Location	Event/decision	Comment
17h07:49		Last radio voice communication from the aircraft	Official
17h20:34	IGARI	Transponder manually switched to Standby abeam IGARI	Official
~17h21:53	U-Turn actual start		Estimated
17h22:30	U-Turn Entry point		Official
17h24:40	U-turn Exit Point	End of the U-Turn after IGARI	Official
~17h36:50	~GOLUD (Kota-Bharu)	Bottom of Descent to FL300	Estimated
17h52:27	South of Penang	Co-pilot mobile phone connected to network	Official
~18h02:40	~Pulau Perak Island		Estimated
~18h13:00	VAMPI		Estimated
18h21:00	MEKAR		Estimated
18h22:12	10Nm after MEKAR	Accelerating in descent	LSTRP, Official timing, approximate official location
~18h23:30	6°34'32"N/96°8.00'E	Electrical power restored	Estimated
		Autopilot engaged	In descent
		Data Link Reset	En-route to NILAM - descending
18h25:27	~NILAM (FL270)	Arc-1 Ab-initio Logon	Official timing only - Heading north
~18h25:40	6°46.90'N/95°58.53'E	FMT part1: Manual turn	To correct towards route P627
18h27:05	6°54.77'N/95°51.58'E	Arc1.1	Official timing only - turning and climbing
~18h27:35	6°53.41'N/95°48.06'E	End of FMT part1	Estimated - still climbing (FL280)
		En-route to POVUS	Heading 233° - still climbing
18h28:06	6°50.90'N/95°44.81'E	Arc1-Boeing	Official timing only - still climbing (FL295)
18h28:15	6°50.19'N/95°43.86'E	Arc1.2	Official - still climbing (FL297)
~18h28:25	6°49.26'N/95°42.64'E	Levelled at FL300	Estimated
~18h37:40	POVUS	FMT part2	Estimated
18h39:58	5°45.75'N/94°29.57'E	Phone Call-1	Official timing only – En-route heading 188°
19h41:03	1°34.61'S/93°31.74'E	Arc-2	Official timing only
20h41:05	8°48.60'S/92°42.17'E	Arc-3	Official timing only
21h41:27	16°03.39'S/92°13.74'E	Arc-4	Official timing only
22h41:22	23°09.83'S/92°24.81'E	Arc-5	Official timing only
23h14:30		Phone Call-2	Official timing only
00h11:00	33°45.88'S/92°57.09'E	Arc-6	Official timing only
00h19:29	34°45.40'S/92°59.56'E	Arc-7	Official timing only
		Controlled Ditching/EoF	Estimated

3 The known trajectory

3.1 Introduction

This chapter addresses the part of the trajectory fully known thanks to published ATC information and radar data.

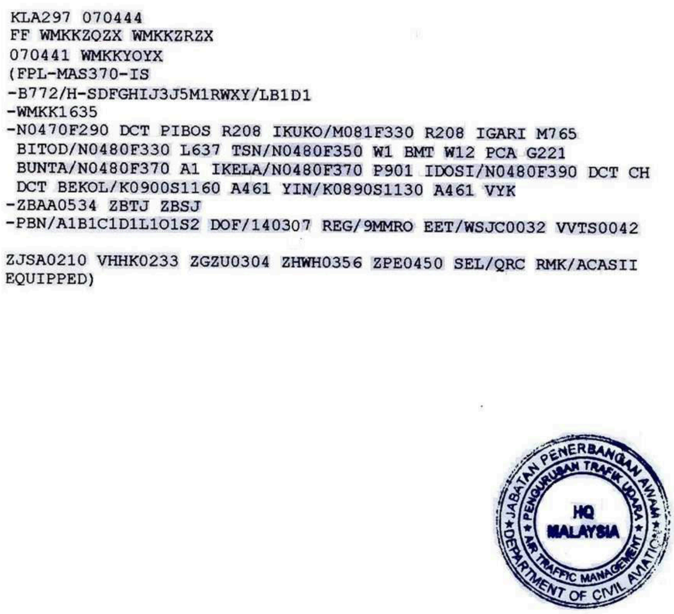
The objective is to reconstruct a realistic trajectory using available official data as well as data from public sources in particular the Boeing trials to simulate the U-turn. We have validated this trajectory by simulation sessions using three different simulators (Prepar3D, FsX and a fixed based simulator in the city of Nantes with an active airliner B777 captain).

3.2 From Kuala Lumpur to IGARI

The segment from take-off to abeam waypoint IGARI is perfectly known due to the radar data, the surveillance ADS-B data and the testimony of the controllers in charge of this flight.

3.2.1 Flight plan and clearances until the transfer

Before the flight, Malaysian airlines filed the ATC flight plan as provided in Figure 7.



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JABATAN PENERBANGAN AWAM
PENGURUSAN TRAFIK UDARA
HQ
MALAYSIA
AIR TRAFFIC MANAGEMENT
DEPARTMENT OF CIVIL AVIATION

Figure 7:MH370 ATC Filed Flight Plan for 7-mar-2014 at 16h35 UTC

Until waypoint IGARI and as stated by the Malaysian report [2], MH370 was a normal flight following its filed ATC flight plan according to the aviation rules until its transfer by Kuala Lumpur ATC to Ho Chi Minh ATC.

In our opinion, this particular moment is the most appropriate time to hijack the aircraft because the flight was not in contact with the Malaysian controller and not yet in contact with the Vietnamese controller.

3.2.2 From the ATC transfer to Waypoint IGARI

Thanks to the transponder on-board the aircraft which responds to the interrogations of the secondary surveillance Radar (SSR) and which also cooperatively broadcasts ADS-B[4] data including the aircraft position in time, the aircraft actual route is precisely known until the last ADS-B message transmitted at 17h20:34 UTC when the transponder knob was manually put on stand-by.

At that time, the aircraft was located exactly abeam waypoint IGARI after having started a turn to the right to follow route M765 to the next planned waypoint i.e. BITOD.

The perfectly known trajectory until that time is illustrated in Yellow in Figure 8.

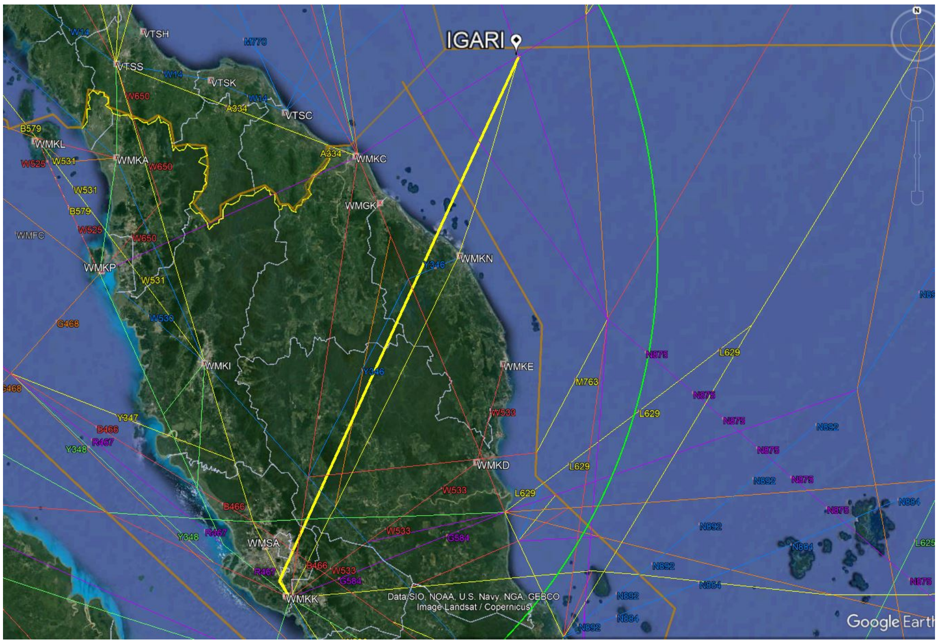

Figure 8: Perfectly known trajectory of MH370 from Kuala Lumpur until abeam waypoint IGARI

3.3 Diversion from the flight plan at IGARI: The U-Turn

3.3.1 Introduction

This section presents the findings of our study focused on reconstructing the portion of the trajectory, which started shortly after 17h20 UTC when the aircraft was abeam waypoint IGARI. A U-turn was performed in less than five minutes. During this time interval the radar data shows that the aircraft performed a sharp U-turn to the left heading abeam northern to Kota Bharu in Malaysia.

The unique available data of this turn is provided on page 3 of the Australian report [4] in a very low-resolution image illustrating the radar track drawn on a GoogleEarth map. Figure 9 presents a zoom of this image, which depicts the aircraft passing abeam waypoint IGARI until the end of its U-turn towards Kota Bharu. A few extra key elements for the analysis have also been added on this image. Unfortunately, the military and the civilian authorities did not officially release any primary radar data.

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[4] *ADS-B: "Automatic Dependent Surveillance – Broadcast" is a cooperative system for aircraft information dissemination*

According to the Malaysian final report [2], the six trials performed by Boeing to simulate such a turn have not been conclusive. It is believed here that it comes from the use of only two officially identified waypoints called “Entry waypoint” and “Exit waypoint” separated by 2min 10 sec. But, when considering the shape of the radar track and the geometry of the U-turn, a new, more detailed analysis is required considering an earlier start of the turn i.e. before the “Entry waypoint”.

3.3.2 Available data

This detailed analysis is based on information provided by the ATSB Transport Safety Report published in June 2014 p3 [4], the Malaysian Safety Investigation Report [2] and its Appendix-1.6E including the results of the Boeing Performance-Analysis [5], the navigation chart for airmen, the ADS-B data published by the Independent Group [6], the GDAS meteorological data provided by Nullschool [7] and the civilian approach radar data provided by the Independent Group [8]. They are reviewed one by one in this section.

3.3.2.1 Military primary radar plots

The unique source of information on the actual aircraft trajectory at, and after, waypoint IGARI is provided on page 3 of the Australian report [4] in a low-resolution image reproduced in Figure 9.

In this unique image, the aircraft position - as acquired and forecasted by the radar - is shown by quasi-white fuzzy successive spots. This path exhibits an unrealistic steep angle impossible to be flown by such an aircraft of this weight. This shape is due to the “coasting” algorithm (i.e. predictive) of the radar tracking system which probably received low-quality echoes from the aircraft at this point in time - or even lost them - probably because being - or close to be - out of range of the radar (cf Figure 10). Thus, the radar extrapolated the path based on the last reliable echoes and also on the a-priori knowledge of the next waypoint via the ATC filed flight plan. When the plots acquisition resumed, the prediction did not match anymore. Thus, the algorithm “jumped” to and restarted from the updated real location of the aircraft and filled the gap of the trajectory with straight lines for reconstructing a continuous track which was not actually flown. This explains the strange shape of the trajectory with such a steep angle.

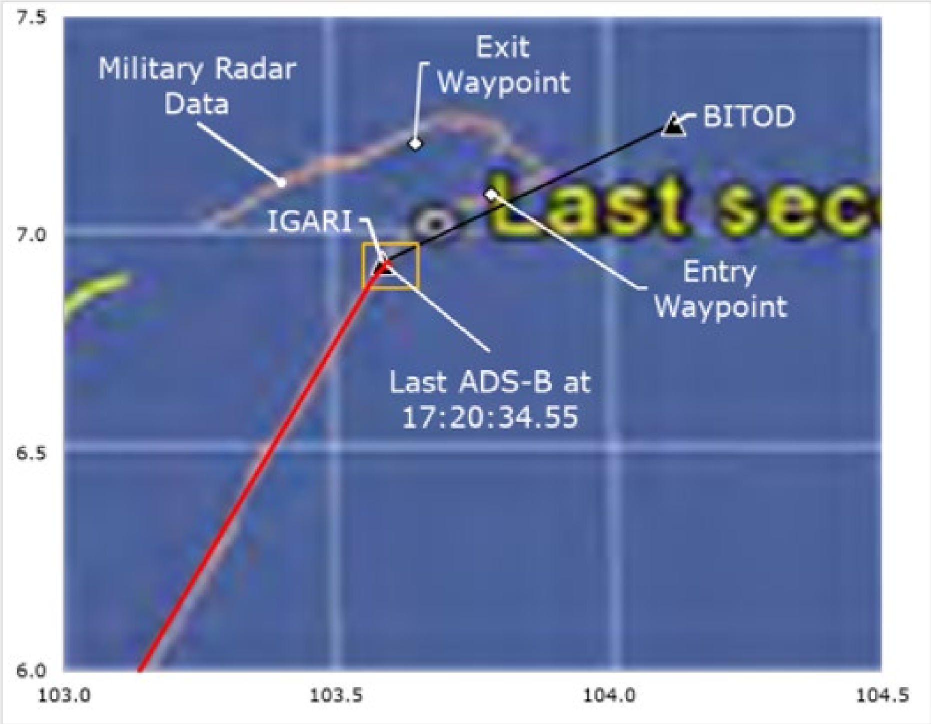

Figure 9 : Military primary radar tracking during the U-Turn between waypoints IGARI and BITOD

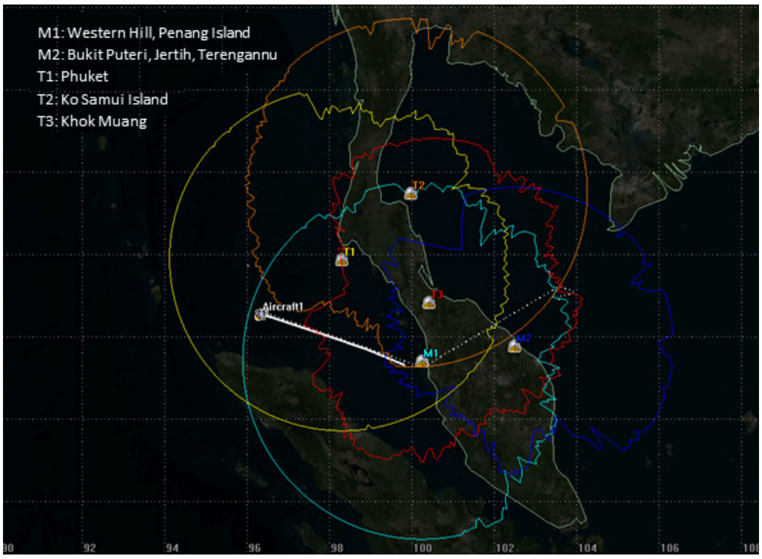

Figure 10: Range of military radar sites for an aircraft at 37,000ft (source B. Hall)

Nevertheless, this low-quality path image is very useful to the overall understanding because it allowed the Malaysian investigators team to define two useful waypoints in the U-Turn. On our side, we have used this image also to "shape" the path to be followed during our simulations according to the best-fit principle especially with the actual acquired plots, ignoring the predicted part.

3.3.2.2 The official Entry and Exit points

The official Malaysian report [2] presents Boeing trials results to simulate the complete U-Turn. They were principally based on those two specific theoretical reference waypoints defined for this occasion and officially called "Entry Point" and "Exit Point". They are located as indicated in Figure 9 and their coordinates are recalled in Table 2 as determined by Boeing. Their time separating interval is 2:10 minutes.

Table 2: Official reference waypoints defined for analysing the U-Turn at IGARI

	Latitude	Longitude
Entry Point	N07.05.7	E103.47.1
Exit Point	N07.12.7	E103.38.7

We have used these two waypoints in our simulations as mandatory waypoints to be overflown.

3.3.2.3 Boeing simulations

Section 2.1 of the Malaysian report [2] presents the detailed results of the six attempts by Boeing to simulate the diversion from the flight plan. A summary is presented in Figure 11. Four attempts were performed with the autopilot engaged and two with a manual piloting. None of the six simulations could match the 2:10 minutes timing between the Entry and Exit points. It should be noted that, by definition, Boeing considered the U-turn to have started precisely at the Entry point.

In its lower part, Figure 11 recalls also the common factors and flight parameters used for the sessions.

SAFETY INVESTIGATION REPORT
MH370 (9M-MRO)

Re-enactment	Session					
	1	2	3	4	5	6
Ground Speed (in knots)	475	475	425	400	475	425
Autopilot Engaged	✓	✓	✓	✓	x	X
Additional Waypoint	x	x	X	N05.15.6 E100.27.5	✓	✓
Bank angle (in degrees)	26°	26°	28°	23°	30-32°	35°
Exit Waypoint Time	Over-Shooting	2 min 45 sec	3 min 3 sec	3 min 30 sec	2 min 40 sec	2 min 28 sec

Table 2.1G - Re-enactment Sessions

Common Factors		
1.	Fuel	41,200 kg
2.	Gross Weight	215,410 kg
3.	Height	35,000 ft
4.	Entry Point	N07.05.7° E103.47.1°
	Exit Point	N07.12.7° E103.38.7°
5.	Autothrottle Engaged	

Table 2.1H - Common Factors

Figure 11: Summary of Boeing unsuccessful sessions to match the U-turn timing (Source Report [2])

These results compared to the geometry of the radar track led us to a new analysis with a new perspective considering an earlier start of the U-turn. This would make the official "Entry point" a simple point to be overflown in the course of the turn (c.f. Figure 9).

During our simulations, the same aircraft configuration was used at flight level FL350.

3.3.2.4 FIRs boundaries

As already underlined by the authors in several previous studies, the choice of the location to perform the U-Turn is particularly well chosen for whoever wants to escape from the civilian ATC and also from Military ATC at night. The U-turn started just after crossing the Kuala-Lumpur FIR northern boundary (c.f. the thick blue-green line in Figure 12) where the Malaysian controller would not pay attention any more as he had “transferred” the flight to the next control sector according to the rules. The turn started before executing the mandatory self-identification by the aircraft to the Vietnamese ATC and hence before calling for his attention. This timely “in-between” tiny location was thus temporarily without sustained attention from both controllers. This transfer would normally be executed within one minute. Actually, the ATC Vietnamese controller reacted 14 minutes later.

3.3.2.5 The Thailand ADIZ

Furthermore, this tiny geographical location must be considered in a wider perspective taking into account the surrounding airspace structure. In this area, another important constraint is imposed to the airmen by the Thai military authorities. Thailand has defined an air defence identification zone (ADIZ) named TADIZ. It provides an early warning system to detect possible incursion into Thai sovereign airspace. ADIZ are not part of any international treaty or body.

To enter TADIZ any intruder must satisfy specific formalities (ATC filed flight plan, early warning and in particular to have an active transponder in working condition, etc.) and being known in advance to the Thai military controller before entering. Its southern boundary is located at about 18Nm north of waypoint IGARI as illustrated in Figure 12 by the double dotted purple line and the red arrow.

The existence of the Thailand ADIZ is a new element brought by the analysis presented here. To our knowledge, none of the previous studies considered it as a constraint for the turn. But we think it was.

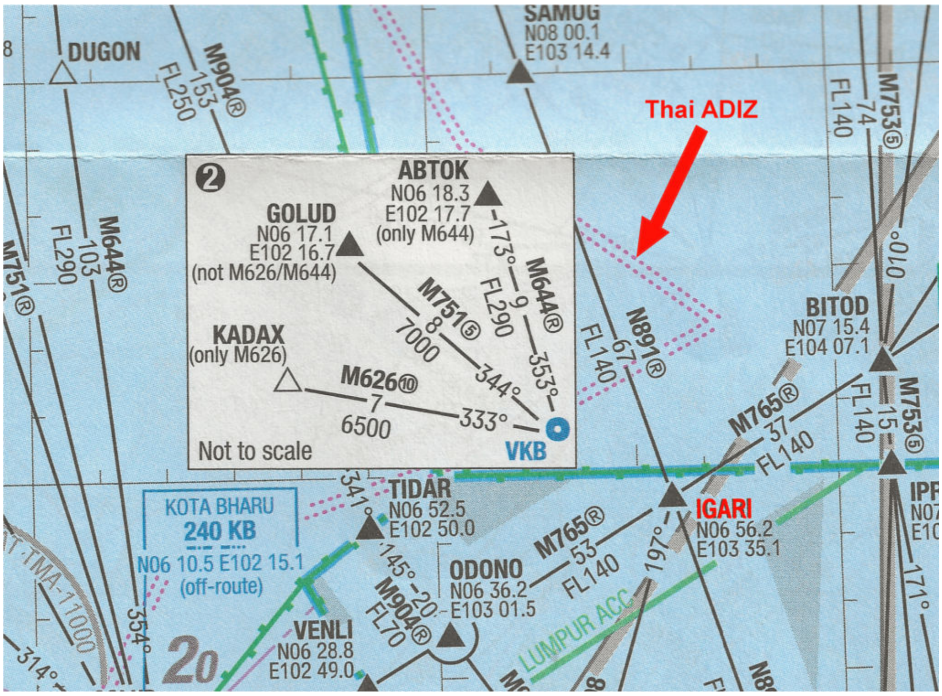

Figure 12: Location of waypoint IGARI at ~18Nm south of the Thailand ADIZ boundary (source: Aeronautical map from Lido/RouteManual AS 14HL 20-04-2017)

The presence of this boundary imposes a high constraint for a person in command planning a U-Turn in this area requiring the turn diameter to be less than 18Nm to avoid drawing Thai military controller's attention. Thai Khok Muang military PSR radar is covering this area with a potential backup from the Ko Samui Island radar PSR.

Due to no compliance to these formalities, the aircraft had to avoid entering the ADIZ absolutely if it wanted to remain discreet.

3.3.2.6 ADS-B data unavailable due to transponder switched to stand-by.

As explained above, until some point in time, the aircraft was transmitting the required information to the air traffic control (ATC) via its transponder as part of the collaborative surveillance system called ADS-B for Automatic Dependent Surveillance – Broadcast. This information (different from ACARS) provides detailed numerical values on the aircraft situation. This includes its call sign, its aircraft type, its precise position, its speed, its flight level and its intent. When this information is actually coming from the aircraft, the controller in charge is informed by a specific icon (usually a "@") enlightened in the aircraft label on his screen.

Thanks to the Independent Group (IG), records of ADS-B data received at the Malaysian ATC station in Terengganu (c.f. Figure 13) have been made publicly available [6]. In addition, the IG clearly demonstrated that the transponder was manually and gradually switched to standby before the last ADS-B data transmission which took place at 17:20:34:55 UTC via an ADS-B point message with no altitude report.

This constitutes an additional element towards a deliberate human action as opposed to an automatic switch off due to a system or electrical failure which would have prevented such an altitude message to be sent.

Figure 13: ADS-B receiving stations (red spots) when the aircraft stopped broadcasting its position (source IG and RMC Story Channel [14])

3.3.2.7 GDAS Meteo data

In our simulations, we have used meteorological data produced by the Global Data Assimilation System (GDAS) accessible via the website earth.nullschool.net [7]. Due to the sampling of the data, Runge-Kuta interpolations were performed both in time and in space (i.e. 4D) at flight level FL350.

The data shows that during the U-turn the meteorological conditions were stable, but not favourable, pushing the aircraft to the west towards the Thai ADIZ with an easterly wind of 11kt from 95°.

3.3.2.8 Civilian approach radar data

To complete the data set, we have used the civilian approach primary radar data as provided by the Independent Group on their web site [8]. The data helps verifying the correct execution of the simulations in checking that the simulated flight was in accordance with the first points of the radar plots after it had finished the U-turn.

This was of great help also for scaling and positioning the unique low-resolution image of the turn on the Google-Earth globe.

3.3.3 Subsequent Hypotheses

3.3.3.1 Analytical review of the data

3.3.3.1.1 What happened at IGARI?

Referring to Figure 14 resulting from the analysis of the ADS-B data by the IG [22] at IGARI the turn initially started as a normal "fly-by" procedure heading to the next waypoint BITOD on route M765 according to the ATC filed flight plan. When abeam waypoint IGARI, the last ADS-B message was sent at 17h20:34:55 UTC. As recalled in section 3.3.2.6 "ADS-B data", this was the result of a deliberate action to switch the transponder to standby.

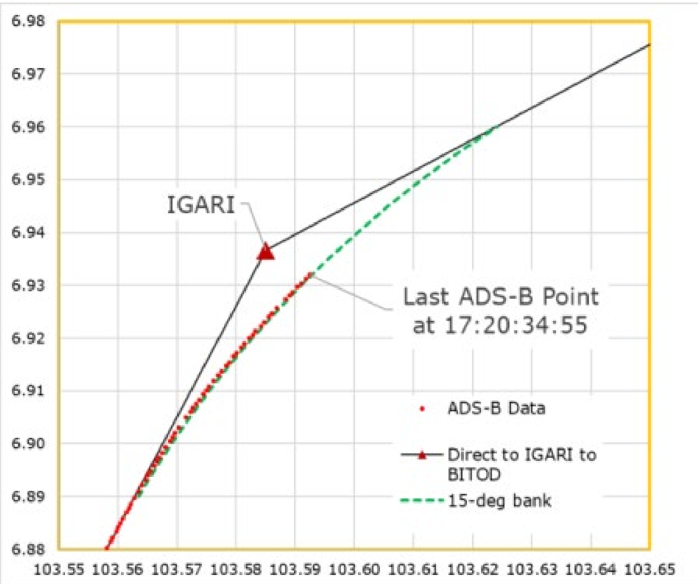

Figure 14: Aircraft Position when transmitting the last ADS-B message (source mh370.radiantphysics.com)

Should the aircraft have continued directly to waypoint BITOD, its trajectory would have been similar to the green dotted trajectory of Figure 14 and the yellow line illustrated in Figure 15. But, comparing this yellow extrapolated path towards waypoint BITOD with the actual path recorded by the radar as illustrated in green in Figure 15, a clear overshoot of waypoint IGARI is visible with a straight-line segment as if the turn was interrupted in its course during few seconds before resuming later. The path appears to follow a broken line heading first at ~36° and then with an evolving heading between ~63° and ~67°.

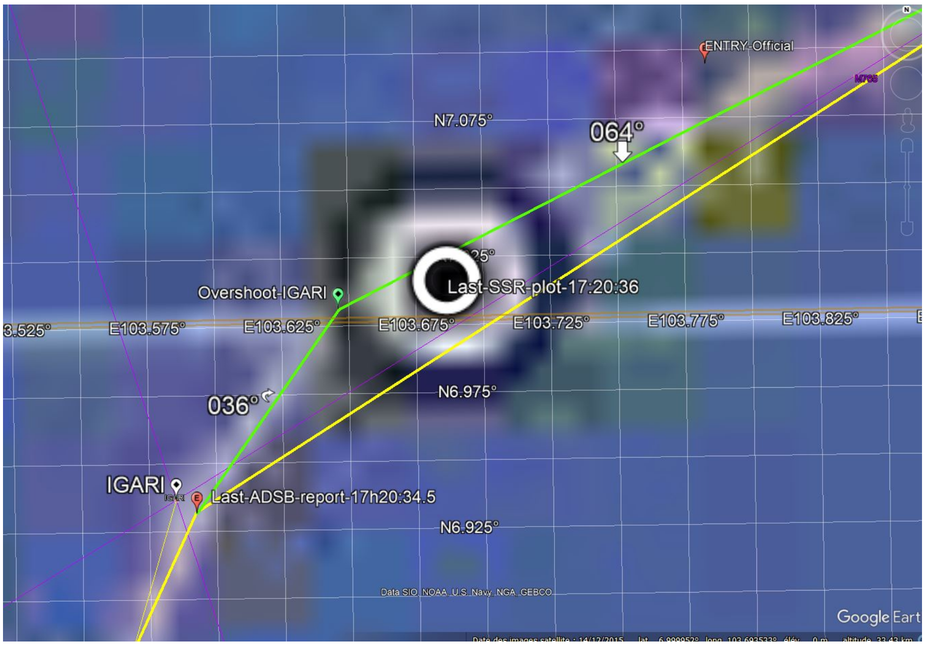

Figure 15: Actual trajectory according to the radar records posting an overshoot at IGARI

In our view, the most probable interpretation of this unusual trajectory cannot be explained by the bad radar data quality only. It is better explained by considering that the turn to waypoint BITOD started initially with the A/P engaged in LNAV and then was interrupted by the person in command by pushing the Heading Hold button which commanded the aircraft to maintain the current heading which was around ~36° at that time.

At this point in time, the person in command was most probably busy preparing the planned U-turn and successive actions to come.

The person in command then corrected the heading manually to the right in direction to route M765 i.e. up to ~67°.

3.3.3.1.2 Why a sharp U-turn?

When scaling and overlaying Figure 9 onto Figure 12, the most probable reason for the sharpness of the U-turn appears clearly in Figure 16. The person in command had to execute a demanding manoeuvre to stay outside of the Thai ADIZ and shows a behaviour as if he was under the Malaysian control. The radar plots indicate a direction remarkably parallel to the Thai ADIZ boundary.

Figure 16: The radar track indicates a sharp turn avoiding the Military Thai ADIZ

3.3.3.1.3 Manual U-turn

Within the constraints identified so far, would the aircraft be able to perform such a U-turn with its autopilot engaged? Simulations have been run to determine the behaviour and the trajectory of the aircraft with the configuration and context described in the official report (weight, speed, met etc.).

All simulations demonstrated that, with the autopilot engaged, the turn is performed at a maximum angle of 25° and that either the trajectory enters the Thai ADIZ or it passes very close to its boundary at a distance of less than 2 Nm depending on the initial conditions. Two extreme examples are provided in Figure 17 illustrating these findings. The red line illustrates the trajectory simulated on our Prepar3D simulator with the “full auto LNAV” function while the white line is with the autopilot and using the track/heading function.

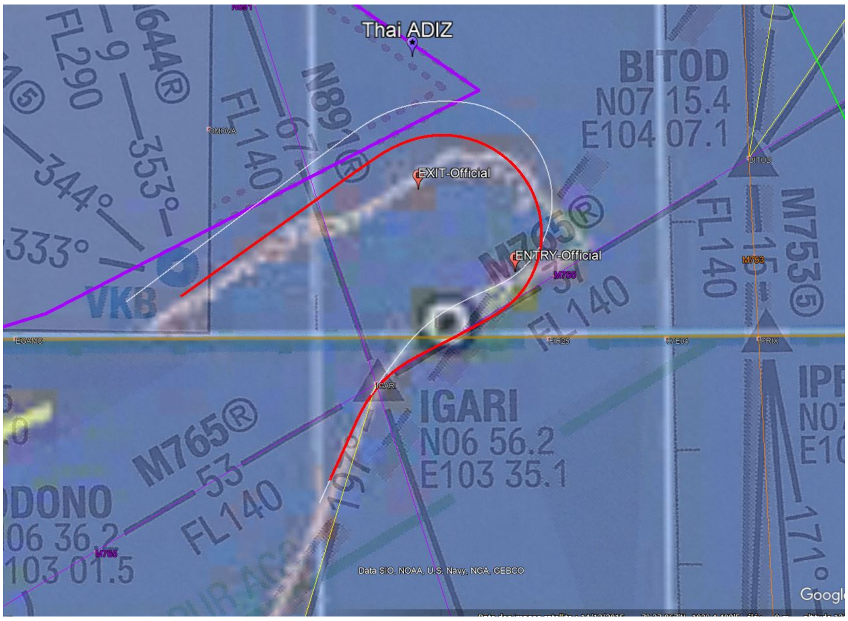

Figure 17: Simulations of U-turn with Autopilot engaged (max banking at 25°)

In addition, Figure 17 illustrates the impossibility to overfly both the official Entry point and Exit point within the measured 2min10s documented in the Malaysian official report [2].

The solution to satisfy the above constraints and match the radar track is to increase the maximum banking angle during the turn.

As the risk to enter the Thai ADIZ is considered too high to keep the autopilot engaged and as the banking angle should be above 25°, the turn was most probably achieved with a manual piloting. Let's recall also that Boeing's conclusion (c) in section 2.1 of report [2] claims that the best time-matching was achieved when manually flown.

3.3.3.2 Hypotheses on the U-turn

Based on this preliminary analysis, the following hypotheses are made:

a. The turn was manually executed to avoid entering the Thai Military ADIZ.
b. The turn started earlier than the official Entry point.
c. There was an overshoot of waypoint IGARI as shown by the radar plots because of the manual intervention.
d. The flying time of 2min10s between the Entry and Exit waypoints is a given data.
e. The aircraft flew back in the small corridor between route M765 and the Thai ADIZ boundary
f. Considering the radar track, the turn was not in circle but was performed with a gradually increasing banking angle leading to a sort of spiral turn making the turn "effective" radius shorter.
g. The initial conditions were identical to those used for the Boeing sessions except two of them which were not sufficiently accurate and had to be corrected thanks to the last ACARS report and extrapolations from GDAS weather data.
h. During the turn, the aircraft did not descend and stayed levelled at about FL350.

3.3.4 Simulations

Several simulations were performed in order to validate the hypothesis of a manual execution of the U-turn. Three different simulators were used.

3.3.4.1 Parameters settings in our simulations

The set of parameters used as initial conditions for the simulations is posted in Table 3:

Table 3: Aircraft and context input parameters for the simulations

Aircraft configuration		***Comment***
Fuel	42,250 kg	Consumption ~6.8 t/h *(cf our detailed computation in Section 3.3.4.5 below)*
Gross Weight	216,650 kg	
Altitude	35,000 ft	
Indicated Air Speed	IAS 280	The IAS 271 given in report [2] was found erroneous as confirmed by our computation and by the simulations *(c.f. Section 3.3.4.5 below)*
Ground Speed	475kt	Initial ground speed from report [2]
Simulator setup		
Autopilot	Engaged then disengaged	Heading hold when abeam IGARI and then disengaged before the U-turn to the left
Auto-throttle	Engaged	
Local conditions		
Wind direction	95°	GDAS data show that the wind was stable during the time of the turn and in its vicinity
Wind Magnitude	11 kt	
Waypoints		
Actual start of the turn	N07.02.13/ E103.42.88	Heuristically defined by tests & trials
Entry point	N07.05.7/ E103. 47.01	As defined p276 in Malaysian report [2]
Exit point	N07.12.7/ E103.38.70	As defined p276 in Malaysian report [2]
Time from Entry to Exit pts	2min 10sec	As defined p278 in Malaysian report [2]

3.3.4.2 Simulations using Prepar3D

The simulations were performed with a personal computer and the Prepar3D software from Lockheed-Martin enhanced with the PMDG add-on including a B777-200ER model equipped with Rolls-Royce TRENT-892 engines. This configuration is similar to the actual 9M-MRO aircraft.

Several runs were performed by airliner Captain Blelly to scan the different possibilities of performing such a sharp U-turn manually. As the result, executing such a turn is feasible and can be repeated identically at will. But this requires professional pilot’s skills in order to maintain the aircraft level during the turn while gradually increasing the banking angle reaching the maximum banking limit in the second portion of the turn, especially at night.

Figure 18 illustrates the particular situation where the banking angle has been progressively increased from 25° at the start of the turn until between ~35° and ~38° which is at the limit. The full video is available at www.mh370-Caption.net (*01-Virage-IGARI-2022-12-07-Prepar3D.mp4*). The visible waypoint ahead of the aircraft is the official Exit waypoint. The timer of the aircraft was triggered when overflying the Entry waypoint. Increasing gradually the banking angle offers the best fit with the known radar track as shown in Figure 19.

Figure 18: Snapshot of the Prepar3D simulator in the U-Turn at time stamp 1min30s after overflying the Entry point

3.3.4.3 Fixed based simulator

During a simulator session organised in Autumn 2022, an active B777-rated airliner Captain was asked to execute such a turn. The initial conditions were those given in Table 3. The simulator is a fixed based simulator located at Skyway Simulation, in the city of Nantes, France. The core of the simulator is the Lockheed- Martin Prepar3D software enhanced with the full cockpit equipment suite FDS-B777-FTD from Flightdeck Solutions.

In a unique trial, the Captain did execute properly the turn overflying the two official Entry and Exit waypoints in 2min 10sec after overflying the newly defined starting waypoint of the turn. This provides an additional evidence supporting the hypothesis that this turn was executed manually.

A video clip of this particular turn is available at www.mh370-caption.net (*02-virage-IGARI-2022-09-Nantes.mp4*).

3.3.4.4 Results of all simulations

The flown trajectory resulting from the different sessions is illustrated by an example in Yellow in Figure 19. It encompasses the overshoot after passing abeam waypoint IGARI and the newly defined starting point of the U-turn earlier that the official Entry waypoint. In addition, both official Entry point and Exit points were mandatory waypoints to be overflown.

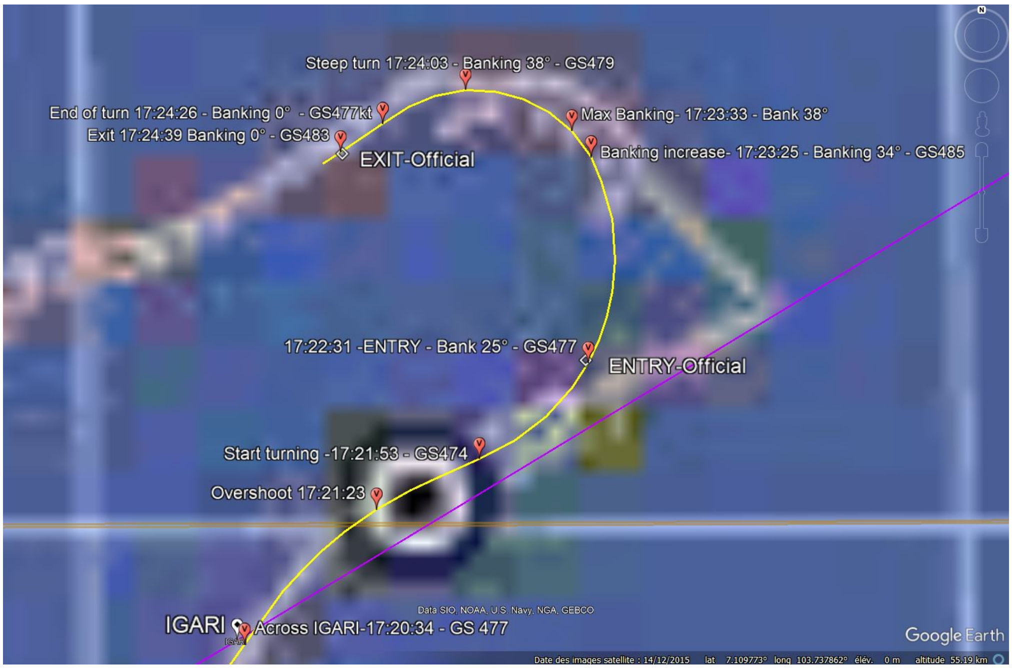

Figure 19: Spiral trajectory flown with Prepar3D simulator (gradual increasing of the banking angle)

The executed trajectory time tags from the video have been converted in UTC time in order to provide better readability for each navigational waypoint.

The first noticeable visual result is the excellent match between the path built from the "acquired" radar plots and the flown trajectory in the simulations. This validates the hypothesis of a high banking turn with an increasing bank angle from 25° up to the acceptable banking limit i.e. ~38°. This is just outside the banking alarm making this situation as a demanding one.

Furthermore, in this example like in a large number of simulation exercises, the timing between the two official Entry and Exit waypoints matched the mandatory interval of 2min10sec within +/- 2sec.

The aircraft parameters at different key points along the trajectory during the U-turn are posted in Table 4. The fuel calculation is justified in Section *3.3.4.5 below*. The flight level was successfully kept constant at ~35000 ft (i.e. ~FL350).

Table 4: Aircraft parameters along the U-turn manually executed

Time (UTC)	***Location***	***Ground Speed (kt)***	***Heading (°)***	***Fuel (t)***	***Banking (°)***
17h20:34	Abeam IGARI	477	025 to ~036	42.3	
17h21:23	Overshoot	476	~057		
17h21:53	Start Turn point	474	~064	42.1	0
17h22:30	Entry point	477	~029	42.0	25
17h23:25	Intermediate	485	~329		34
17h23:33	Intermediate	481	~315		max~38
17h24:03	Intermediate	479	~269		max~38
17h24:26	Intermediate	479	~237		0
17h24:40	Exit point *(+2'10" after Entry)*	483	~236	41.8	0

3.3.4.5 Fuel consumption estimation

To be as accurate as possible, the estimation of fuel is worth dedicating some attention for the most realistic reconstruction of the trajectory as possible. To that effect, and like all other existing studies, our computations are based on the last known value of fuel on-aboard which is 43.8t as reported at 17h06:43 UTC in the last aircraft ACARS message which is presented in Table 5 from [15].

Table 5: Last ACARS position report including the fuel on-board (last column) [15]

Greenwich Mean Time (GMT) - UTC	1641:43	1646:43	1651:43	1656:43	1701:43	1706:43
Altitude (ALT) – Feet	103	10,582	21,193	28,938	34,998	35,004
Calibrated Airspeed (CAS) - Knots.	168.4	261.8	301.1	303.1	278.0	278.4
MACH	0.255	0.478	0.669	0.783	0.819	0.821
Total Air Temperature (TAT) - °C	31.1	23.4	11.6	2.5	-13.4	-13.1
Static Air Temperature (SAT) - °C	27.3	10.4	-11.8	-27.4	-43.9	-43.8
Latitude (LAT)	2.667	3.074	3.553	4.109	4.708	5.299
Longitude (LONG)	101.715	101.760	01.988	102.251	102.434	102.713
Gross Weight (GWT) – lb	492,520	489,200	486,240	483,840	481,880	480,600
Total Remaining Fuel Weight (TOTFW) - kg	49,200	47,800	46,500	45,400	44,500	43,800
Wind Direction (WINDIR)	140.3	107.6	1.8	58.4	69.6	70.0
Wind Speed (WINDSP)	1.25	9.38	19.50	10.63	17.38	17.13
True Heading (THDG)	-33.5	27.7	27.8	26.0	26.8	26.7

Table 1.9A - ACARS Position Report

The Exit point was overflown at 17h24:40 UTC i.e. 2min10s after the Entry point. Thus, the time interval between 17h06:43 and the time at the Exit point is basically ~18 min.

In the operational flight plan (OFP) filed by the company less than two hours before departure and signed by Zaharie Shah, the estimation of fuel consumption for this particular flight was made taking into account the meteorological forecast of the day as well as the performance factor due to the overconsumption of the aging engines.

Let’s consider the two waypoints “AC” and “PCA” planned to be overflown at about 40min past IGARI when the aircraft was supposed to have reached FL350 and be levelled. Table 6 presents the fuel estimation figures at those two locations (highlighted in green).

Table 6: Fuel estimation made in the filed operational flight plan for the “en-route” after IGARI

MAS 0370 / 1		PAGE 5 / 9 (07MAR14 15:05)								7 MAR 2014
WPT	AWY	TTRK	SAT	WS	WC	GS	DIST	ZEET	TOTM	FUELRM
LAT/LONG		MTRK	TDV	TP	WIND	FL	ZATA	ZETA	MOCA	RQFUEL
AC	W1	077	M45	0	M002	481	0033	0:04	1:23	
N1056.3	E10711.3	078	P09	52	016/005	350			0[illegible]2	36.5
BMT	W1	028	M45	0	M004	479	0117	0:15	1:[illegible]8	26 minutes
N1240.0	E10807.4	028	P09	53	016/005	350			1[illegible]4	34.9
PCA	W12	035	M45	0	P008	490	0094	0:11	1:49	
N1357.4	E10902.6	035	P09	58	272/016	350			104	33.6

This table shows that for the planned travel time of 26min between waypoints AC and PCA, the fuel consumption was estimated at 2.9t (i.e. 36.5t – 33.6t). This means ~112kg/minute or 6,8t/h. Somehow, this is confirmed by the model of the simulator which posts a figure of 2 x 3.4t/h = 6.8t/h as shown in Figure 20 and reported in Table 3 as well as by our Constraint Assessment Tool[5] (CAT) as reported in Table 7.

Figure 20: Cross-checking of our computation with the simulator model

If we make the hypothesis that the fuel consumption per time unit abeam waypoint IGARI would have been very close to the one between waypoints AC and PCA as the aircraft configuration is almost identical, then we can induce that to reach the Exit point from the location of the last ACARS message in 18 minutes, the aircraft consumed ~2,016kg of fuel. Thus, at the Exit point the fuel on-board was most probably 43.8 – 2.0 = 41.8t.

Similarly, the journey between the location at the last ACARS message and waypoint IGARI leads to a fuel consumption equal to ~1,570kg. Thus, abeam waypoint IGARI the fuel on-board was ~42,230kg rounded at 42.2t. This figure was used in our simulations replacing the estimated value of 41,200kg posted by Boeing in the Malaysian report [2] which is probably due to a transcription error.

To complement the fuel consumption analysis, we have performed a second computation thanks to an improved version of the CAT tool at the same constant flight level of FL350. The CAT is based on IG member Dr Ulich's fuel consumption model and it computes the consumption every second also taking into account the GDAS meteorological data. The results are provided in Table 7.

Table 7: On-board Fuel estimation by the CAT tool

Name	Longitude °	Latitude °	Time UTC	Wind Speed (kt)	Wind Direction °	Delta-Isa	Fuel (kg)
Abeam IGARI	103.5933	6.9310	17:20:34	11.5	95.4	11	42,229
Overshoot-IGARI	103.6469	7.0071	17:21:16	11.4	95.4	11	42,149
ENTRY-Official	103.7835	7.0950	17:22:30	11.4	95.3	11	42,003
EXIT-Official	103.6450	7.2117	17:24:40	11.4	95.2	11	41,755

[5] CAT tool : specific software developed for trajectory and fuel consumption calculation

Thus, the two sets of figures - computed separately- are in accordance with each other by less than 25kg and have been used in place of Boeing's figures as initial conditions for the performed simulations (c.f. Table 3). These figures have been confirmed by the Prepar3D simulator model also.

3.3.5 Conclusions on the U-turn after waypoint IGARI

The results of the analysis above show that considering a manual execution of the U-turn after crossing IGARI is well justified and probably the most likely action performed by the person in command at this point in time to turn and avoid entering the Thai ADIZ. Different simulations on different simulators performed by airliner Captains have validated such a hypothesis. It required skills from experienced pilots but it is possible within the measured timing.

Consequently, a manual U-turn is the hypothesis retained for the rest of the study.

3.4 From the Exit Waypoint to the last radar contact

In this section, our analysis focuses particularly on the leg starting at the exit of the U-turn estimated at 17h24:40 UTC and finishing at the last known position of the aircraft at about 10 Nm after waypoint MEKAR at 18h22:12 UTC as reported in the Malaysian report [2] which we call LaST Report Point (LSTPR). This is the second part of the MH370 known trajectory.

3.4.1 Available data

From the last transponder message received at 17h20:34 UTC when abeam waypoint IGARI, the aircraft was still tracked by the military. And today, the trajectory can be reconstructed thanks to additional radar data sources and one extra piece of information coming from the Celcom mobile telecommunication company at Penang. This complete set of available data is reviewed below.

3.4.1.1 Military primary radar plots

The first source of information is still the image provided in a low-resolution on page 3 of the Australian report [4]. However, this time the full picture presented in Figure 21 will be considered because it covers the aircraft flight path until the last radar contact after waypoint MEKAR. The two segments of interest are

a) the short visible path after the Exit point (end of the Pink line) and then

b) after the gap, the path followed by the aircraft from 17h30:33 till 18h22:12 UTC (Yellow line).

The location of the aircraft at 18h22:12 UTC is the last known position and it will be referred as the last primary radar plot or LSTRP waypoint in this study.

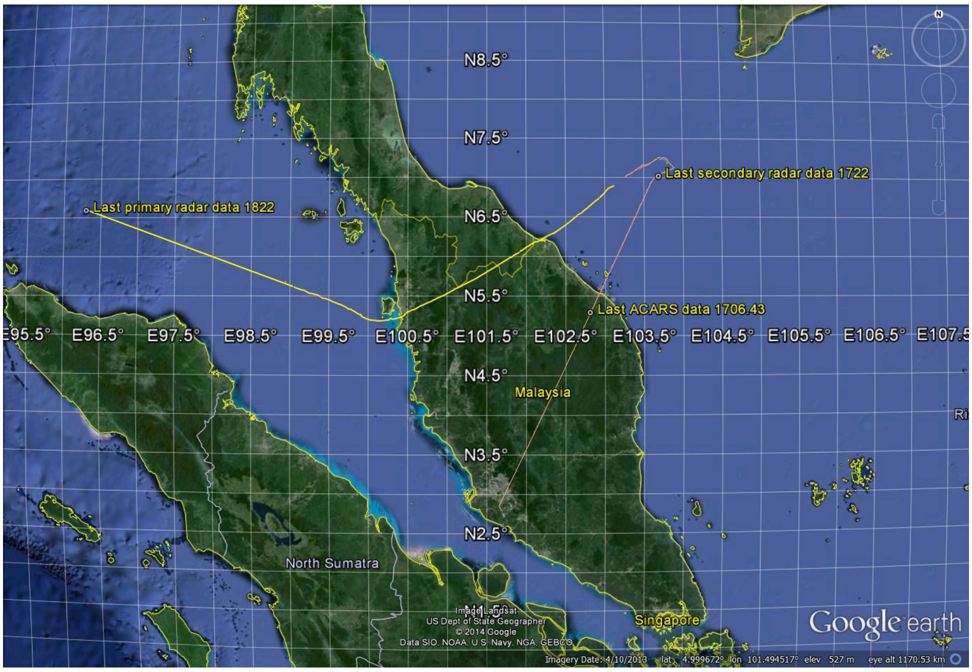

Figure 21: MH370 flight path derived from primary and secondary radar data (source ASTB)

Unfortunately, the military authorities did not release any primary radar data officially except the picture captured at the Lido Hotel conference (c.f. Figure 23).

3.4.1.2 Civil Primary Radar Data Plots (RDP)

Thanks to the Independent Group, civil primary radar data has been made publicly available on their web site [8]. An overlay of this data on top of the military plots shows the very good match of the respective paths. A deeper analysis was made by the Independent Group in [8] providing trust in this information and confirming the same conclusion stated in section 1.1.3 of the Malaysian report [2] on the localisation of the track but also on the high level of "noise" in the measuring of the time stamps.

The data comes from the Terminal Primary Approach Radar at Kota Bharu airport and at Butterworth airbase. The range of these systems is approximately 60 Nm and 80Nm respectively. They are calibrated to track aircraft at a shorter range and lower altitude than MH370 was flying.

Unfortunately, the data includes some gaps, but it comes into six useful data sets providing time and distance in slant range. Furthermore, the time stamps include irregularities and the distance measurements are provided as raw data without any post-processing that usually a radar system does before presenting the data on the controller screen. Nevertheless, the graphical fusion of the military data and the civil data shows a remarkable match as illustrated in Figure 22.

Figure 22: Comparison of military primary radar (yellow) and civil primary radar (magenta and purple)

Like the military data, for which a warning is made in the Malaysian report [2], the civil radar data are subject to inherent measurement uncertainties both in time and slant range. Thus, the computed instantaneous ground speed magnitude based on the raw data with no filtering posts scattered values outside the flight envelope of the aircraft.

Computing altitude and speed from 2D-Radar data without complementary SSR data is not possible without making assumption on one or the other. Furthermore, the provided time data is too erratic leading to computed speed values which are not realistic. In a short study [26], we have shown that in numerous segments these values are above the upper limit of the flight envelope (overspeed) and in one segment the speed is too low and very close to the manoeuvrability speed limit.

Thus, we consider that the speed computations cannot be made on solid ground as the data is not timewise reliable.

It is very important to keep in mind that "no matter what", a pilot will never go outside the flight envelope and the fact that the MH370 flew during so many hours proves that the person in command respected this rule. Taking into account the local wind at that time, considering a TAS speed above ~535kt should not be an option. In addition, the certified maximum operating altitude for a B777 is 43,100 ft.

Building on the airmen's way of managing the speed (or the Mach) and also on Captain Blelly's experience, we only used the time stamps known as key information such as the time of exiting the U-turn at 17h24:40 UTC, the detection of the co-pilot's mobile phone at Penang at 17h52:27 UTC and the last radar plot at 18h22:12 UTC. This data can be used to establish average ground speeds which we used further to tune the possible TAS or Mach on successive segments. Average speeds are routinely used by a pilot. For example, after the U-turn and during the descent, the person in command increased the IAS up to ~310kt which was further maintained steadily in the cruise at FL300 until waypoint VAMPI. This IAS is the recommended minimum consumption speed for descent by Boeing.

3.4.1.3 *Military radar "blips"*

The last radar information available is still the pictural element shown to the Next of Kin during a conference in 2014 and replicated in Figure 23. This time the radar blips are represented as yellow dots with fuzzy unreadable labels. The set is incomplete, probably due to a malfunctioning element of the radar elevation beam forming, but the most important information provided is the last radar blip (LSTRP) at 18h22:12 UTC located at about 10Nm after waypoint MEKAR.

At this particular point, we will use the data provided in the Malaysian report [2]:

- Time = 18h22:12 UTC
- Heading = 285°
- Distance = About 10 Nm after MEKAR (i.e. ~251Nm from Butterworth and not 200Nm)
- Ground speed = 516kt
- Altitude = 29,500ft (QNH)

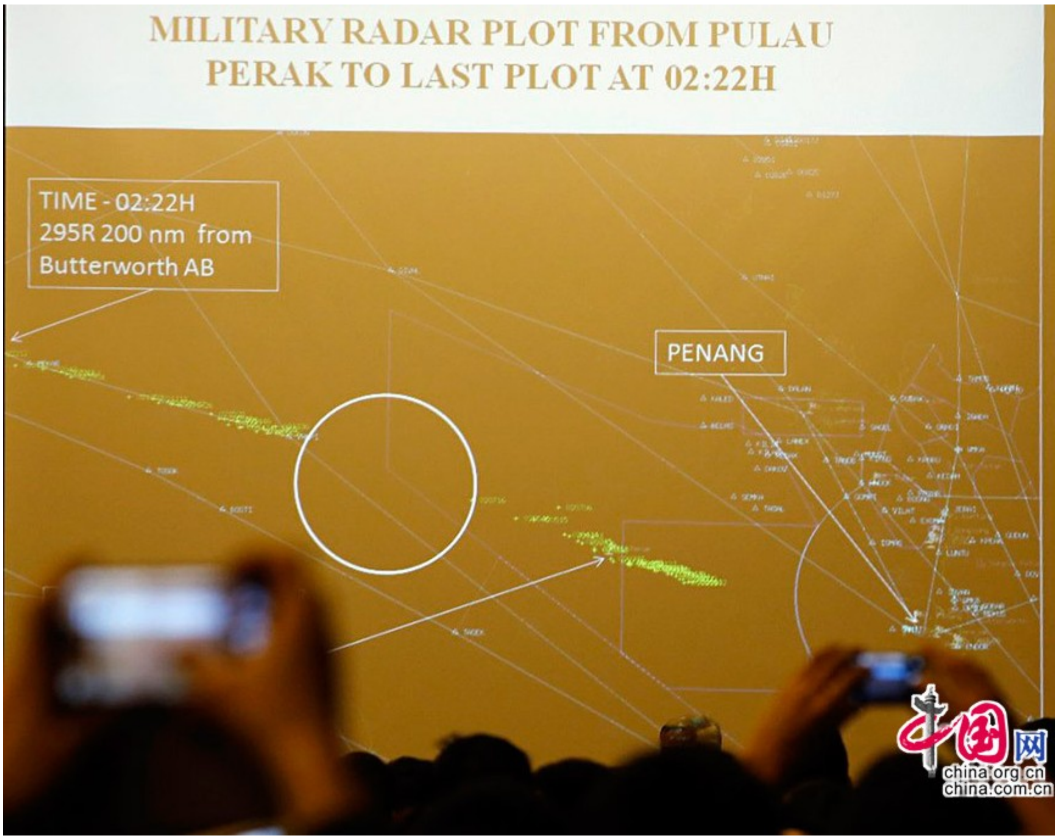

Figure 23: Military Radar records shown to Next of Kin at Lido Hotel, Beijing on 21st March, 2014

3.4.1.4 *Detection of the co-pilot's mobile phone*

An additional piece of key information is provided by the Malaysian Police report. It is the brief connection of the co-pilot's mobile phone at 17h52:27 UTC to a Celcom Location Base Station in Penang Island. The BBFARLIM2 station sectorial range is indicated to be approximately 32km i.e. ~17.3Nm on the ground (c.f. the boundaries of the primary lobe in Red in Figure 24).

Using the radar plot locations around this time stamp, one can derive an approximate location of the aircraft at 17h52:27 UTC as illustrated in Figure 24. Its coordinates are [5.2187°N; 100.2919°E] approximately 10Nm in the south of the Celcom terrestrial antenna.

Following the airmen's way of flying, this point was used as a mandatory timely waypoint in the trajectory reconstruction.

One could ask why the co-pilot's mobile phone was detected there? According to Captain Blelly's investigation [1], there is a high probability that the co-pilot who had been trained for depressurised cabin situation could have used small portable oxygen tanks. Some of them are available to cabin crew for moving along the aisles in emergency situations. Thus, he could have tried to place a phone call through one of the cabin windows. At this point in time (17h52 UTC) the oxygen supply capacity for the passengers was exhausted, thus the co-pilot had to use a portable oxygen tank.

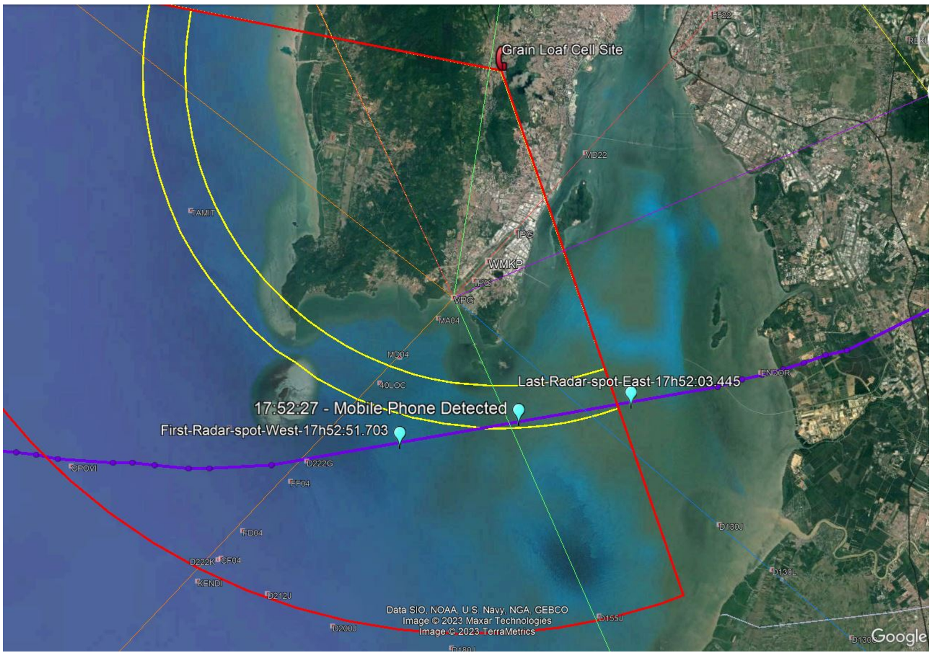

Figure 24: Estimated aircraft position when the mobile phone was detected at 17h52:27UTC

How the mobile phone could succeed to get connected and why the call did not go through? Figure 25 presents an approximate extrapolation of the terrestrial cell antenna secondary lobe power diagram versus the elevation. By design, the power level of this "1 bar" lobe is not strong enough to be received above 32000ft in true height. One can see in Figure 25 that at FL300, which was ~31500ft in true height, the beam could just barely be detected at a location between 9 to 10Nm approximately.

The possible geographical ring where a mobile phone could get connected is illustrated by its two Yellow boundaries in Figure 24 and between the two Orange vertical lines in Figure 25. The aircraft crossed it marginally during ~30 seconds only. This explains why a phone call could not be completed.

In addition, this event is an extra evidence that the aircraft was below the height of 32000 ft as he could not have succeeded to be connected at a higher altitude.

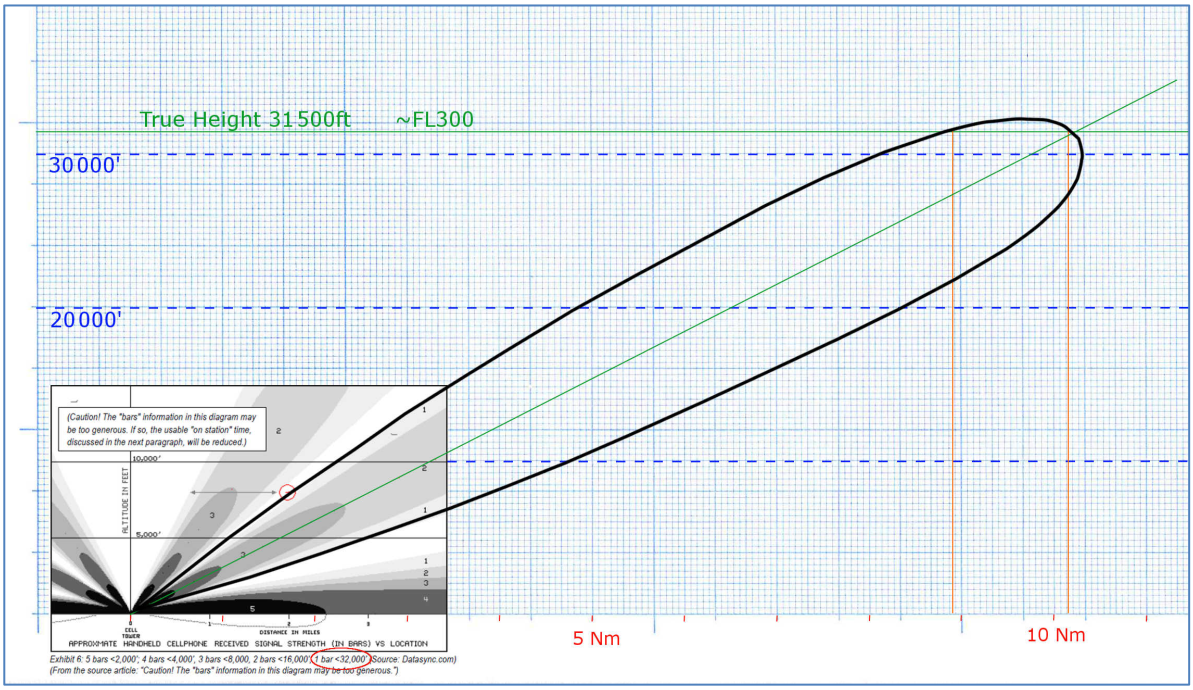

Figure 25: Extrapolation of the Celcom terrestrial antenna secondary lobe power diagram (source Datasync.com)

For information, the correspondence between the flight level and the true height (i.e. above mean sea level) during the path from the U-turn to Pulau Perak is provided in Table 8. At that time, in the south of Penang, the delta ISA was 11°.

Table 8: correspondence between the flight level and the true height above sea level

Flight Level	True height (ft)	Delta ISA °
FL350	36,540	11
FL330	34,450	11
FL300	31,320	11
FL300	30,840	7
FL300	31,560	13

3.4.1.5 Undisputable Facts on Distance and timing

There are absolute distance and timing figures between the Exit point and the last radar contact at 18h22:12 UTC. According to the above data, the aircraft flew 485.4Nm between the Exit point after the U-turn and the last radar contact position at 10Nm northwest of MEKAR. Furthermore, the time interval between these two locations is 57min32sec.

Thus, following the pilots' way of estimating legs, the reference value of the average ground speed for this leg is 485.4Nm flown in 57'32" = 506kt.

3.4.2 From the U-turn Exit waypoint to Penang

In this section, a plausible manually piloted trajectory will be reconstructed from the Exit point of the U-turn estimated at 17h24:40 UTC and the estimated location where the co-pilot's mobile phone was detected at 17h52:27 UTC.

3.4.2.1 Hypotheses

According to Captain Blelly's investigation [1], the person in command triggered several actions as soon as possible in order to make the aircraft invisible and undetectable by the civil ATC. Firstly, he disconnected all electrical generators from the electrical network to create a situation difficult for both the crew and passengers. This also triggered the deployment of the RAM Air Turbine (RAT) to provide the necessary power to manually pilot the aircraft.

Secondly, the person in command voluntarily depressurised the aircraft to simulate a pressure incident to keep the passengers and the crew seated with their oxygen masks on and later suffering hypoxia when the oxygen exhausted approximately 22 minutes later. The aircraft then descended to FL300, probably to be able to better sustain the low pressure inside the cockpit. It is not compulsory to switch off the Air Conditioning systems (packs) to depressurise the aircraft. This can be done manually, thus keeping the temperature drop acceptable inside the cockpit.

When each of these particular actions took place is difficult to evaluate precisely. Below is the list of their results and their consequences provided as the basic hypotheses for our analysis:

- No more electro-magnetic emissions from the aircraft including aircraft position lights because the electrical generators were disconnected
- The electricity was provided by the RAT and led to a manual piloting
- Descent to a lower altitude ~ FL300 in approximately 15min
- Constant FL300 from Kota Bharu to South Penang
- Depressurised aircraft and oxygen mask put on (27h oxygen endurance for a single pilot in the cockpit)
- No need to put the air conditioning packs off for aircraft depressurisation: only manual full opening of the outflow valves.
- Low flow for air conditioning is always available in the aircraft to maintain a bearable temperature
- The radar plots show lateral irregularities which are unusual for an aircraft controlled by the autopilot, this is an additional element supporting the manual piloting hypothesis
- The navigation was made via the Captain's Navigation Display in using some waypoints as visual targets in conjunction with Penang VOR (VOR In, then VOR Out) mainly.
- The flight passed to the South of Penang Island at about ~10Nm when the co-pilot's mobile phone got connected very briefly at 17h52:27 UTC with no call going through.
- The average ground speed between the exit of the U-Turn and South Penang is thus estimated at ~506kt +/-2.5kt.

3.4.2.2 No electromagnetic emissions

As explained above, the U-turn required the full attention and dedication of the person in command. Thus, it is most probable the person in command waited for the U-turn to be completed before making sure that the aircraft ceased emitting any detectable signal and remained "electromagnetically" silent. This encompasses the telecoms (including the ACARS, IFE, etc.), the lights but also the DME (Distance Measuring Equipment).

For a pilot, the simplest and the most effective way to be sure to switch off all systems at once is to disconnect the electrical circuits from the four generators (main and backup). By successively pressing the button of each generator on the overhead panel, the person in command ensured the disabling of all systems capable of communicating outside without any exception. This supposes the APU rotating knob had been turned on and then off just after to avoid its auto-restart. This implies also that subsequently the aircraft was flown with the sole electrical power provided by the RAT (Ram Air Turbine) but also in parallel with the full hydraulic power of the properly working engines. This implies a subsequent manual piloting. The RAT was deployed either automatically or manually.

Regularly pilots are trained to fly in such conditions during flight simulator training sessions. So, it is believed that the PIC was well trained for this. In addition, let's remind the LATAM B777 flight 8084 in December 2018 from Sao Paulo to London which flew about ~50 minutes with the RAT power only without any problem.

3.4.2.3 Depressurised aircraft and descent until Kota Bharu

The scenario including a descent after the U-turn executed at FL350 down to a lower level at about FL300 fits well with the hypothesis of depressurisation. The increase of speed until 17h37 UTC matches well with a descent with the throttle kept in a fixed position due to the disconnection of the auto throttle when the electrical power went off. Also, the autopilot was not available anymore.

Nevertheless, it should be noticed that during our simulations of the U-Turn, the ground speed at the Exit waypoint point was in fact at about ~476kt at Mach 0.787 on average (c.f. Figure 18). This is a higher speed at the exit than the radar computed value of ~458kt. Noticeably, in this manoeuvre the instantaneous speed is very variable.

At such a flight level, the most logical operational speed reference to use is the Mach number. At waypoint IGARI the Mach was set at ~0.821. Our analysis shows that during the descent, the aircraft accelerated with an average Mach of 0.835 until reaching IAS 310kt as illustrated by a screen capture taken during one of our simulations in Figure 26.

Figure 26: Flight parameters in the late part of the descent to FL300

This makes the average ground speed equal to 507kt with a standard deviation σ = ± 2 kt for the descent. This is well below the maximum possible Mach of 0.870. The meteorological data indicates a tail wind evolving from 11kt from 95° to 17kt from 75°. Overall, the average TAS was about ~495kt according to our computation.

To be levelled at FL300 at Kota Bharu, the rate of descent is estimated between 300 to 500 feet per minute (fpm) during 15 minutes approximately.

During this leg, the navigation could have been a mix of visual usage of the navigational display waypoint icons of Kota Bharu as a global direction and of the Penang VOR-In radial as the aircraft was well within its range. The light of the city of Koa Bharu could have been of help too.

An interesting question is why the person in command chose to level at FL300? Our answers could take the form of a chess player preparing several moves in advance. First, as explained above, this level was probably an acceptable level for sustaining the low pressure and a bearable temperature in the cockpit. Second, FL300 is sufficiently high to behave as normal En-route traffic above Kota Bharu and Penang terminal areas. Thirdly, FL300 is a low flight level for the targeted Malacca Straight area and its routes thus staying safe and below the long-haul traffic usually flying above. Fourthly, FL300 offers the highest ground speed for any selected IAS or Mach for the best specific fuel consumption. Finally, FL300 is judiciously chosen with a good ratio consumption/range as no climb would be necessary afterwards as demonstrated in the chapter dedicated on the unknown trajectory later in this report (c.f. Chapter 4).

3.4.2.4 From Kota Bharu to South of Penang

At Kota Bharu, and levelled at FL300, the operational speed reference to consider is now the Indicated AirSpeed (IAS) as the aircraft normally switches automatically from Mach to IAS when arriving at an IAS of 310kt. Our analysis shows that in this leg the average IAS was ~310 ± 1 kt. Thus, it appears that the person in command flew manually at that quasi-constant IAS acquired during the descent at FL300. It is a safe way of flying well below the maximum possible IAS of 330kt.

Overall, the average ground speed of this leg is equal to ~506kt with a standard deviation σ = ± 2.5 kt. Our simulations confirmed that an average IAS of ~310kt is the best fit.

The leg “Exit Waypoint to South of Penang” is illustrated in Figure 27. Some small trajectory lateral adjustments are mentioned in the Malaysian report [2] which we read as the result of manual flying and following a radial-In to VOR Penang (the autopilot was unavailable).

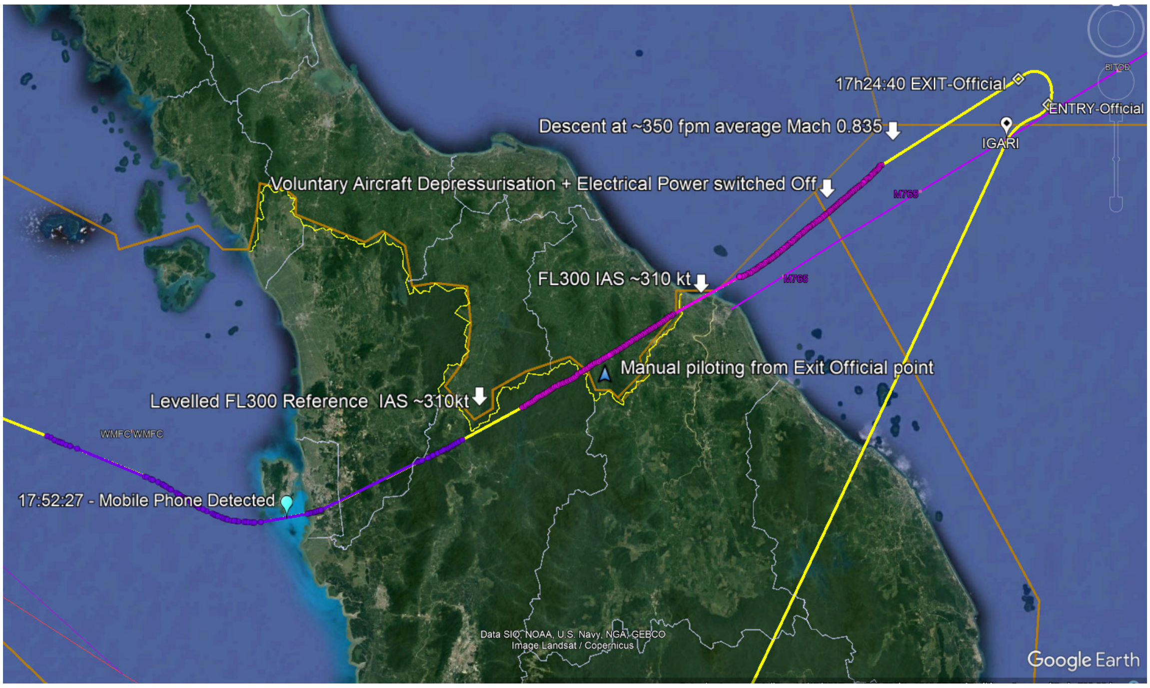

Figure 27: Path and scenario between Exit Waypoint and South of Penang

3.4.2.5 Fuel consumption

To evaluate the fuel consumption the same method was used as above. Three types of computations were performed: the airmen's method, our CAT tool fuel consumption model and the measurement of the fuel indicated by the FMC of our simulator. The results are posted in Table 9.

Table 9: On-board fuel during the leg Exit Waypoint to South Penang

Time	***Location***	***Fuel On-Board (t)***		
		Airmen's	*CAT Tool*	*Simulator*
17h24:40	U-Turn Exit waypoint	41.8	41.8	41.8
17h37:00	Kota Bharu	-	40.5	40.4
17h52:27	South Penang (Phone detected)	38.5	38.6	38.4

The different methods are in accordance about the hourly fuel consumption which is evaluated between 6.9t to 7.3t. Thus, in spite of the descent, the aircraft consumed above average because it was at lower levels than the optimised ones.

3.4.2.6 Simulations

Several simulations were run according to the flight profile and hypotheses described above. A video of one run is available at www.mh370-caption.net (*03-Exit-to-VAMPI-manual-506GS.mp4*). The lessons learned from the simulations are that the person in command must have changed the Mach number along the descent in order to keep the aircraft within the speed envelope without gaining too much speed as the auto-throttle was disengaged. Thus, on this leg the Mach number decreased from 0.850 initially down to 0.815 in cruise.

Mach 0.815 at the bottom of the descent at FL300 led to an IAS of 310kt, which is due to the average wind conditions used for this leg i.e. a constant wind of 14kt from 85° underestimating its positive evolution. Changing the meteorological conditions in the Prepar3D simulator is not straightforward. Nevertheless, under manual piloting, our simulator overflew the point of the mobile phone's connection in just 5 seconds ahead of schedule.

3.4.3 From Penang to the Last Radar Plot

In this section, the analysis focuses on the second leg starting at the estimated location where the co-pilot's mobile phone got connected at 17h52:27 UTC in the south of Penang until the last known position of the aircraft at about 10 Nm after waypoint MEKAR at 18h22:12 UTC which is the last bit of information about the MH370's known trajectory.

3.4.3.1 Hypotheses

For this leg, the only available data includes two "large field of view" images and one set of civil primary radar raw data with low precision time stamps. According to the Malaysian report [2], the aircraft was turning to the northwest direction at 17h52:27 UTC. Then it flew on a quasi-direct route to waypoint VAMPI and disappeared from the radar after waypoint MEKAR.

Even though the numerical radar data provided by the IG [8] is raw with unreliable time tags, its geographical location matches well the military radar track. Both show lateral excursions of the aircraft which cannot come only from the imprecision of these plot measurements. An aircraft controlled via the LNAV function on a direct route to waypoint VAMPI would not present such lateral deviations. It is concluded that in continuity with the previous leg, the person in command was still manually controlling the aircraft following a radial-out from VOR Penang.

Building on the above conclusions and to maintain continuity, the following hypotheses form the basis to our analysis of this leg:

- The aircraft was still manually piloted as the radar plots show lateral irregularities which are unusual for an aircraft controlled with LNAV
- The aircraft was still depressurised and the person in command was still wearing his oxygen mask
- The electrical power was still provided by the RAT only
- No electro-magnetic emission was possible still
- The flight level was maintained constant at FL300 from South Penang to waypoint MEKAR
- The navigation was still made via the pilot Nav Display by visually using waypoint VAMPI icon as a target in conjunction with Penang VOR-Out
- Knowing the time difference from South of Penang to LSTRP, the average ground speed is estimated at ~508kt.

3.4.3.2 From South of Penang to VAMPI

The path flown by the aircraft is clearly identified by the radar plots as presented in Figure 28. The lateral deviation just after the turn is not a typical trajectory flown with the LNAV function activated. This is also visible on the image at the Lido Hotel in Figure 23 above. Under LNAV, the aircraft would have taken a more direct route to waypoint VAMPI as illustrated by the Red line in Figure 28.

Figure 28: Civil Primary radar track overlaid on the military radar track from South of Penang to waypoint VAMPI (source ATSB [4])

As there is still no evidence of electrical power restoration, the person in command was still piloting the aircraft manually, using the navigation tools at their disposal i.e. waypoints icons on the navigation display as visual aids and the radial out from VOR Penang. Just after the turn at Penang, the pilot most probably used the “track select” function for adjusting at best his route to waypoint VAMPI.

Remark: The aircraft path displayed in Figure 28 is represented by a perfect straight line while the display in Figure 23 show irregular locations around the line direction to VAMPI. Thus, we believe that the image provided by ASTB [4] in Figure 28 has been edited and a broken line at VAMPI has been simply drawn from the last radar plot before Pulau Perak until the LSTRP via VAMPI. This will be addressed in more details in section 4.3.4 below.

Based on the available information on the route followed and the time difference between the location of the connection of the mobile phone at Penang and the LSTRP position, the average ground speed has been estimated at ~508kt. This implies that the aircraft flew abeam waypoint VAMPI at about ~18h13:00 UTC. Taking into account the necessary final acceleration between waypoint VAMPI and LSTRP leading to a ground speed at 516kt (Malaysian Report [2]), the simulation sessions showed that the average ground speed between South of Penang and waypoint VAMPI was actually ~506kt.

Taking into account the wind characteristics along the path, this would mean that the aircraft was manually piloted still using the IAS reference of ~310kt.

3.4.3.3 From VAMPI to the last radar plot (LSTRP)

For simplicity and because it does not impact the trajectory too much- and like many other studies -we considered that waypoint VAMPI has been overflown in order to stay well within the FIR Kuala Lumpur. Using the poor-quality data at hand, the IG member B. Holland succeeded to overlay timestamps on the Lido Hotel image as shown in Figure 29.

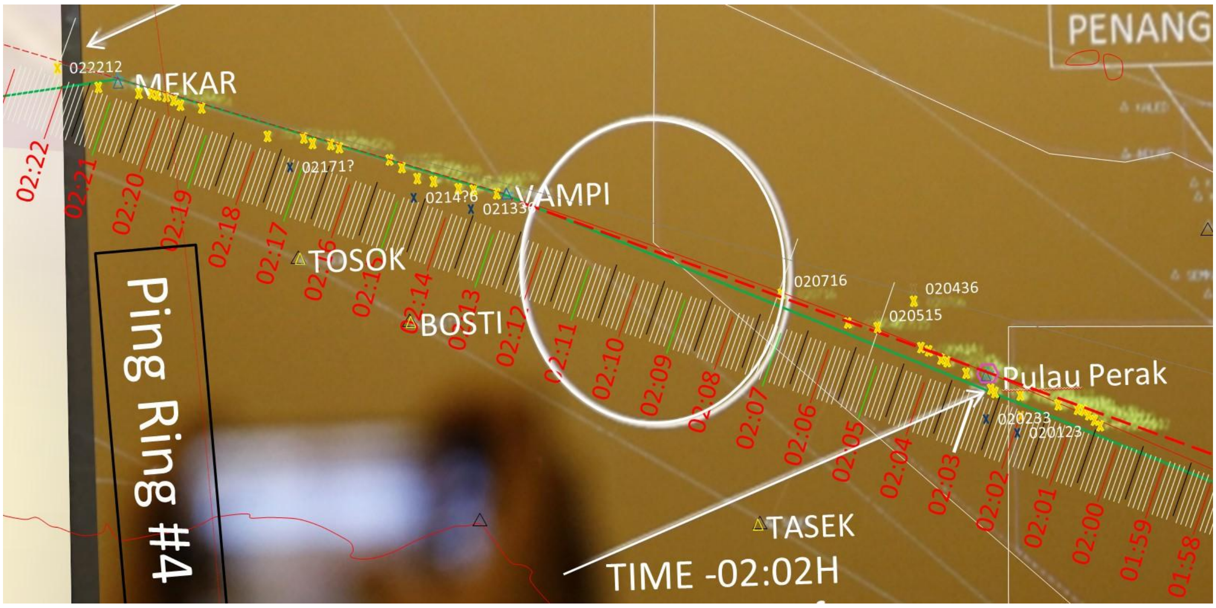

Figure 29: Enlarged Lido Hotel image with timestamps (source Bill Holland)

3.4.3.4 Geometric considerations

Let us consider the yellow crosses in the first place i.e. the location aspects of Figure 29. They represent the aircraft locations as reported by the military radar. The timestamp 18h22:12 as mentioned in the Malaysian report [2] had to be extrapolated in the top left corner and is supposedly positioned at 10Nm from waypoint MEKAR in the continuation of his current route.

Getting closer, it is possible to mix this information with the data provided in the Malaysian report [2] in which it is stated that at the last radar plot (LSTRP) the aircraft's track was 285°, its ground speed was 516kt and its altitude was 29,500ft without more details. The most logical assumption is to consider it as a QNH altitude. Figure 30 provides a data fusion image on GoogleEarth and presents the trajectory that best fits with the available information. The green line is a visual best fit of the yellow crosses from VAMPI to MEKAR and from MEKAR it follows the track at 285°. One can see that the aircraft was initially a little south of route N571 at 286° then further south of it after MEKAR at 285°.

This is coherent with the hypothesis of a manual flying because if LNAV was engaged the trajectory would have been much closer to route N571 and the waypoints VAMPI and MEKAR would have been more closely overflown and the aircraft would have turned to the right towards NILAM.

This slightly offset trajectory will be used in our simulations later in section 3.4.3.6 Simulations

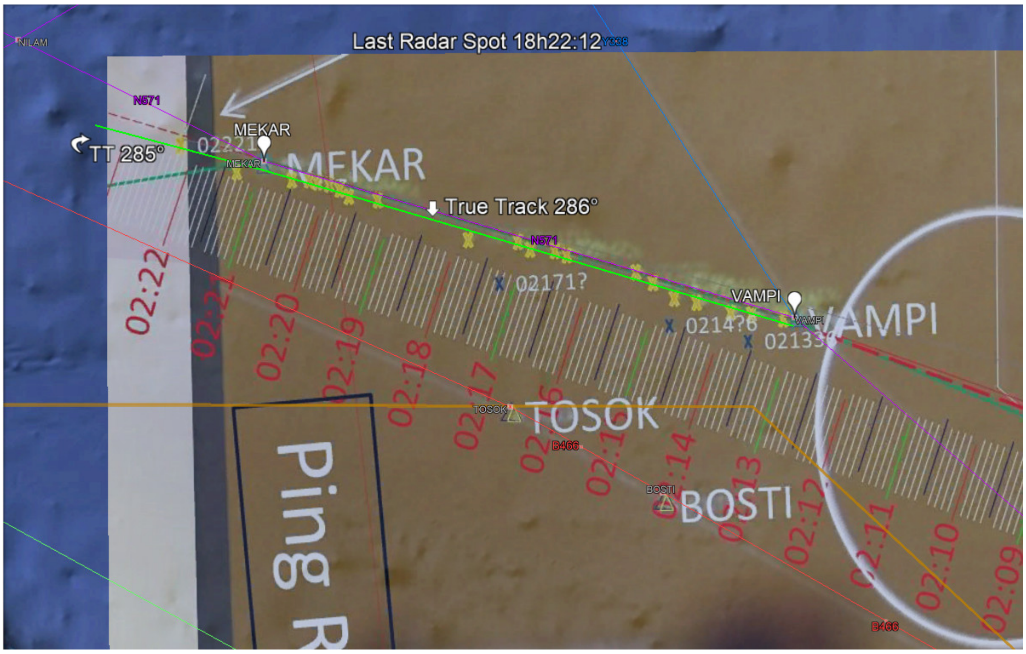

Figure 30: Induced trajectory between VAMPI and LSTRP (Green broken line at MEKAR)

3.4.3.5 Time and velocity considerations

Considering the ground speed of 516kt at the LSTRP (c.f. Malaysian Report [2]), we made the hypothesis that the IAS was kept quasi-constant between South of Penang and waypoint VAMPI and that an acceleration tool place afterwards as indicated above. The computation, as a simulation would do, includes the fuel consumption and the wind changes along the path. Table 10 presents the results of the computations.

Table 10: Estimation of the IAS, ground speed and on-board fuel between 17h52:27 and 18h21:00

Time	*Location*	*IAS (kt)*	*Ground Speed (kt)*	*On-board Fuel (t)*
17h52:27	CPMPh (South of Penang)	310	506	38.6
		310 ± 1	506 ± 1	
18h13:00[6]	VAMPI	310	506	35.9
18h21:00[7]	Abeam MEKAR	316	509	34.8

From waypoint VAMPI to the LSTRP, the aircraft slightly accelerated and after waypoint MEKAR it started a slow descent. The segment from south of Penang to MEKAR was at FL300 and the radar data detected altitude 29,500 ft at LSTRP, thus a 500 ft descent had to take place.

This scenario and figures were selected for our simulations.

3.4.3.6 Simulations

To verify these assumptions, several sessions of simulations were performed with the Prepar3D simulator and its PMDG add-on according to the flight profile described above. A video of one of the runs until VAMPI is available at www.mh370-caption.net (*03-Exit-to-VAMPI-manual-506GS.mp4*). The simulations confirmed that the person in command used a constant reference IAS of about 310kt

[6] *This timestamp is computed by the CAT and confirmed by our simulations*
[7] *Idem as footnote above*

until waypoint VAMPI. Thus, on this leg, the Mach number was stable at ~0.815 (GS=506kt). A screenshot taken during one simulation is provided in Figure 31 illustrating the different parameters values (in Red circles) and the aircraft condition manually piloted.

Figure 31: Screenshot of the simulator between South of Penang (CPMPh) and VAMPI with the RAT deployed

For this segment, the wind was considered constant with the average values of 15kt from 76°, this explains the difference between the IAS estimated by the CAT and the simulator value. Under these conditions, Captain Blelly could achieve reaching waypoint MEKAR at 18h21:00 UTC as expected under a fully manual piloting.

From waypoint MEKAR to the LSTRP, the Malaysian report [2] indicates a distance of 10Nm and a final ground speed of 516kt. The simulation of a descent manually piloted from the vicinity of waypoint MEKAR confirms the estimated figures above (IAS 326kt and ground speed 517kt) as illustrated in Figure 32 taken when approaching LSTRP waypoint.

Figure 32: Screenshot of a simulation manually piloted at the end of the descent to 29,500 QNH at LSTRP (18h22:12)

3.4.4 Conclusions on the leg from the Exit Waypoint to the last radar contact

The results of the analysis above show that considering a manual piloting from the end of the U-turn after crossing waypoint IGARI until the last radar contact is well justified and is probably most likely. Different simulations performed by an airliner Captain have validated such a hypothesis.

In summary, the estimated parameters of the trajectory leading to a successful match of the timing at the reference locations are reported in Table 11.

Table 11: Estimation of the IAS, ground speed and on-board fuel between 17h52:27 and 18h21:00

Time	Location	Velocity (kt)	Ground Speed (kt)	On-board Fuel (t)	
				Estimated	Simulation
17h24:40	U-Turn Exit waypoint			41.8	41.8
		M0.835	506		
17h37:00[8]	Kota Bharu			40.5	40.4
		IAS 310	506		
17h52:27	South of Penang			38.6	38.4
		IAS 310	506		
18h13:00[9]	VAMPI	IAS 310	508	36.0	35.8
18h21:00[10]	Abeam MEKAR	IAS 317	509	35.0	34.8

3.5 Conclusions on the known trajectory

It has been shown that this known trajectory could been flown manually by an excellent qualified pilot maintaining the flight parameters quasi-constant on these two segments (Altitude, speed and track) in a difficult meteorological environment and with a degraded electrical power system and in depressurised conditions.

[8] *This timestamp is computed by the CAT and confirmed by the simulations*
[9] *Idem as footnote above*
[10] *Idem as footnote above*

4 The unknown and recalculated trajectory

4.1 Introduction

This chapter addresses the part of the trajectory recalculated thanks to the published Inmarsat data measured via their communications satellite and thanks to our aeronautical operational computations.

The main objective of this chapter is to reconstruct an operationally realistic piloted trajectory using the few pieces of data available either from official sources or from other public sources and in particular, the Inmarsat report [3]. The validation of such an inferred trajectory is also addressed thanks to the many simulation sessions based on the Prepar3D[11] model with the PMDG add-on.

The focus of our study is on the part of the trajectory starting shortly before 18h22:12 UTC when the aircraft exited the Malaysian radar coverage. The aircraft radar blip was lost a little bit more than one minute after passing abeam waypoint MEKAR.

But to ease the understanding, the starting point of this chapter was chosen to be waypoint MEKAR at the estimated time around 18h21:00 UTC on March 7th, 2014. The study is organised as follows:

1. Section 4.2 reviews the reduced set of data available and recalls the context when the aircraft passed abeam waypoint MEKAR
2. Section 4.3 addresses the leg from the last radar plot (waypoint LSTRP) until the phone call of the ground at around 18h40 UTC. It includes a series of three turning manoeuvres leading to the south and which is commonly called FMT (Final Major Turn).
3. Section 4.4 details the reconstructed trajectory after the FMT, which is a quasi-straight-line path to the south.
4. Section 4.5 presents the different possibilities for the final descent and the related actions performed by the person in command leading to a probable soft ditching and creating a minimum number of pieces of debris.

One should keep in mind that what is presented in this report is a highly probable inferred, reconstructed trajectory. However, until the moment the wreckage is found, it remains a hypothesis.

4.2 Available data

Once any trace of the aircraft was lost by the Malaysian military surveillance system, the only available undisputable data comes from two sets of measurements made by Inmarsat.

In addition to this data, other sources of information were found valuable for the analysis in particular the controlled airspace structures.

4.2.1 Inmarsat data

This study will often refer to the only public source of information provided by Inmarsat in a cornerstone document [3] in which the numerical values of the BTOs and BFOs measurements are provided among other important information.

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[11] *B777-200ER Simulator from Lockheed Martin with Rolls-Royce engines*

In short, the Burst Time Offsets (BTOs) provide an estimation of the distance between the aircraft and the satellite while the Burst Frequency Offsets (BFOs) provide an estimation of the frequency shift of the signal (Doppler effect) due to the relative velocity between the aircraft and the satellite.

During each stage of this analysis, validation sessions were performed for consolidating our recalculated trajectory. The method consists in comparing Inmarsat measurements with an estimation of the values of BTOs and BFOs at key moments well defined by Inmarsat itself in [3] and called the Arc crossings (for ex. Arc1-crossing).

To estimate the numerical values, we have developed specific tools as explained in Section 4.4.3 below.

During the reconstruction of the FMT, the following Inmarsat data have been used with a specific nomenclature as presented in Table 12.

Table 12: Inmarsat BTOs/BFOs considered for the FMT reconstruction

Time (UTC)	Name	BTO (μs)	BFO (Hz)	CBFO (c.f. [9])
18:25:27	Arc1*	12520	142	Not calibrated
18:27:04	Arc1.1	12520	175	156
18:28:06	Arc1-Boeing	12500	144	144
18:28:15	Arc1.2	12480	143	143

*: In spite of some discussion on Arc1 BFO possibly impacted by packet collision as well as by some adjustment due to the OCXO (Oscillator Cristal Oven) behaviour of the aircraft satellite communication system as discussed by Bobby Ulich in [9], this data has been taken into account to shape the turn.

4.2.2 FIRs

Other important data comes from the airspace structure along the reconstructed trajectory. In particular, the FIRs (Flight Information Regions) in which the aircraft flew (or avoided) are worth considering. As explain in the report [2], with the exception of a short 5 minutes excursion in Ho Chi Minh FIR, the person in command ensured to stay within the FIR Kuala Lumpur until waypoint MEKAR and onwards to the west.

In doing so, the person in command did not draw other FIRs controller's attention. But at MEKAR, the aircraft was approaching the boundaries of FIR Chennai in India and of FIR Jakarta in Indonesia. Figure 33 presents the main elements of the airspace structure in the vicinity of the last radar plot LSTRP at 18h22:12 UTC.

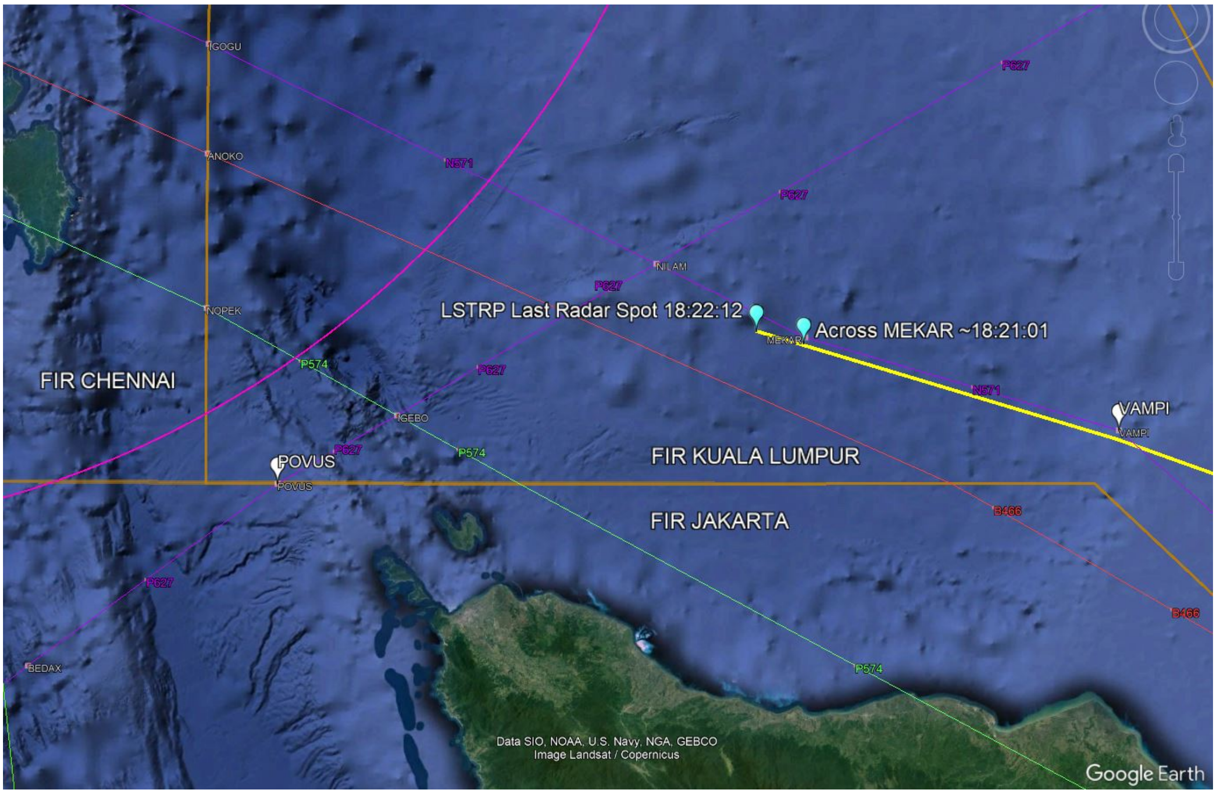


Figure 33: Airspace structure in the vicinity of the last radar plot LSTRP at 18h22:12 UTC

For a pilot who wanted to stay the least visible as possible and drawing the least attention as possible, crossing the minimum number of FIR boundaries is most probably the best choice.

Another noticeable element to be avoided is the Indian military radar based at Car Nicobar whose maximum range at FL300 is represented in purple in Figure 33.

4.2.3 Southeast India ADIZ[12]

In addition, in the vicinity of the FMT, an additional constraint comes from the sovereign limit imposed by the Indian military authorities. In particular, India has defined the Southeast India ADIZ whose boundary coincides exactly with the FIR Chennai boundary. As MH370 transponder (normally broadcasting the flight parameters) was on standby and as no ATC flight plan had been filed, the aircraft had to avoid entering FIR Chennai by any means avoiding drawing Indian military controllers' attention. Figure 34 highlights the location of the ADIZ illustrated by the Purple double dotted line.

Subsequently, one can apply this constraint to all waypoints located on the FIR Chennai boundary and conclude that they could not have been overflown without drawing the attention of the Indian controller. In particular, this encompasses the following waypoints: IGOGU, ANOKO and NOPEK as visible in Figure 34.

[12] Air Defense Identification Zone c.f. [16] for definition and more details

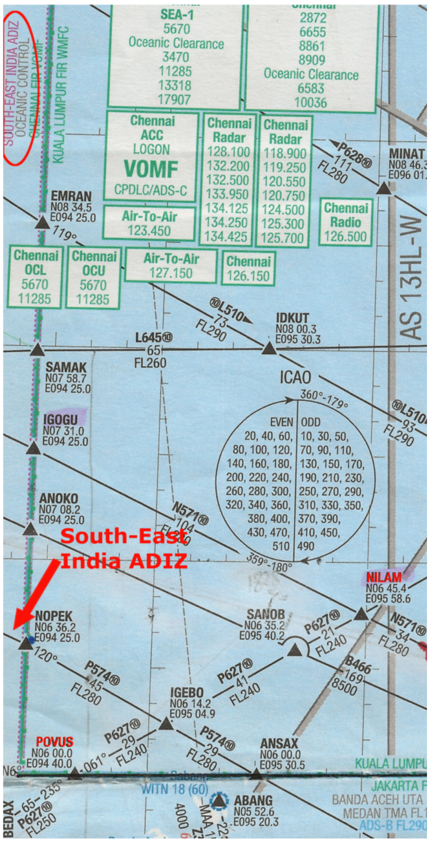


Figure 34: Boundary of South-East India ADIZ (Source Lido/Route Manual AS 14HL Apr. 2017)

4.2.4 *Routes and Waypoints*

Keeping in view that at waypoint LSTRP the aircraft was on its way to entering a new FIR and the person in command's care to be seen as the least threatening as possible, the best way of crossing a FIR boundary is to follow a registered airway. Two routes are possible: continuing on Route N571 or turning to the southwest on Route P627 in light purple in Figure 33, in Figure 34 and also in Figure 35.

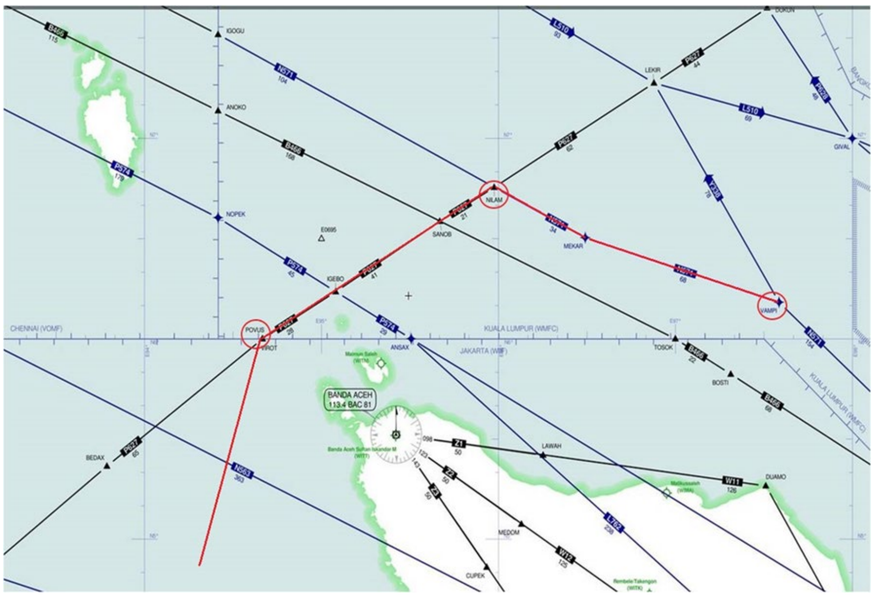


Figure 35: Malaysian Airspace including routes N571 and P627 with the intended route (Skyvector)

4.3 The « Final Major Turn[13] » (FMT)

Based on the Inmarsat BTOs and BFOs, the recalculated FMT presents a shape including unintended turns. In particular, the change from route N571 to route P627 was missed and the aircraft actually turned right first heading north towards waypoint NILAM before turning left to recover a direct route to waypoint POVUS. This manoeuvre - matching the Inmarsat data - appears to have been an unexpected turn and calls for a clear understanding of what could have happened in the cockpit. Overall, the FMT includes two parts; one around waypoint NILAM and a second one at waypoint POVUS. We dedicated specific effort to analyse this peculiar branch of the trajectory.

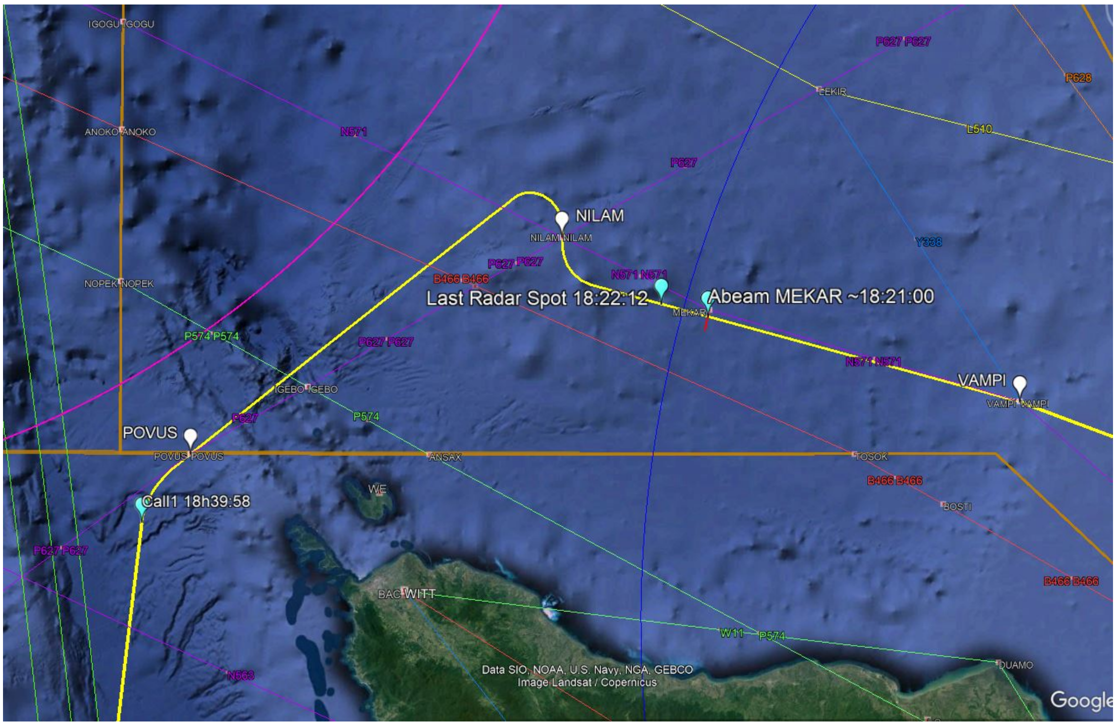


Figure 36: Recalculated FMT (Part1 around NILAM & part2 at POVUS)

In this section, the analysis focuses particularly on the leg starting at the last known position of the aircraft LSTRP at 18h22:12 UTC (c.f. Malaysian report [2]) until the beginning of an established southern route after the first unanswered phone call from the MAS Flight Operation office at 18:h39:58 UTC usually called “Phone call at 18h40”.

The FMT is the first part of what we call the MH370 recalculated unknown trajectory. Because of the nature of the Inmarsat data, the way to proceed is to make hypotheses, infer a trajectory and compare the related computed BTOs and BFOs with Inmarsat’s measured values.

Thanks to Inmarsat analysis in [3], it is established that the aircraft took a route towards a Southern direction globally. Subsequently and referring to the choice of route N571 then of P627, the aircraft

[13] *FMT: commonly used terminology to designate the manoeuvre to the south at large and considered as the last turn*

flew between the Andaman Islands and Sumatra Island avoiding the South-East India ADIZ and crossed the boundary between FIR Kuala Lumpur and FIR Jakarta at waypoint POVUS only.

4.3.1 Hypotheses at the Last Radar Plot

At waypoint LSTRP, the aircraft situation was the following:

- The aircraft was at 10Nm from waypoint MEKAR and was coming from somewhere in the South of abeam MEKAR on route at 285°
- As the segment from the south of Penang to MEKAR was flown at FL300 and as the last radar data indicates an altitude of 29,500 ft at the LSTRP, the aircraft had to descend at some point.
- From MEKAR to the LSTRP, the aircraft had accelerated because of this descent and reached an IAS of 325kt i.e. a ground speed of ~516 kt.
- Concerning the electrical power, all facts during the leg starting at waypoint IGARI concur to conclude that it was switched off voluntarily in a reversible way. This would have triggered the deployment of the RAM Air Turbine (RAT), which provides the minimum essential electrical power needs. Thus, the aircraft could have been piloted with the basics electrical systems only in parallel with the full hydraulic systems powered by the running engines.
- The person in command had probably spotted the lights of the Indigo 6E53 traffic coming ahead
- The cockpit may be still depressurised and the person in command may be still wearing an oxygen mask but it is possible that re-pressurising may have occurred earlier.

4.3.2 From Last Radar Plot to the electrical power restoration

The fictious waypoint LSTRP was not a particular location or a point in time for the person in command. It is just the mandatory starting point for any subsequent recalculated trajectory. Nevertheless, it corresponds to both the Butterworth radar range limit and the Penang VOR range limit.

In Section 4.3.1 above, the situation of the aircraft is detailed at that point as well as the working hypotheses. The next known waypoint to consider is the crossing of Inmarsat Arc1, which we call Arc1-Crossing. Its existence results from voluntary previous actions performed by the person in command.

The main action was the restoration of the full electrical power on the electrical network of the aircraft and in particular on the left part which powers the SATCOM provoking its logon to the Inmarsat satellite network at 18h25:27 UTC (Arc1) after its power-on self-test (POST). Considering our hypotheses, it is believed that this was done was restored by pressing the four push buttons controlling the generators located on the overhead panel.

After this, and since the aircraft was probably still depressurised, it is estimated that it was the right time also to subsequently press the pressurization button to the “auto” position (even though it could be possible to do it manually in a softer way). One should keep in mind that it would take a minimum of 20 minutes to restore and stabilise the aircraft interior pressure. So, the person in command was most likely still wearing an oxygen mask during the beginning of the FMT.

So far, the person in command took care to keep the aircraft “electromagnetically silent” including in particular the telecoms (ACARS, IFE, etc.) and lights. It is then possible the person in command was then getting ready to manage the demanding restart of numerous systems normally available in cruise as well as to keep the aircraft "en-route" to Route P627.

4.3.2.1 The flown path

The path flown by the aircraft from abeam MEKAR is on track ~285/286° at a slight increasing ground speed of ~522kt and probably due to the slow descent which started earlier.

Considering the necessary SATCOM power-on self-test operations at cold start after such a long power interrupt, an estimated minimum time of 2 minutes was counted for this to be completed. As the SATCOM was operational at 18h25:27 UTC, the power restoration is estimated at around ~18h23:30 UTC or a little bit earlier. In addition, we assume that the heading remained most likely constant around ~285° since abeam waypoint MEKAR until shortly after the power restauration.

Consequently, the power restoration is estimated to at a location close to [6.575°N; 96.133°E] which is southeast of waypoint NILAM. At this point in time, the aircraft position relative to route N571 is key.

4.3.3 From the electrical power restoration to the Arc1-Crossing

The power restoration triggered a kind of countdown for the person in command to complete several necessary actions.

The following hypotheses are made:

- The highest priority for the person in command was to engage the A/P either with LNAV either with track/heading select to free himself and get time for other important tasks like stopping any telecommunication downlink as soon as possible.
- To do so, the person in command must ensure that the aircraft follows the intended route which was from MEKAR to NILAM. But as the systems' reboot took some time, the aircraft was flying away in the south of route N571. The aircraft was still on selected magnetic track 286° and arrived somewhere in the south of NILAM. In addition, the radar plot indicates that it was on track 285° thus it was further to the south.
- It is important to note that, at waypoint MEKAR, Route N571 includes a change of direction from 292° to 296° explaining this discrepancy. With the LNAV function engaged, the aircraft would have slightly turned to the right to precisely follow the route. This is an additional element to believe that the aircraft was not in automatic navigation.
- Additionally, because of the automatic setting of the speed during the power restoration which is very low at 200kt, the person in command had to set it at a much higher value and at least at the current speed or more. We estimate that it was about IAS 325kt selected i.e. 5 kt below the maximum operating speed.
- Simultaneously, at power restoration, the A/P kept the rate of climb/descent at its current value. According to the BFO at Arc1, the aircraft was descending at around -1000fpm, thus as we believe that the aircraft was already descending from the power restoration and reached FL270 somewhere close to or after NILAM.
- This descent could come from the rush (or from a lack of attention) of the person in command to perform the next actions paying no attention to correct it. It is also possible that at this stage the person in command was aware of the INDIGO aircraft coming ahead at FL330 with the risk of a potential traffic encounter in few minutes and commanded a voluntary descent below route N571 minimum en-route level at FL280 to cross the opposite traffic.

- Then, the person in command has engaged the LNAV function of the A/P in keying waypoint NILAM in the FMC followed by “Execute” and in pressing the LNAV button on the MCP dashboard. This made the aircraft automatically navigate towards waypoint NILAM.
- Subsequently, as the aircraft was in the south of NILAM it automatically turned right to this waypoint. It is considered that this turn is not accidental as there appears to be no reason for the aircraft to go this specific point in the middle of the Malacca Straight.
- Considering the path followed and the timing, NILAM appears to be overflown at the time of crossing Arc-1 by coincidence. Thus Arc-1 Crossing is considered to be at waypoint NILAM as illustrated in Figure 37.

4.3.3.1 The flown path

Based on these hypotheses, a corresponding path was recalculated and is presented in Yellow in Figure 37 with the approximate timing and location of the key events.

It should be noted that these path and timings were validated with our simulator in using the identified flight parameters. A video of this leg is available at www.mh”70-caption.net *(04-FMT-Final-Major-Turn.mp4)*.

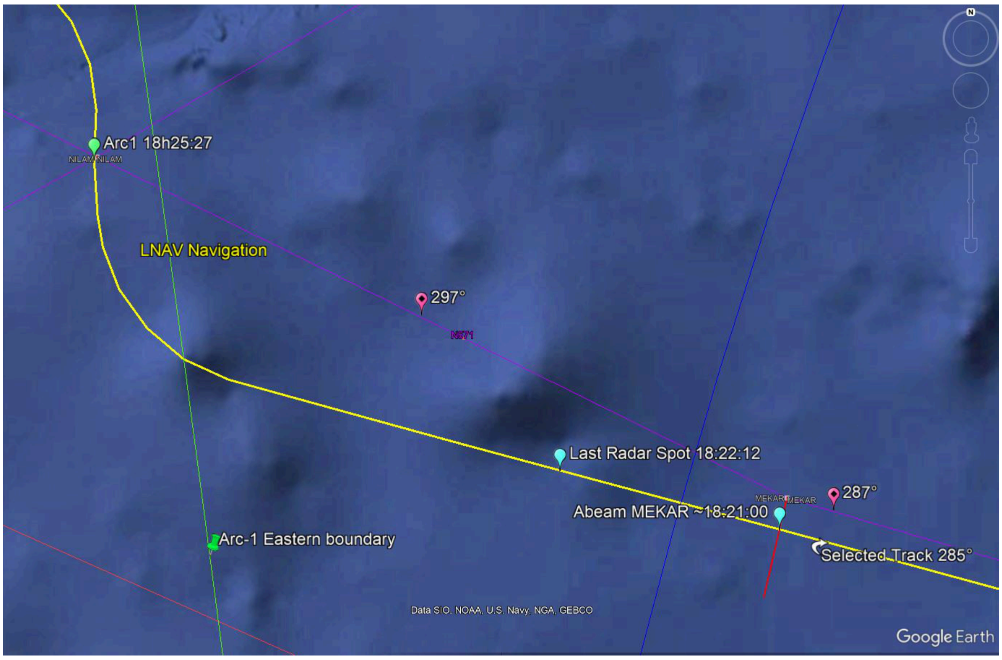


Figure 37: Recalculated and simulated flown path from waypoint MEKAR to Arc-1 crossing point

4.3.3.2 Person in command's workload in the cockpit

For the person in command, the second priority was to be fast enough to stop any communication being broadcasted especially via the ACARS and the IFE through the SATCOM.

In addition, any means to identify the flight had also to be erased in the onboard systems. The Malaysian report [2] states that “when the Satcom link was re-established, no Flight-ID was present”.

The only way to complete both, is to perform a “data link system reset” manually first just after the power restoration via the “communication manager” master page followed by an “auto message off” command. This instantaneously blocked any ACARS message to be sent and at the same time erased the flight and company information in the FMC, in particular the Flight ID. This is underlined in Red in Figure 38. These successive manipulations took some time, explaining why the aircraft, initially on “heading select”, was in the south-east of waypoint NILAM without the person in command realising it.

As shown in Figure 39, the only occurrence of an automatic data link reset is after each flight and takes place between nine and ten minutes after the last engine is shut down and with any passenger entry door open. No reset occurs at power up. This is why the data link reset made after the electrical power restoration was manual.

In addition, the Flight ID information is kept in the FMS as long as the electrical power is available which is until the main battery power is exhausted. This means that the Flight ID is permanently stored during the flight. Thus, only one option remains to have the Flight ID erased: to perform a data link reset manually.

The master manager page provides the capability to reset the data communication system. Manager messages related to the master features are also presented on this page.

Data Link System Reset

If the DATA LINK SYSTEM RESET key is selected, the CONFIRM RESET key is displayed. If the CONFIRM RESET key is selected, the following occurs.

On the ground:

- all new messages are deleted
- all messages queued for downlink are deleted
- all review messages are deleted
- ATC reports are deleted

In flight:

- flight information and company new messages are deleted
- flight information and company messages queued for downlink are deleted
- flight information and company review messages are deleted
- ATC displays reset to default values

On the ground or in flight:

- flight information and company displays reset to default values
- center VHF radio is selected as the default and set to data mode on the ground or voice mode in flight
- AUTO MESSAGES OFF is deselected
- COMPANY MESSAGES FUTURE is deselected
- ADS OFF is selected
- ADS EMERGENCY OFF is selected

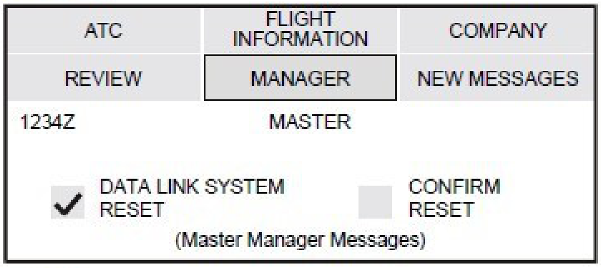
Figure 38: Data Link System Reset description (Source Company FCOM)

COMMUNICATIONS

777

Flight Manual

Master Manager



77710042

The master manager page provides the capability to reset the data communication system. Manager messages related to the master features are also presented on this page.

If the DATA LINK SYSTEM RESET key is selected, the CONFIRM RESET key is displayed. If the CONFIRM RESET key is selected, the following occurs:

- ATC connection is reset to **NOT ESTABLISHED**,
- Review messages are deleted,
- The center VHF radio is selected as the default,
- The VHF default radio set to the DATA mode on the ground; in the air, the default radio is set to VOICE,
- ACARS is set to the AUTO mode,
- Automatic messages are set to ON,
- The future company messages to printer feature is deselected,
- Downlink message parameters are initialized,
- Two seconds after selection, the CONFIRM RESET key is removed from the display and the DATA LINK SYSTEM RESET key is displayed as not selected.

This reset does not occur at power-up.

The data communication system is automatically reset after each flight. Reset occurs approximately 9 minutes after the last engine is shut down, and with any passenger entry door open.

Data link capability for the flight management system, FMS, and EICAS related maintenance functions, and cabin functions are not reset with this feature.

Figure 39: Extract from a company FCOM on Data Link Reset automatic occurrence

This explains why the logon-on request at 18h25:27 UTC includes only one signal unit while it should have included two as detailed in Table 13 which includes the very first logon request on the ground without the Flight ID, the last logon request on the ground with the Flight ID, the last ACARS report with the Flight ID and the first airborne logon request without the Flight ID.

Table 13: Log-on requests with and without Flight ID

Time	Channel	Type of signal Unit	Hexadecimal content	Request	Meaning
12:50:19	POR-R600-0-36D6	0x10 - Log-on Request (ISU)/Log-on Flight Information (SSU)	**1F** D0 10 75 00 8F 85 D0 FC 05 02 01 00 00 00 00 00 F4 6C	First Log-on on ground	1F: first log-on: No Flight identifier received by SDU as it had been erased at the end of previous flight MH371
15:59:55	IOR-R600-0-36F8	0x10 - Log-on Request (ISU)/ Log-on Flight Information (SSU)	**2F** D0 10 75 00 8F C5 D0 FC 05 82 09 00 00 00 00 00 97 1F	Last Log-on on ground-Part 1	2F+3F sequence = Flight identifier (MH370) received by SDU via ARINC 429
15:59:56	IOR-R600-0-36F8	0x10 - Log-on Request (ISU)/ Log-on Flight Information (SSU)	**3F** D0 10 75 00 8F C5 9A 82 A6 66 6E 60 40 41 00 00 93 88	Last Log-on on ground-Part2	Normal sequence after 2F
...					
17:07:39	IOR-T1200-0-3718	0x71 - User Data (ISU) - RLS	... DB 73 B3 C4 **CD C8 B0 B3 37 B0** 99 8C ...	Last ACARS report	... 3D**MH0370** ... Thus, Flight ID was present in the system memory at that time
18:25:27	IOR-R600-0-36E1	0x10 - Log-on Request (ISU)/ Log-on Flight Information (SSU)	**1F** D0 10 75 00 8F C5 D0 FC 05 82 09 00 00 00 00 00 B4 06	First Log-on in flight - Arc1	1F: similar to 12h50 log-on: No Flight identifier received by SDU (cf above)

Thus, from that moment, no identification of the flight nor any exchange of information was possible anymore. Nevertheless, the SATCOM was still powered and continued to respond with its terminal identification number only to the almost-hourly handshakes initiated by the Inmarsat ground segment.

4.3.4 From Arc1-Crossing to Arc1.2-Crossing… a manual turn

Once the person in command finished their head-down work, it would be realised that the aircraft had passed NILAM heading north. Immediately, the A/P would be disengaged, the descent stopped and a manual turn to the left initiated. The turn had to be sharp with a high banking to recover a direct track to waypoint POVUS quickly and to conform as closely as possible to route P627. In addition, being at ~FL270, the person in command also had to climb the aircraft to recover the planned flight cruise altitude i.e. FL300.

Considering the key points of FMT part1 and according to the information provided by the Inmarsat BTOs and BFOs in Table 12, the following conclusions are made:

- Around NILAM, the aircraft was heading north and descending. At 18h25:27 UTC Arc1 crossing took place nearby coincidently. The person in command had just finished switching off the communication functions.
- Realising the wrong course of the aircraft controlled by the engaged LNAV function, the A/P was disengaged and manual control taken back.
- First, the person in command turned left and then climbed before crossing Arc1.1 at 18h27:05 UTC with a rate of climb between ~1500-~2200fpm according to the calibrated BFO or to Inmarsat BFO.
- The turn ended at ~233°/234° in executing a direct to POVUS but still climbing
- At 18h28:06 UTC (Arc1-Boeing) and at 18h28:15 UTC (Arc1.2) the aircraft was still climbing at ~2000fpm on the same route.
- A short while later, having reached the targeted FL300, the climb ended. The route was maintained as a “direct to POVUS” with a high speed to get out of this zone as fast as possible.

The detailed data of this FMT part1 is provided in the summary Table 14 (further below) where the geodetic coordinates of the key locations where determined and/or verified by our simulations.

Figure 40 illustrates the FMT part1 from power restoration to Arc1.2 at 18h28:15 UTC. It shows that the reconstructed arc-crossings with a different colour each are well within their respective arc boundaries of the corresponding colour.

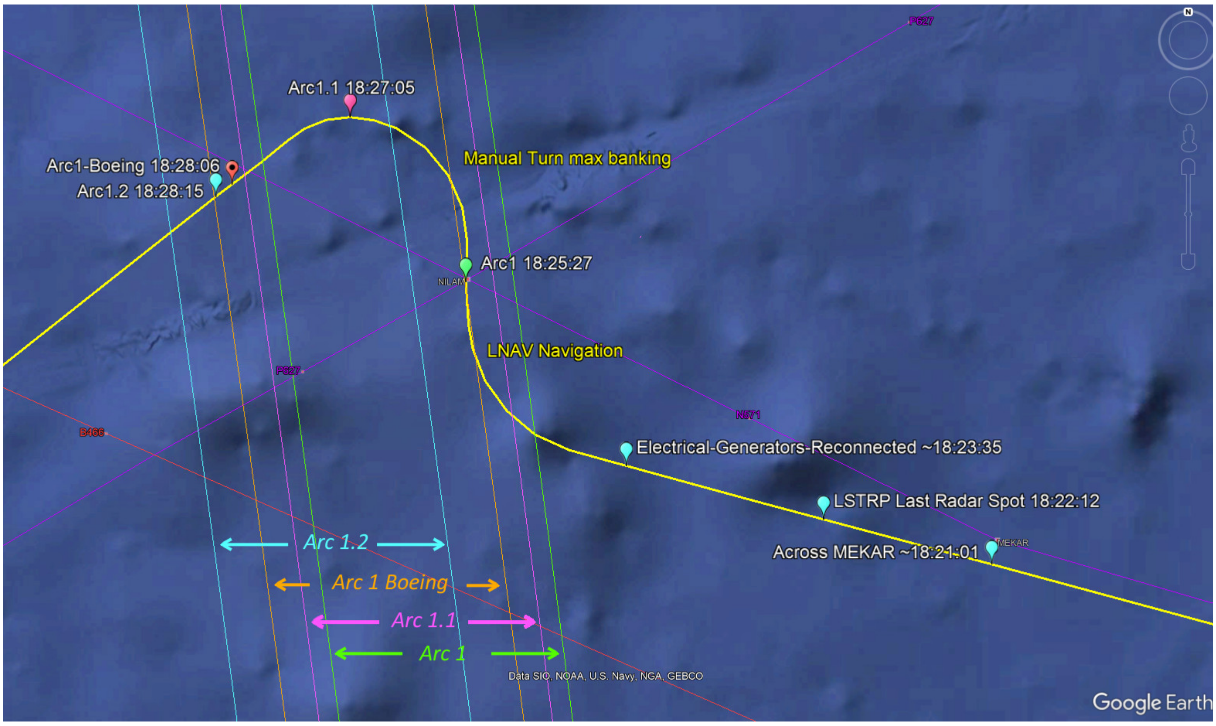


Figure 40: FMT part1 from power restoration to Arc1.2 at 18h28:15 UTC

The initial turn to the north is imposed by Inmarsat data. If the aircraft had flown on the same heading from MEKAR, its speed would not match the data as it would have been too slow.

4.3.5 From Arc1.2-Crossing to POVUS

This part 1 of the FMT turn could have been spotted as an erratic navigation to any potential ATC controller both from India or Indonesia who could have seen it. Thus, to avoid drawing their attention, the PIC had to go away as soon as possible from this zone. Consequently, speed was probably increased to Mach 0.850/ IAS 325kt just below the maximum operational speed of the aircraft.

At this stage, as the flight became stable and levelled, the most appropriate navigation way is to engage the autopilot and its LNAV function and execute a direct route to waypoint POVUS.

Why targeting waypoint POVUS in our opinion? Because it is a good way to avoid entering the South India ADIZ and the Indian Car Nicobar radar coverage. In addition, staying close to route P627 would have been the best way not to draw Indonesian controller's attention.

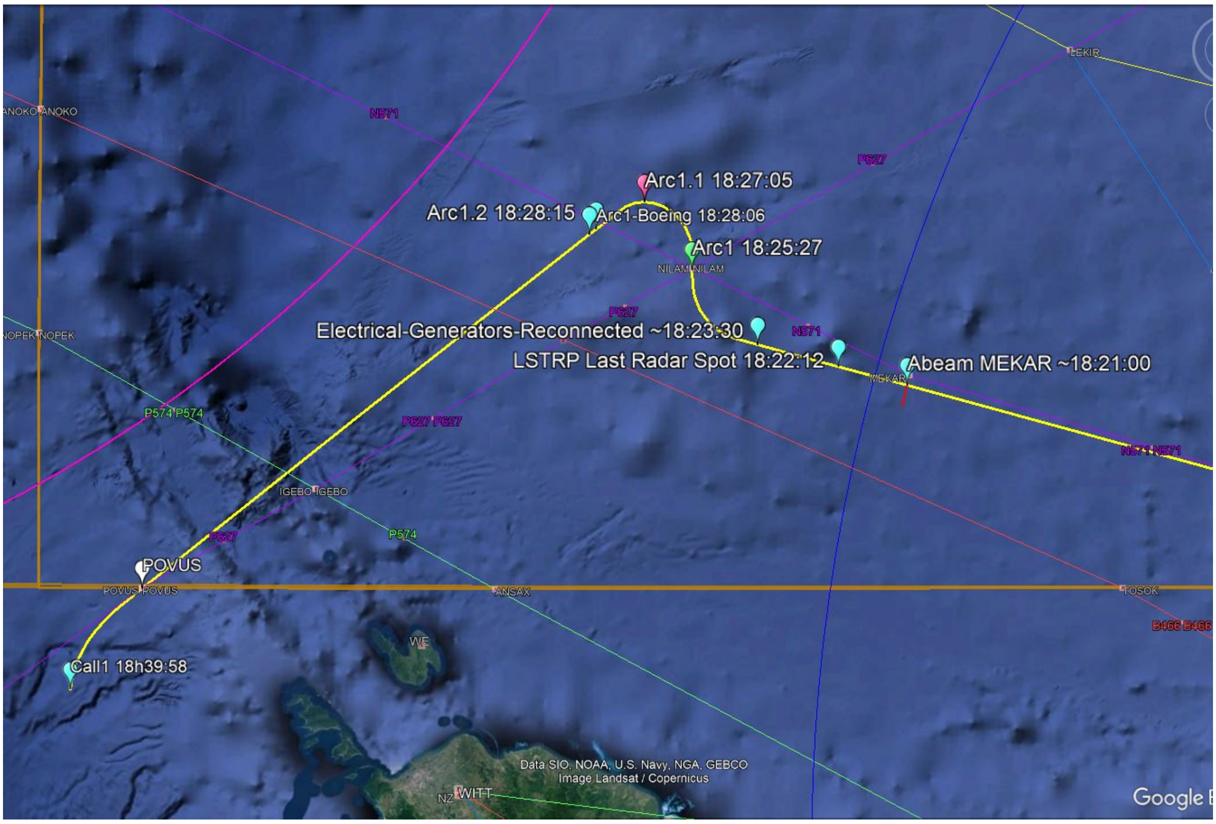


Figure 41: Final Major Turn Part1 (LSTRP-Arc1.2) and Part2 (POVUS-Phone Call1)

4.3.6 From POVUS to the Phone call-1 location

After waypoint POVUS, the PIC selected a southern trajectory. The initial selection of a magnetic track at 188° is justified by the presence of adverse cumulonimbus clouds development in the south-west of Banda Aceh as depicted in Figure 42 and underlined by the Red circles. In addition, this track ensures that the aircraft stayed away from the Sibolga military radar coverage. Choosing a more eastern direction would have been most probably too risky.

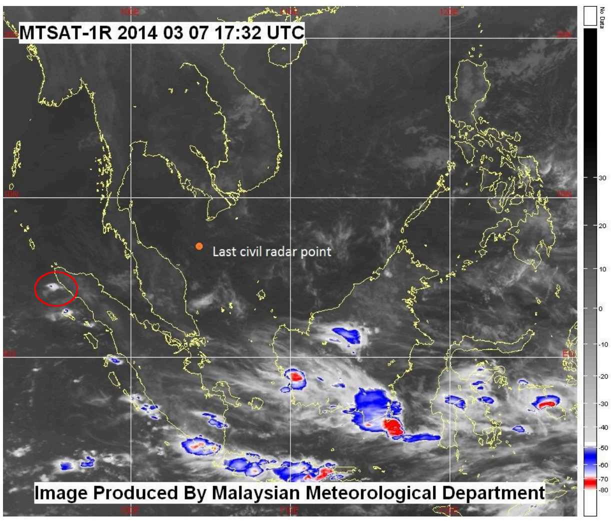


Fig. 42a: Cumulonimbus development at 17h32 UTC on March 7th

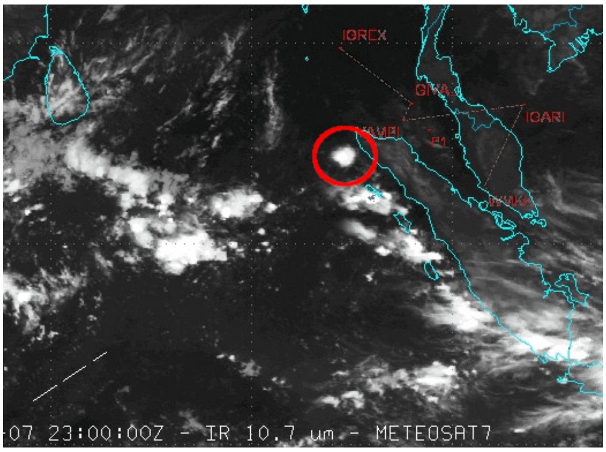


Fig. 42b: Cumulonimbus evolution at 23h00 UTC on March 7th

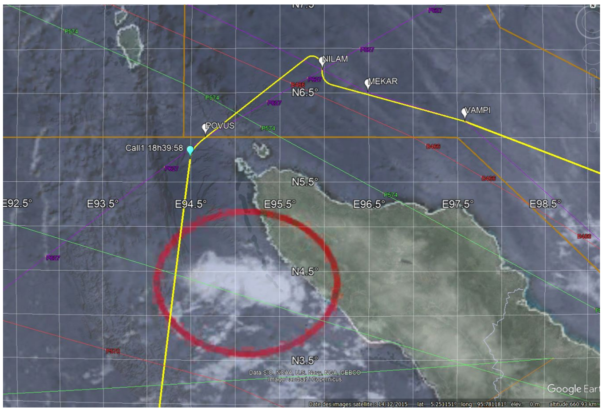


Fig. 42c: Path chosen to avoiding the cumulonimbus around 18h40 UTC

Figure 42: 188° Track selection to avoid meteorological adverse weather when exiting the FMT

At that time, the PIC chose the linear waiting speed recommended by the FAA/ICAO procedures at 30000ft which is IAS 265 kt as indicated in Figure 43.

ICAO Holding Airspeeds (Maximum)
FAA Holding Airspeeds (Maximum)

Altitude	Speed
Through 6,000 feet MSL	200 knots
6,001 feet MSL through 14,000 feet MSL	230 knots (210 knots Washington D. C. & New York FIRs)
14,001 feet MSL and above	265 knots

Figure 43: ICAO/ FAA maximum holding airspeeds (Source Company)

Thus, under the current weather conditions at that time, it corresponds to Mach 0.706. Subsequently, taking into account the wind, the ground speed was ~ 432kt. In fact, the usual way of the pilots to maintain speed is to adjust the Magenta IAS index indicator on the Primary Flight Display (PFD) scale using the Mach/speed button.

The hypothesis is made from this point onwards that the PIC maintained M0.706/IAS 265 kt for the rest of the flight at FL300 until Arc-6 crossing time.

Why did the person in command decide to fly at FL300 with the recommended linear waiting speed? The person in command had to make a trade-off between the fuel consumption, the time to stay airborne and the range. Climbing and/or choosing another speed would have consumed more fuel thus reducing available flight time and range. We think that at this point in time, the person in command was concerned about maintaining fuel in view to remain airborne as long as possible.

The justification of the selected Mach and flight level is provided later in section 4.4.1 below.

4.3.7 Compliance with Inmarsat data

The trajectory described above was reconstructed thanks to the Inmarsat data and validated by simulations. At all the key points and arc crossings, the estimated BTOs – when available – and BFOs are within the confidence intervals as defined by Inmarsat in [3] i.e. ±50µs and ±7Hz respectively. Table 14 summarises the computed BTOs and BFOs at these points with the comparison with Inmarsat measured values.

Table 14: BTO and BFO computed values at Key points during the FMT

BLELLY-MARCHAND Reconstructed Flight Path Results GDAS													
								Total Burst Freq. Offset Hz			Burst Time Offset (µs)		
	Time UTC	Lat°N	Lon°E	Altitude (100ft)	True Track (°ETN)	Speed (kt)	Vertical Speed (fpm)	Pred.	Meas.	Error	Pred.	Meas.	Error
Arc1	18:25:27	6.75	95.97	273	0	492	-1000	143	142	-1	12554	12520	-34
Arc1.1	18:27:04	6.91	95.86	273	269	488	2200	172	175	3	12516	12520	4
Arc1-Boeing	18:28:06	6.85	95.75	294	234	466	2000	144	144	0	12460	12500	40
Arc1.2	18:28:15	6.84	95.73	295	233	481	2000	143	143	0	12452	12480	28
Phone Call 1	18:39:58	5.76	94.49	300	187	432	0	88	88	0	11870	n/a	n/a

Note: At Arc1.1 the Calibrated CBFO is 156Hz. This value is matched with a rate of climb of 1500fpm. At this transitional point is between the descent and its subsequent climb, the instantaneous rate of climb at this stage of this demanding manual turn could have been within [0;3000] fpm. Thus both 1500 or 2200fmp are admissible as the aircraft rate of climb is very variable in manual piloting conditions.

4.3.8 Simulations

All characteristics determined above have been used for our simulation sessions.

Several sessions of simulations were performed with the Prepar3D simulator and its PMDG add-on according to the flight profile described above.

A video is available for this particular part of the recalculated FMT trajectory (MEKAR to Call1) at www.mh370-caption.net *(04-FMT-Final-Major-Turn.mp4)*.

The lesson learned from the simulations is that both manually piloting this trajectory and disabling the communications in the cockpit were performed by a qualified person only because of their complexity and need for detailed knowledge to handle the technical aspects.

4.3.9 Conclusions

The results of the analysis above show that considering a complex piloting from the last radar contact until the estimated location when the phone call 1 from the ground took place is a solid hypothesis. Different simulations were performed by airliner Captain's Blelly and have validated this hypothesis.

Concerning the fuel consumption, the only published data comes from Appendix 1.6E [5] of Boeing whose assumptions were based on ISA (International Standard Atmosphere) values and on a linear levelled trajectory with the corresponding speed. In our study, we calculated the actual true airspeed based on the GDAS data of the day. This is reflected in Table 15.

Table 15: Fuel estimation during the FMT

	Location	***IAS (kt)***	***Ground Speed (kt)***	***On-board Fuel (t)***	
				Calculated with GDAS weather	Boeing calculated at ISA
18h22:12	Last Radar Plot	IAS 325	517	34.7	34.2
18h28:06	Arc1-Boeing	IAS 290	466	34.1	33.5
18h34:00	En route to POVUS	M0.850/IAS325	522	33.2	n/a
18h39:58	Call-1	M0.706/IAS265	432	32.4	n/a

4.4 En-route at 188° from Phone Call 1 to Arc6

This chapter addresses the leg from the Call 1 location until the crossing of the 6th arc as illustrated in Figure 44.

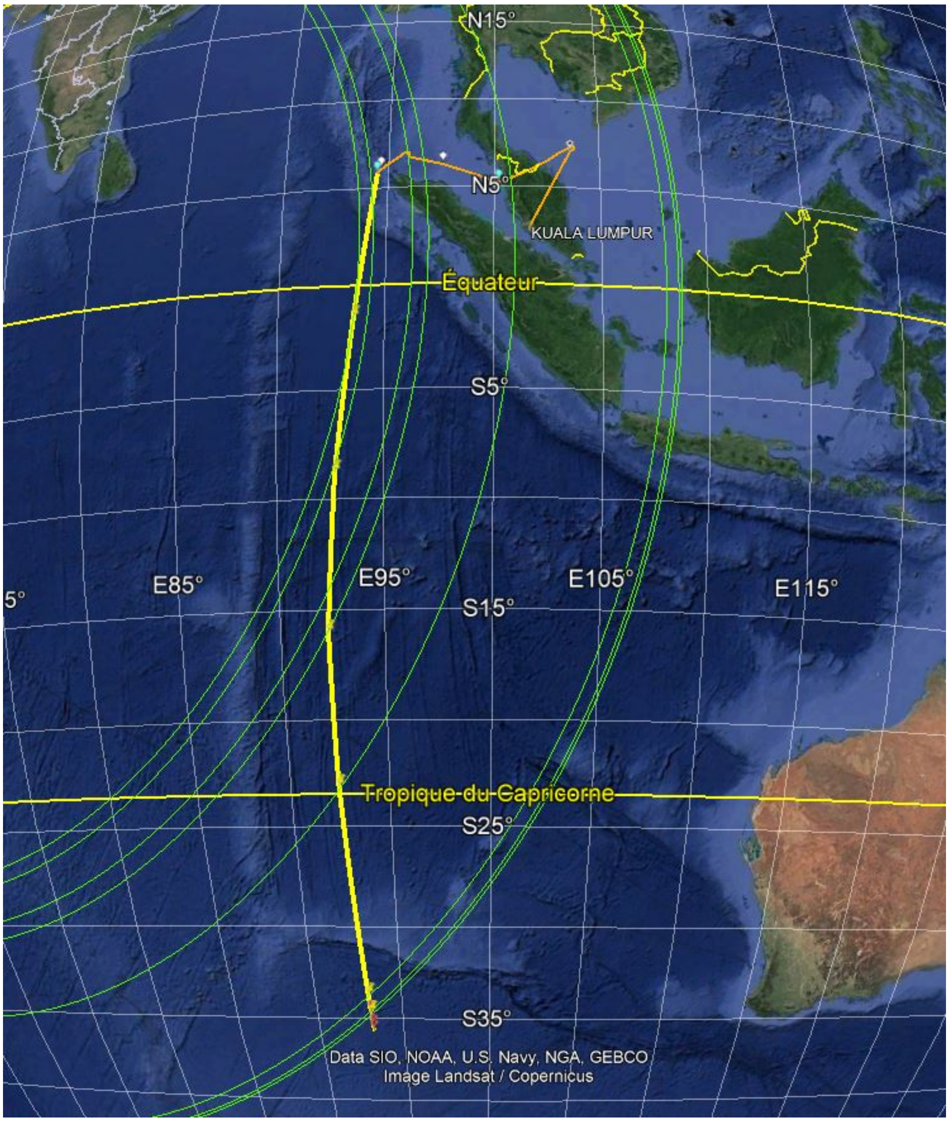


Figure 44: Southern part of the reconstructed unknown trajectory (Yellow)

4.4.1 Speed and Altitude Computation

The first point of the southern part of the trajectory (we will also call it "southern leg") is the location of the aircraft at 18h40' UTC where the 1st phone call took place. The chosen last point of this southern leg is the crossing point at Arc 6. As the latter is the starting point of the final leg, it is specifically analysed in more details in the next section 4.5 addressing the end of the flight.

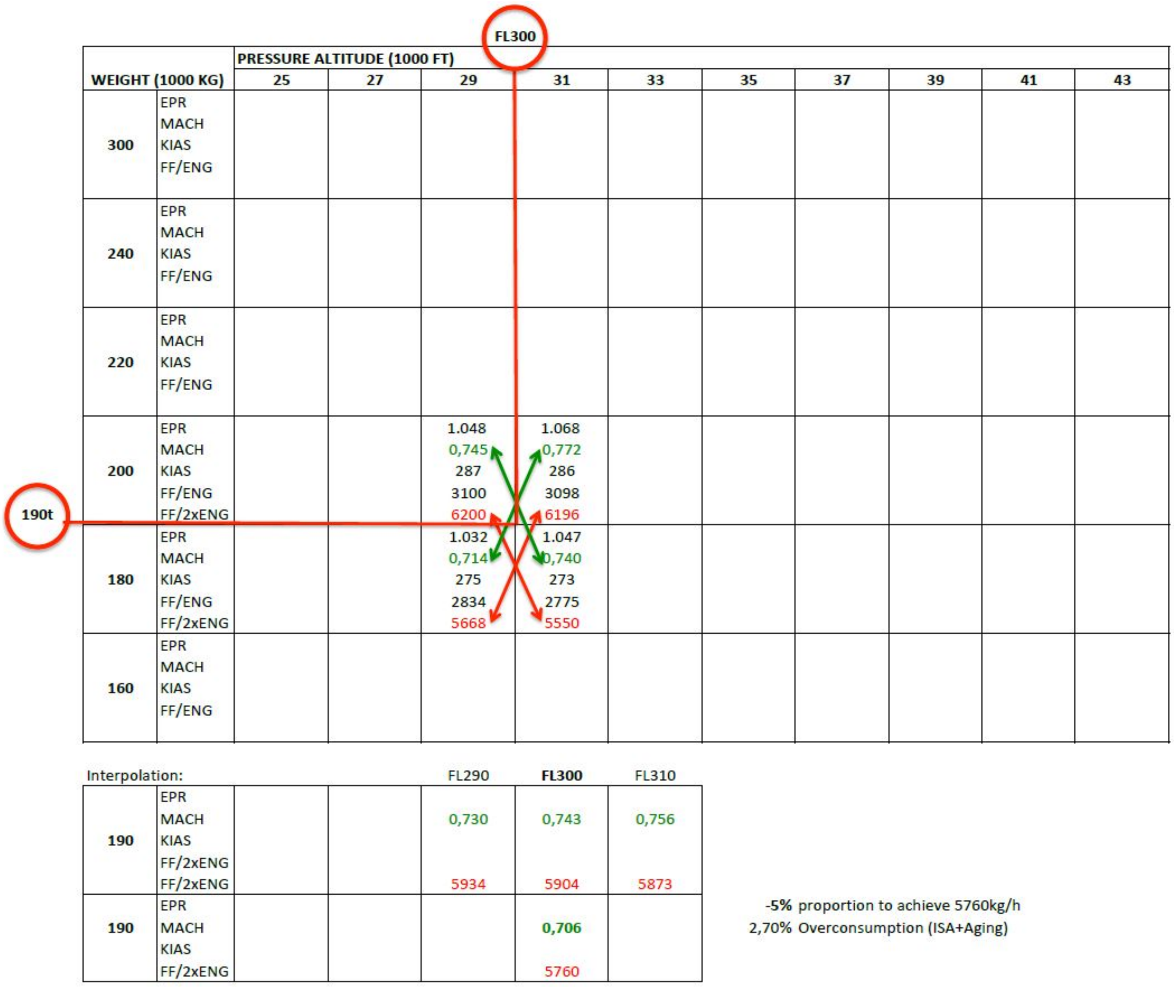
In order to reconstruct the southern part of the trajectory (illustrated in Yellow in Figure 44), the following hypotheses were made and the following data was used:

1. At 18h40 UTC, the amount of fuel remaining on board is estimated at ~32.4 tons as presented in Table 15.
2. The flight level was maintained at FL300.
3. The Arcs have been precisely constructed at this flight level using Inmarsat official reported data.
4. For that day, GDAS measured meteorological data with ISA correction has been used for FL300.
5. “Performance in flight” data of the B777-200ER powered by R&R Trent-892 engines has been used.
6. Corrections for the overall fuel overconsumption were applied as follows: +1.5% of performance factor (aging of the engines) and +1.2% due to a high temperature on that day based on an estimation of a weighted average ISA +12° and following Boeing’s recommendation to add +1% per 10° of extra ISA.
7. The flight time estimated by the ATSB between 18h40’ UTC and the supposed flame out of the second engine – two minutes before the last logon request at 00h19’39 UTC – is 5h37’30” i.e. 5.625 decimal. *Note: This is a starting working hypothesis as in our actual End of Flight hypothesis the logon request came approximately ~30 seconds after the left engine manual shut down with the APU running.*

From these hypotheses and data, straightforward and coherent computations can be made:

1. The hourly consumption is equal to the average 32.4t /5.625h = 5760kg/h. This represents the actual hourly fuel consumption on that day including the +2.7% of overconsumption coming from the two factors identified above.
2. At mid-term of the southern route i.e. ~21h28’ UTC, the aircraft **average** mass is estimated at approximately ~190 tons.
3. In Boeing’s look-up table “performance Inflight Long Range” for the B777-200 ER, one has to look for the value 5760 kg/h for a reference weight of 190t. Unfortunately, neither this entry nor FL300 exists. Thus, a double cross-interpolation is required. A relevant extract of the lookup table is provided in Figure 45 with the corresponding details of the computation.
4. The double interpolation results in 5904kg/h for Mach 0.743 in Long Range Cruise (LRC) mode at FL300. In order to determine the Mach and the flight level corresponding to the value of 5760 kg/h for 190t, one must deduce 5% and then add +2.7% because of the overconsumption (c.f. above) since the look-up table is provided for brand new engines at ISA.
5. Figure 46 presents the curve “B777-200ER Cruise Mach, Fuel Flow, and Ratio of Specific Air Range to LRC Specific Air Range” provided by the IG in [10]. Considering the reduction of 5% of fuel computed above and reading the point “-5%” of fuel flow from the nominal point (1;1) on this curve, one can see that the corresponding Mach reduction is also 5%. Notably, on that curve at -5% fuel flow and -5% Mach, the air range is identical to LRC specific air range according to Boeing.

6. Thus, applying this reduction to the speed, one can conclude that for FL300 the Mach number becomes M 0.743([14]) – 5% = M 0.706. This Mach value offers a Maximum Air Range for FL300 as indicated by Boeing in table 4 of Appendix 1.6E [5]. Interestingly in the same table, M0.706 is given as the Mach of the Maximum Range Cruise (MRC) mode (in ISA) for this flight level.



WEIGHT (1000 KG)		PRESSURE ALTITUDE (1000 FT) 25	27	29	31	33	35	37	39	41	43
300	EPR MACH KIAS FF/ENG										
240	EPR MACH KIAS FF/ENG										
220	EPR MACH KIAS FF/ENG										
200	EPR MACH KIAS FF/ENG FF/2xENG			1.048 0,745 287 3100 6200	1.068 0,772 286 3098 6196						
180	EPR MACH KIAS FF/ENG FF/2xENG			1.032 0,714 275 2834 5668	1.047 0,740 273 2775 5550						
160	EPR MACH KIAS FF/ENG										

Interpolation:

				FL290	FL300	FL310
190	EPR MACH KIAS FF/2xENG FF/2xENG			 0,730 5934	 0,743 5904	 0,756 5873
190	EPR MACH KIAS FF/2xENG				 0,706 5760	

-5% proportion to achieve 5760kg/h
2,70% Overconsumption (ISA+Aging)

Figure 45: Extract of the look-up table from FCOM - Long Range Cruise Control Trent 892 (Source PMDG and Company FCOM)

[14] *LRC Mach is given as 0.743 after interpolation from the look up table and 0.742 in the graph. The impact of this difference is negligeable.*

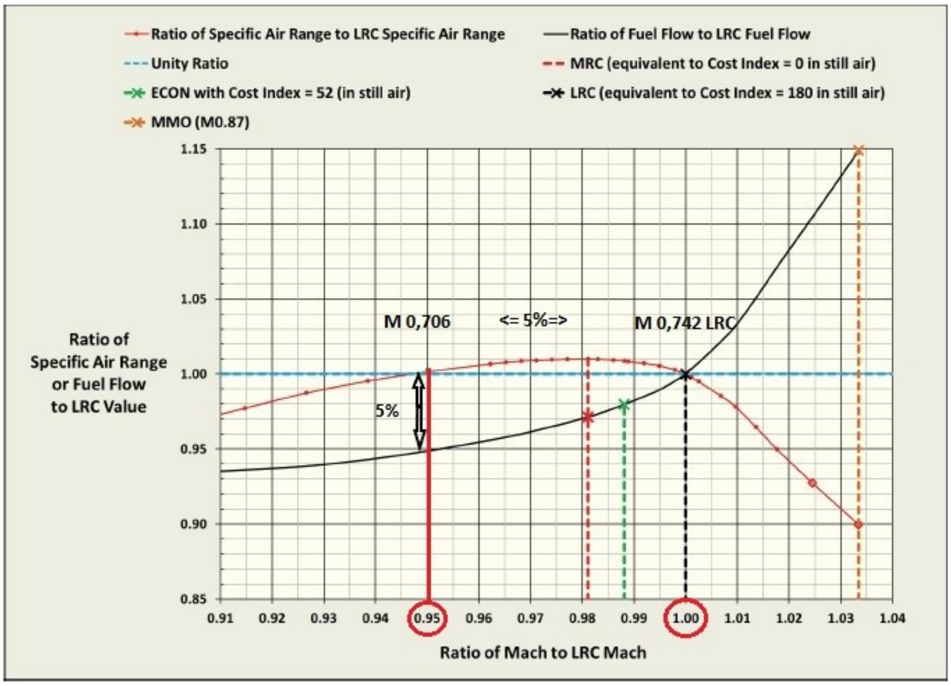


Figure A-1. B777-200ER Cruise Mach, Fuel Flow, and Specific Air Range

Figure 46: Specific consumption-distance for the B777-200ER (Source: Independent Group [10] p73)

Under these conditions, one can conclude that the flight level was indeed FL300 with a linear waiting speed at a Mach equal to M0.706 (i.e. IAS of 265kt) as deduced in section 4.3.6 with its Figure 43. During the southern leg of the trajectory, the average fuel consumption was indeed 5760kg/h which is confirmed by our simulator in Figure 47 taking into account the average aircraft weight.

Thus, from a pilot experience, it is believed that the chosen speed mode was “Mach Selected” which is adapted to a journey without any FMC route nor a specific targeted waypoint for the end of the flight.

In our fuel consumption considerations after the restoration of the electrical power, the assumption is made that the air conditioning packs were functioning. Thus, no subsequent fuel flow reduction is included in the computation nor accounted for. However, one or the other could have been switched off to reduce fuel consumption, but this is not known.

Figure 47: Fuel consumption modelled by our simulator at FL300 and at Mach 0.706.

4.4.2 Reconstructing the "Southern Leg"

Keeping this hypothesis of a levelled flight at a constant Mach, the southern leg can be reconstructed in using straight-line segments between the arcs taking into account the local meteorological conditions. This leads to (in UTC time):

1. From 18h40 to 19h41 (arc 2) = 61' => TAS[15] = 431 kt, GS = 434 kt and Distance = 442 Nm[16]. The great circle distance of 442Nm is "drawn" from the location of the 1st phone call at 18h40' to intercept arc 2.
2. From 19h41 to 20h41 (arc 3) = 60' => TAS = 430 kt, GS = 434 kt with distance = ~435 Nm[16]
3. From 20h41 to 21h41 (arc 4) = 60.3' => TAS = 430 kt, GS = 431 kt with distance = ~434Nm[16]
4. From 21h41 to 22h41 (arc 5) = 60' => TAS = 427 kt, GS = 426 kt with distance = ~425 Nm[16]
5. From 06h41 to 08h11 (arc 6) = 90' => TAS = 425 kt, GS = 425 kt with distance = ~635 Nm[16]

The detailed characteristics of the southern leg of the reconstructed trajectory are posted in Table 16. Figure 4 and Figure 44 graphically illustrate this southern leg.

Making an "aeronautical reading" of the data show that probably in the first place the person in command input a magnetic track reference at 188° on the MCP[17]. Then, somewhere in the south of the Tropic of Capricorn between 23°S and 25°S, the current true track of 178° was input as the reference to follow making the southern leg a quasi-straight line as illustrated in Figure 44. The magnetic declination became too large of approximately ~10°, thus the navigation mode was changed to use true north.

The initial selection of a 188° magnetic heading has been explained in Section 4.3.6 above.

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[15] *TAS: True Air Speed*
[16] *Distance: computed with the exact time interval, it is not rounded thus a slight difference vis-à-vis the ground speed*
[17] *MCP: Mode Control Panel*

Table 16: Detailed characteristics of the "southern leg" from Blelly-Marchand

Arc UTC	Longitude °	Latitude °	Longitude °decimal	Latitude °decimal	True Direction °	Ground Distance Nm	Wind °/kt	Tempera-ture °C	ISA °C	Air Distance Nm	Delta Time h min s	Total Time min s	Mach	True Air Speed kt	Ground Speed kt
18h40'	94°29'00.34"E	5°45'00.21"N	94.493	5.756									0.706		
					187	442	(086/17)	-30	15	437	1h01'05"	1h01"		431	434
19h41' arc2	93°31'00.45"E	1°34'00.37"S	93.529	-1.577									0.706		
					186	435	(073/11)	-30	14	429	1h00'02"	2h01'		430	434
20h41' arc3	92°42'00.10"E	8°48'00.36"S	92.703	-8.810									0.706		
					184	434	(088/11)	-30	14	428	1h00'22"	3h01'		430	431
21h41' arc4	92°13'00.44"E	16°03'00.24"S	92.229	-16.057									0.706		
					179	425	(250/5)	-33	12	426	0h59'55"	4h01'		427	426
22h41' arc5	92°24'00.49"E	23°09'00.50"S	92.414	-23.164									0.706		
					178	635	(268/38)	-36	9	641	1h29'38"	5h31'		425	425
00h11' arc6	92°57'00.05"E	33°45'00.53"S	92.952	-33.765			252/34	-39	5				0.706		
FL195					178	59	248/25	-40	5	61	8'29"		0.700	421	412
00h19'29" arc7	92°59'00.34"E	34°45'00.24"S	92.993	-34.757				-41	4			5h39'36"	0.702	420	403
					178		245/34							411	396
00h19'38"	92°59'00.39"E	34°46'00.24"S	92.994	-34.773								5h39'45"	0.742	404	390

4.4.3 Validation of the "southern leg" with Inmarsat data

The next necessary step is to answer the question: how does the reconstructed trajectory compares to Inmarsat data? Table 17 presents the detailed characteristics of the full reconstructed trajectory. To ease the comparison, the same format has been used as in Table 9 of Inmarsat paper [3] in which an example of a possible trajectory is proposed (c.f. the red trajectory in Figure 49). This level of details offers the possibility to better understand the different components of the offsets (the BFOs[18] in particular). Extra elements have been included in our table like the BTOs[19] as well as additional waypoints allowing a more accurate comparison.

Please note that the same frequency bias δf = 150 Hz has been used as in Inmarsat report. In the same spirit, the same first four waypoints are posted to demonstrate the precision of our computation tools. The first tool is an Excel workbook initially created by Yap F. Fah, NTU, Singapore (Version 4) that we have enhanced gradually as our knowledge improved up to the current version 7. In particular, we have implemented an improved version of SK999-Satellite model which precisely fits Inmarsat ephemeris. The second tool, the Constraint Assessment Tool (CAT Version 3), is a specific homemade software developed in the frame of CAPTIO. It includes functions similar to the Excel workbook above enhanced with extra operational functions like the fuel consumption estimation, actual local meteorological data 4D interpolation, arcs generation at any altitude, great circle route computation, debris drift simulation etc.

In Table 17, one can see that the reconstructed trajectory complies with the two Inmarsat defined constraints: BTOs are within the error margin of +/-50µs and BFOs are within the error margin of +/-7Hz. Thus, this makes it an acceptable proposal for a piloted trajectory.

Please note that Table 17 does not include the BFO (-2Hz) of the last burst emitted by the SATCOM at 00h19:38 UTC. This peculiar case is addressed as a variant of the final descent presented in the next section. Details can be found in Annex 1: Variant 2 of the End of the Flight" of this report.

[18] *BFO: Burst Frequency Offset is a frequency shift due to an imperfect correction of the Doppler thus providing an instantaneous information on the speed and/or track of the aircraft*

[19] *BTO: Burst Time Offset provides an information on the instantaneous distance between the aircraft and the satellite at a given time*

Table 17: Blelly/ Marchand's Reconstructed Flight Path Results (same formatting as Table 9 in Inmarsat report)

Reconstructed Flight Path Results (ref. Inmarsat paper Table 9)																					
									Δ Fup							Total Burst Freq. Offset BFO (Hz)			Burst Time Offset BTO (µs)		
	Time UTC	Lat°N	Lon°E	Altitude (100ft)	True Track (°ETN)	Speed (kt)	Mach	Vertical Speed (fpm)	Aircraft (Hz)	Satellite (Hz)	Δ F down (Hz)	δ f comp (Hz)	δ Fsat + δ AFC (Hz)	δf bias (Hz)	Pred.	Meas.	Error	Pred.	Meas.	Error
Nominal-1-Inmarsat	16:30:00	2.75	101.72	0	0	0	-	0	0	-6	-84	0	29	150	89	88	-1	14910	14920	10
Nominal-2-Inmarsat	16:42:31	2.80	101.70	20	333	235	-	1200	218	-6	-80	-180	28	150	130	125	-5	14930	14900	-30
Nominal-3-Inmarsat	16:55:53	4.00	102.20	280	25	461	-	1500	-394	-4	-75	453	26	150	155	159	4	15210	15240	30
Nominal-4-Inmarsat	17:07:19	5.37	102.85	350	25	468	-	0	-459	-3	-71	490	24	150	131	132	1	15610	15660	50
Arc1	18:25:27	6.75	95.97	273	0	492	0.811	-1000	-138	-1	-37	159	10	150	143	142	-1	12554	12520	-34
Arc1.1	18:27:04	6.91	95.86	273	269	488	0.797	2200	870	-1	-36	-821	10	150	172	175	3	12516	12520	4
Arc1-Boeing	18:28:06	6.85	95.75	294	234	466	0.757	2000	742	-1	-36	-720	10	150	144	144	0	12460	12500	40
Arc1.2	18:28:15	6.84	95.73	295	233	463	0.754	2000	731	-1	-36	-709	10	150	144	143	-1	12452	12480	28
Phone Call 18h40	18:39:58	5.76	94.49	300	187	432	0.706	0	167	-2	-30	-205	8	150	88	88	0	11870	N/A	
A2	19:41:03	-1.58	93.53	300	187	434	0.706	0	10	-1	0	-50	-2	150	108	111	3	11485	11500	15
A3	20:41:05	-8.81	92.70	300	184	433	0.706	0	-180	6	29	142	-2	150	145	141	-4	11769	11740	-29
A4	21:41:27	-16.06	92.23	300	182	429	0.706	0	-348	17	56	315	-18	150	172	168	-4	12770	12780	10
A5	22:41:22	-23.16	92.41	300	178	425	0.706	0	-519	30	78	494	-29	150	205	204	-1	14499	14540	41
Phone Call 23h14	23:14:30	-27.02	92.69	300	178	427	0.706	0	-586	38	88	566	-33	150	224	217	-7*	15682	N/A	
A6	00:11:00	-33.76	92.95	300	178	423	0.706	0	-683	50	100	671	-37	150	252	252	0	17994	18040	46
A7	00:19:29	-34.76	92.99	195	178	420	0.670	-4000	-759	52	102	678	-38	150	186	182	-4	18373	18400	27

*: *the data of the Phone Call at 23h14 is usually considered as statistically non-independent.*

Figure 48 replicates Figure 14 of Inmarsat paper [3] for comparison. The red plot represents Inmarsat data. The blue curve represents our computed estimation of the BFOs along the reconstructed trajectory. The matching is very good as the average BFO error is -1Hz and the standard deviation of the BFORs is σ ~2.5Hz. Furthermore, when considering the available extra BFOs (like the one we named Arc-1.2 for example) which are not usually considered by the other studies, the BFOR σ becomes ~3.0Hz with the same average BFO error of -1Hz.

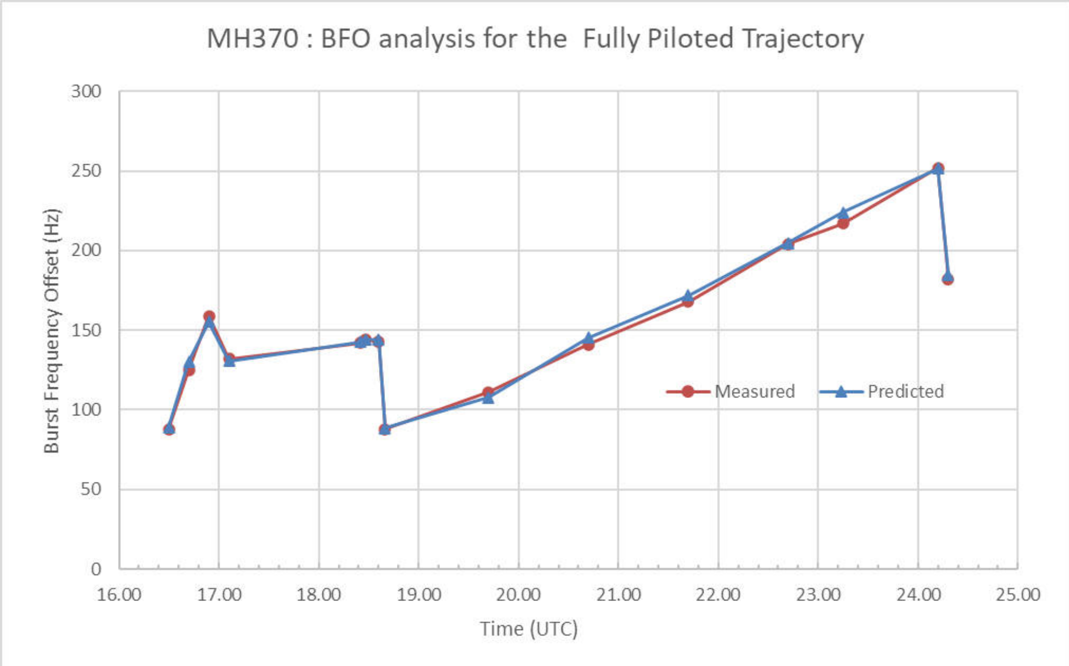

Figure 48: Comparison of Inmarsat BFO versus Captain's Blelly trajectory BFO (BFOR σ ~3.0Hz)

The comparison of the reconstructed trajectory with Inmarsat's example is presented in Figure 49. The similarity of the two paths between arc 2 and arc 6 is striking. Nevertheless, the arc crossing points are different except those at arc 7 which are very close i.e. less than a nautical mile apart.

However, Inmarsat's final major turn (FMT) is wider and is located ~75Nm further to the northwest compared to the FMT turn found here. The difference is explained by a greater average speed as well as a higher altitude in Inmarsat example in which the variable speed and the flight level have been considered closer to "standard" airline operational values.

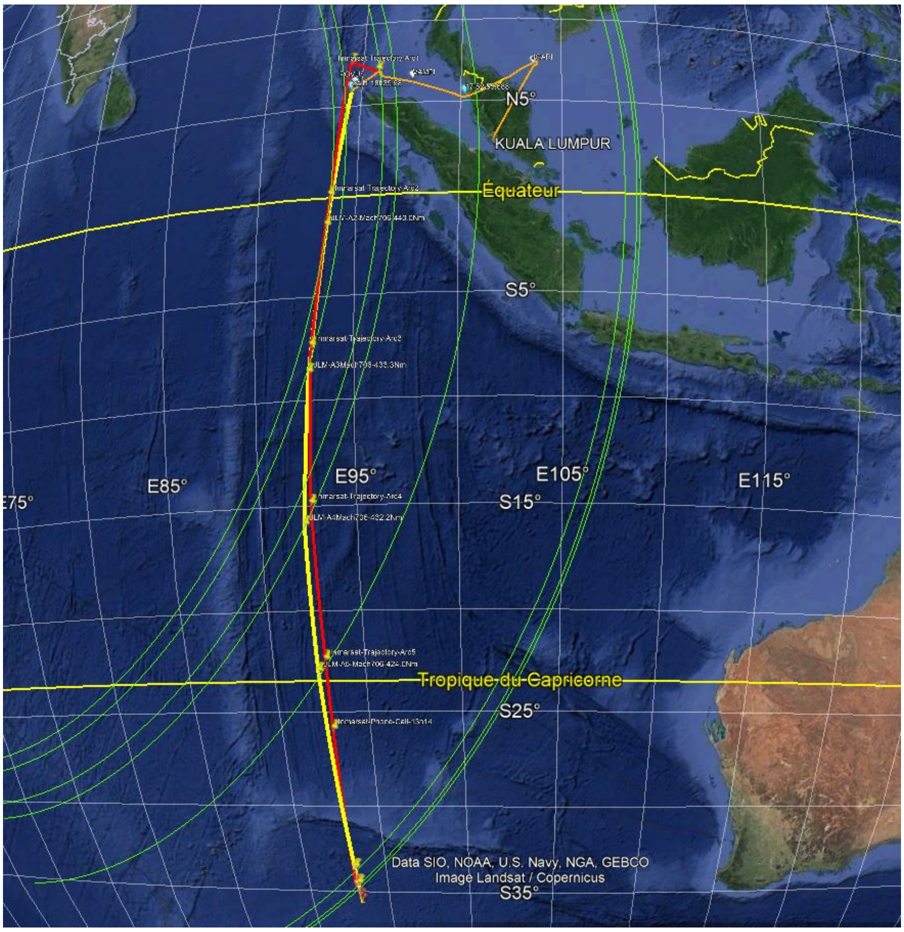

Figure 49: Trajectories comparison - the reconstructed trajectory (Yellow) and Inmarsat example (Red)

4.5 The Final Descent to the End of the Flight

The final descent is a phase which was – and still is – the object of numerous studies. A lot of them, as the official report for example, assumed that the aircraft was not piloted anymore when the descent started. Few studies made the hypothesis that the end of the flight was well controlled by a pilot carefully preparing a ditching. This hypothesis of a well mastered piloted descent from FL300 down to sea level ending in a controlled ditching is the basis of the work presented below.

The analysis was complex as numerous parameters had to be considered like the different horizontal speeds, the different average rates of descent, the remaining fuel at key points as well as the validation of this leg with the relevant measured BFOs and BTOs. An attempt to detail the method in a simple way follows:

4.5.1 Hypotheses and basic parameters:

1.1. At the arc6, the flight was level at FL300 and the Inmarsat handshake was complete and normal.
1.2. The ground speed was GS=410 kt at ISA +4° (which increased to ISA +8° at FL230 then decreased to ISA+5° at sea level)
1.3. The quantity of fuel is estimated at about ~800 kg.
1.4. The shortest straight-line ground distance flown by the aircraft in 8’30” between arc6 and arc7 is 59 Nm.
1.5. The wind decreased from 251°/33kt towards 220°/20kt at sea level

1.6. The top of descent was at FL300 at Mach M0.706 when the right engine flamed out due to fuel starvation.
1.7. The true track at 178° was kept from the top of descent to sea level
1.8. In this method, the computations consider the crossing point of arc 6 as the starting reference location for measuring the time and distances until the ditching.
1.9. Arc7 is where the logon request to the Inmarsat network took place within approximately ~30 seconds following the left engine manual switch-off. The electrical outage provoked a "break power transfer" to the APU electrical supply which was started just before. This triggered a reboot automatically followed by a logon request as described in the Boeing Maintenance Manuel. In this documentation, it is stated "When the ac (electrical alternative current) system changes from one power source to another ***in the air*** it does ***break power*** transfers" and "a (SATCOM) automatic log-on occurs when the system powers up". It is assumed that the oscillator oven (OCXO[20]) of the SATCOM did not cool down during such a short break power (few seconds) leading to a fast restart.
1.10. The hypothesis is made that the person in command in command managed to keep the necessary quantity of fuel for the APU until touch down keeping all flight control surfaces operational during a well-controlled gliding descent and ensuring a full flaps configuration for a controlled ditching.
1.11. It is important to realise that if with the two engines flamed out, the APU out and with the RAT only, it would be impossible to deploy the flaps for a ditching at reasonable speed. The impact would have been at high-speed producing numerous pieces of debris. The small number of found debris tends to support the conclusion on a low-speed ditching for MH370.

4.5.2 Profile of the descent

2. The different steps of the descent are sketched in Figure 50. By setting a reference initial time at T_0=00h11' UTC, these steps can be detailed as follows:

2.1. T_0= 00h11': at arc 6, both engines were running and the SATCOM answered the satellite interrogation (ping). The remaining fuel is estimated at ~800kg. It was not evenly distributed between the tanks because the right engine consumed more than the left one. At this point in time, the total fuel consumption of both engines was about 88kg/min i.e. 5280kg/h according to Boeing fuel performance table for the B777-200ER with a mass of 175t.
2.2. T_1= T_0+1': at about +1 min, the right engine flamed out because of a fuel shortage in the right tank. This is illustrated by the "N-1" tag in Figure 50. Thus, from this moment, all aircraft electrical systems were powered by the left engine only. The auto pilot and the flight director were still functioning and were available to the person in command who most likely kept the "Mach selected" mode active (it had been used in cruise until now). Thus, during the descent to come, the IAS progressively increased up to ~310kt which was maintained. The only setting input made by the person in command on the MCP to the A/P was a constant reference vertical speed value of around V/S ~ -1000fpm. This is the only situation where an aircraft with one engine off would accelerate during a descent in the mode "Mach selected". As a consequence, the TAS is estimated to be around ~434kt when the aircraft crossed FL230. This basically confirms that the aircraft did fly 59Nm in 8'30'' with an average ground speed of ~416kt taking the wind into account. At a rate of descent of ~-1000fpm, the consumption of the unique running engine is estimated at ~71kg/min i.e. ~4300kg/h.

[20] *OCXO: Oven Controlled Crystal Oscillator*

2.3. At the beginning of the descent after the right engine flamed-out, ***the person in command started the APU and opened the fuel cross-feed valves*** to be able to use all of the remaining fuel and to dry out the tanks (the aircraft was descending with a negative pitch with a small quantity of fuel). After being switched on, the APU takes approximately one minute to supply electrical power.

2.4. $T_2 = T_0$ +8'00": close to ~FL230 **the left engine was voluntarily manually stopped** as illustrated by the "N-2" tag in Figure 50. Thus, the aircraft started gliding with a slight increase of the pitch down. At this point, either by surprise or in a short period of inattention, a short lack of pitch control increased the vertical down speed during few seconds up to around -4000fpm as indicated by Inmarsat data.

2.5. $T_3 = T_0$ +8'29": The aircraft crossed flight level ~FL195. Logon request from the SATCOM producing an estimated BFO of 185Hz compared to Inmarsat measured 182Hz. Remember that following the left engine cut-off few seconds ago, no more power was available to the left AC bus which powers the SATCOM. Thus, the APU – the sole remaining source of power – took over from the left engine and powered the left AC bus in addition to the right AC bus it already powered. This left AC bus power Off/On sequence induced an electrical power break transfer leading to an automatic SATCOM power-off/power-up and subsequently to an automatic logon request initiated at T_3.

2.6. $T_4 = T_0$+8'38": within 9 seconds after T_3 the SATCOM logon to the network was properly completed according to the Inmarsat protocol. But, contrary to the previous logons, no other airborne system could logon subsequently and in particular the IFE[21]. This leads to conclude with confidence that the ELMS (Electrical Load Management System) shed the low priority utility buses and loads for dedicating the power to the high priority systems like the demanding pumps providing the hydraulic power to the flight control surfaces. One should keep in mind that the engines were stopped at this point in time and no hydraulic power was available anymore from them. This was an emergency configuration for the sole APU electrical generator powering the whole aircraft especially the electric pumps for the control surfaces.

At this point in time, the Inmarsat measured BFO of -2Hz raises questions. If this value is correct, it implies a rate of descent of at least -14500fpm meaning that the aircraft was diving just after the crossing of arc 7. No convincing technical explanation has been found for this "extraordinary" BFO. Nevertheless, we analyse it in Annex 1 of this report and present an alternate descent path including an explanation for this BFO. Since all searches of the wreckage in the Arc7 area were unsuccessful and since very few debris were found eventually, the best interpretation is operational: the person in command recovered from this unexplained dive and the aircraft continued its controlled gliding descent before a proper ditching.

2.7. $T_5 = T_0$+8'40" and later: In the gliding descent, the person in command could have used one of the two procedures they were probably aware of and maybe had even anticipated them:

2.7.1. Either a descent with the two engines inoperative at Boeing recommended IAS of 270kt called "drift down two engines inoperative". The estimated average ground speed would have been around 306kt with a rate of descent of about ~-2200fpm corresponding to a descent from FL195 in less than ~9 minutes. Thus, the maximum estimated distance flown from arc 7 would be ~45 Nm (without considering the reduction of speed induced by the full flap at 30° at the very end) ending with a ditching at $T_6 = \sim T_0$+ 17'20''.

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[21] *IFE: In Flight Entertainment - a system that manages passengers communications (telephone, sms) and entertainment in the cabin*

2.7.2. Or a descent with the two engines inoperative at the minimum speed with the flaps at 0°. Therefore, its IAS would be Vref (function of the aircraft mass i.e. 175t) augmented by 80 kt which would mean an IAS = ~210kt in this case. This would have allowed flying in descent at no risk of stalling during approximately ~17 minutes. The aircraft glide ratio led to a rate of descent around ~ -1150 fpm and an average ground speed of ~236kt. The maximum estimated distance from arc 7 would be about ~ 67 Nm (without considering the reduction of speed induced by the full flap at 30° at the very end). Thus, the ditching would have occurred at T_6 = ~ T_0+25'30''.

4.5.3 Estimated point of ditching

Thus, based on the hypothesis of a constant true track, the estimated minimum and maximum flight distances lead to these points:

- The minimum ditching zone coordinates are: **-35.518° S and 93.025° E**
- The maximum ditching zone coordinates are: **-35.875° S and 93.039° E**

These are illustrated in Figure 51. But of course, other tracks and variable rates of descent could be envisaged for estimating the ditching location. This is taken into account in section 5 below where a new search zone is proposed.

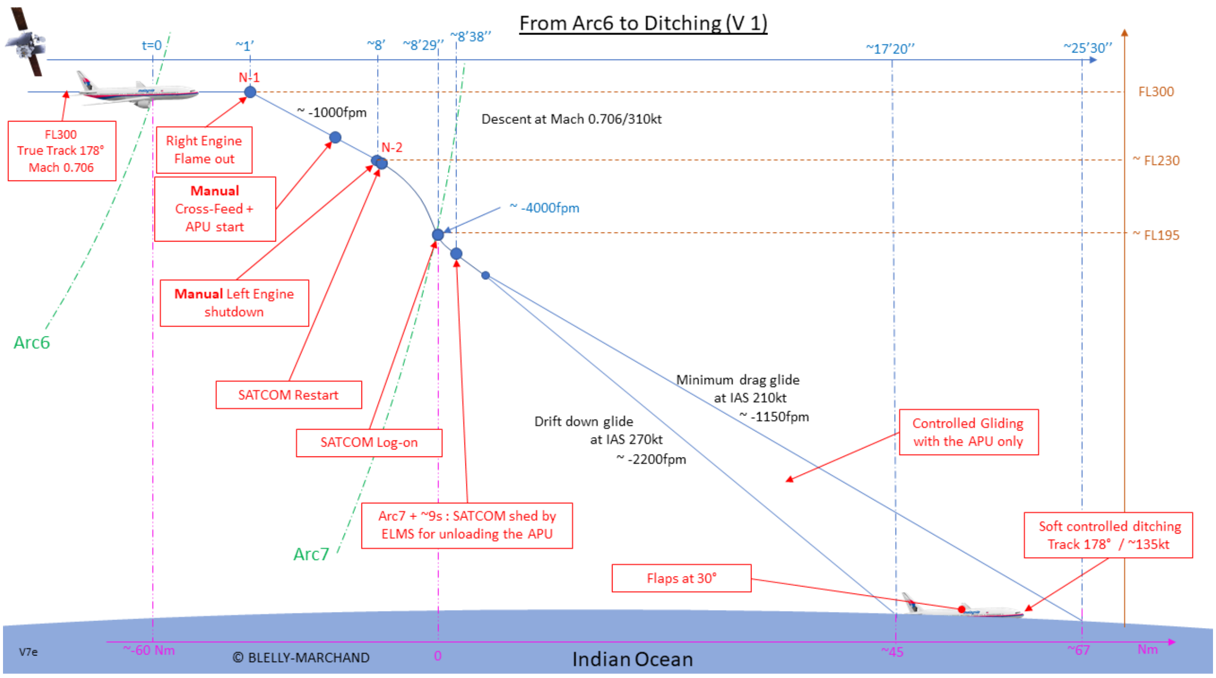

Figure 50: Considered end of the flight path (Blelly-Marchand) – Variant 1

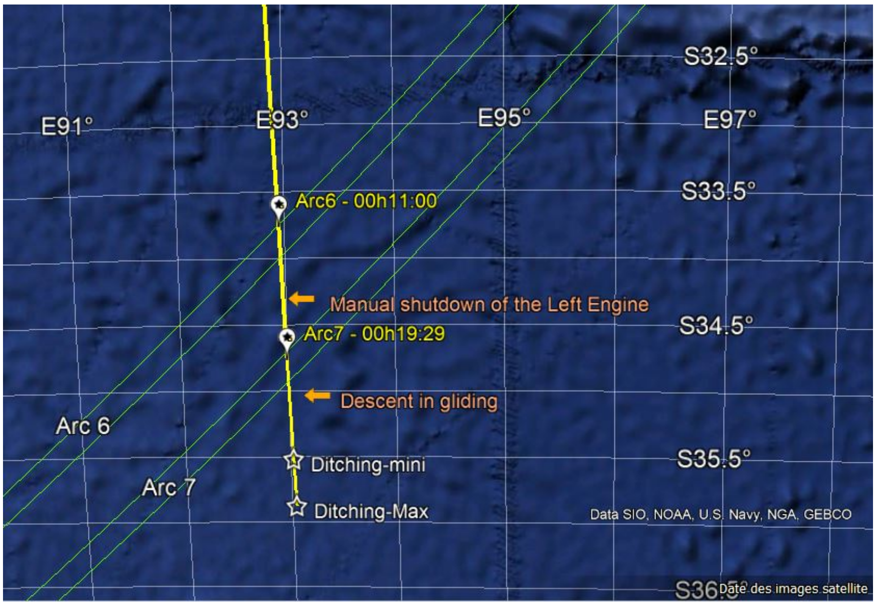

Figure 51: Estimated northern and southern possible locations of the controlled ditching (white stars)

4.5.4 Simulations

Two sets of simulations were performed for both variants of the final descent with the drift down (270kt) parameters and also with the minimum speed (210kt) parameters.

They confirmed the findings both in time, distance and fuel.

Two videos, one video sample per variant, are available at: www.mh370-caption.net :

- Variant 1 with descent at -4000fpm et minimum speed
(06-last-descent-V1-210kt-MinDrag.mp4)

- Variant 2 with descent at -4000fpm / -14500fpm and then drift down at IAS 270kt
(07-last-descent-V2-270kt-DriftDown.mp4)

5 The proposed new search zone

This concludes on the characteristics of the identified zone where to search the wreckage and which is proposed as a viable candidate for future underwater search campaigns.

In this region, two under-water search campaigns have been conducted until 2018. They covered areas on both sides of the arc 7 as illustrated in Figure 52 in Brown (Fugro) and in Blue (Ocean Infinity) based on the hypothesis that the plane crashed close to Arc7 after a quasi-vertical dive. They have been unsuccessful because we think that the very good gliding capability of the plane had not been considered nor was the possibility that a person in command was still in command. Considering the complexity of the known trajectory and its obvious realisation with somebody in command, we think that there is basically no reason for it to be different at the end of the flight.

The proposed new search zone is depicted in Green in Figure 52. It has a ~15 Nm wide trapeze shape prolongating the already scanned zone to the south by ~25 Nm. The zone includes a contingency margin of ~7.5Nm on each side of the true track of 178° to cover the case where the aircraft could have deviated slightly. This search zone is valid for both End of Flight variants presented in this report.

The proposed new search zone surface is estimated of ~350 Nm^2 approximately. It is small compared to the potential search zone of 10 000 Nm^2 envisaged by Ocean Infinity during a potential future 100-day campaign in 2023 or 2024. According to this daily rate, the proposed new search zone would be scanned in less than 5 days.

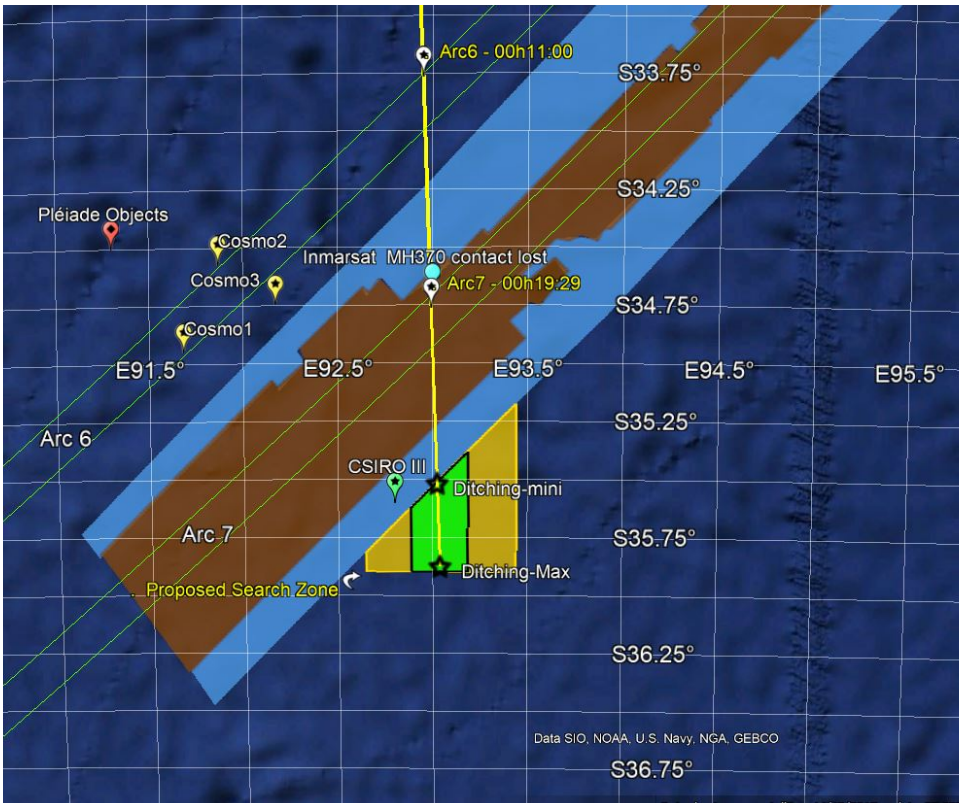

Figure 52: Proposed new search zone (Green area) potentially covered in less than 10 days

In order to take into account the possibility that the aircraft might have drifted to the left or to the right from the initial track at 178° due to different factors, an enlarged proposed new search zone is illustrated in Orange in Figure 53. It covers approximately 1200Nm^2.

Figure 53 shows also the AIS tracking of Ocean Infinity "Seabed Constructor" vessel during its 2018 campaign in Brown dots.

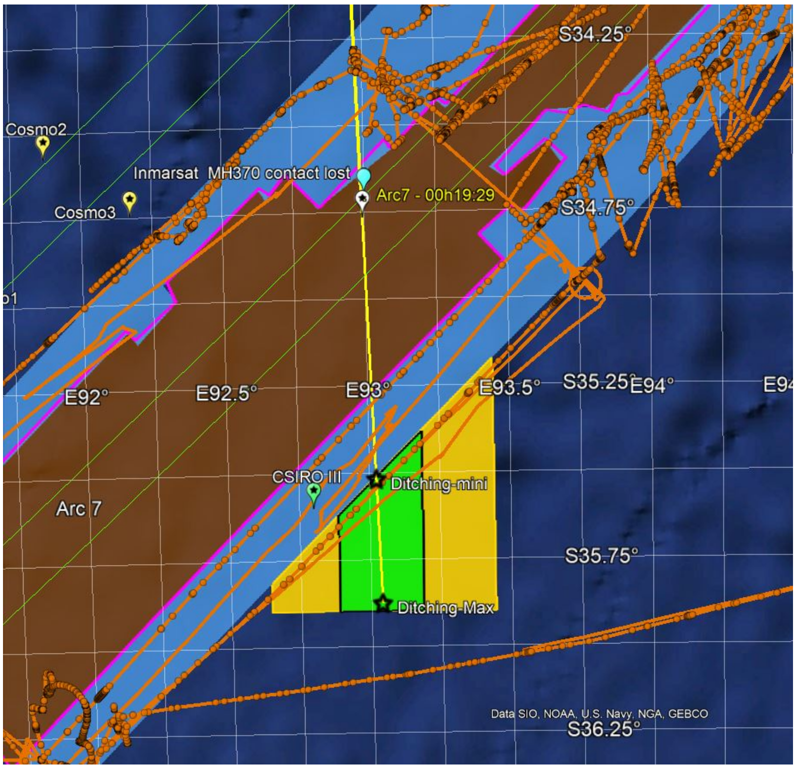

Figure 53: Extended proposed new search zone complementing the previously scanned areas

6 Conclusions

A complete reconstructed trajectory - validated by simulations - has been successfully presented in this report. It is based on the hypothesis that the aircraft was piloted all the way through until a kind of soft ditching producing only a few small pieces of debris. Due to a final descent while gliding, the identified point of impact is in a small zone around mid-point [-35.70°S; 93.03°E] located just outside of the area already searched until 2018.

All the elements presented above have been shown to be aeronautically and technically possible. They could be carried out and flown by a qualified person.

For each element described here, one can ask whether it was possible, justified and validated by simulation. The answer to all is “yes”. None of these elements can be eliminated as they all could have happened as described. They form a coherent and realistic piloted trajectory matching the Inmarsat measured data. Today we are not aware of any other possible trajectory with no gap like the one presented here.

But until the wreck is found, this trajectory remains a hypothesis.

Any contact for technical discussion or other exchange is possible via our mail addresses provided on page 1 of this report.

7 Additional elements of interest …

7.1 Visual detection of satellite images

Several relevant elements must be mentioned in relation to the geographical location of the ditching zone and the proposed search zone.

The first element comes from the report on the analysis of the “optical” images captured by the French satellite PLEIADES 1A on 23rd march 2014 [11]. From these images, a set of approximately 12 objects were identified as “possibly man-made”. All of these objects include a top surface of 20 m^2 or larger. Their geographical location is pinpointed as “Pléiades objects” in Figure 52. This is in coherence with the results of one of the drift studies from the Australian organisation CSIRO (CSIRO report III) [13].

In addition, the Italian satellite “COSMO-Skymed” provided Synthetic Aperture Radar (SAR) data acquired on 21st March 2014. The geographical location of the objects identified as “possibly man-made” is illustrated by Cosmo Yellow tags in Figure 53.

7.2 How does our trajectory compare with Boeing Performance Analysis?

In Appendix-1.6E-Aircraft-Performance-Analysis-MH370-(9M-MRO) [25] to the Malaysian report [2], Boeing present the results of their performance analysis in which potential trajectories are defined based on different values of the true air speed.

Figure 54 presents the range computation made by Boeing considering first the flight level and then the TAS at standard ISA.

Table 4: Range Capability for Altitude/Speed Combinations (from Arc 1)

	Flight Level	True Airspeed (knots)	Mach (*=MRC)	Time (hours)	Range (nm)
	FL400	494	0.861	5.0	2491
	FL400	475	0.828	5.9	2803
	FL400	469	0.818*	6.0	2806
	FL400	417	0.727	6.1	2538
	FL350	500	0.867	4.7	2356
	FL350	475	0.824	5.6	2657
	FL350	466	0.824	5.9	2747
	FL350	443	0.769*	6.2	2711
	FL350	400	0.694	6.6	2624
VMO-MMO	FL300	500	0.848	4.5	2270
LRC	FL300	437	0.742	5.7	2523
MRC	FL300	416	0.706*	6.1	2552
V Stall	FL300	323	0.548	6.8	2181
	FL250	471	0.782	4.6	2151
	FL250	383	0.642*	6.1	2363
	FL250	291	0.483	6.8	1970
	FL150	407	0.65	4.5	1835
	FL150	333	0.532*	5.8	1923
	FL150	250	0.399	6.75	1662
	FL030	345	0.535	4.2	1446
	FL030	284	0.437*	5.7	1534
	FL030	235	0.359	6.2	1464

Figure 54: Range computation by Boeing – FL300 is of interest – Arc1-Boeing is at 18h28:06 UTC (Source [25])

Based on these results they constructed possible flight paths as shown in Figure 55. In our case, the blue paths at FL300 are of particular interest.

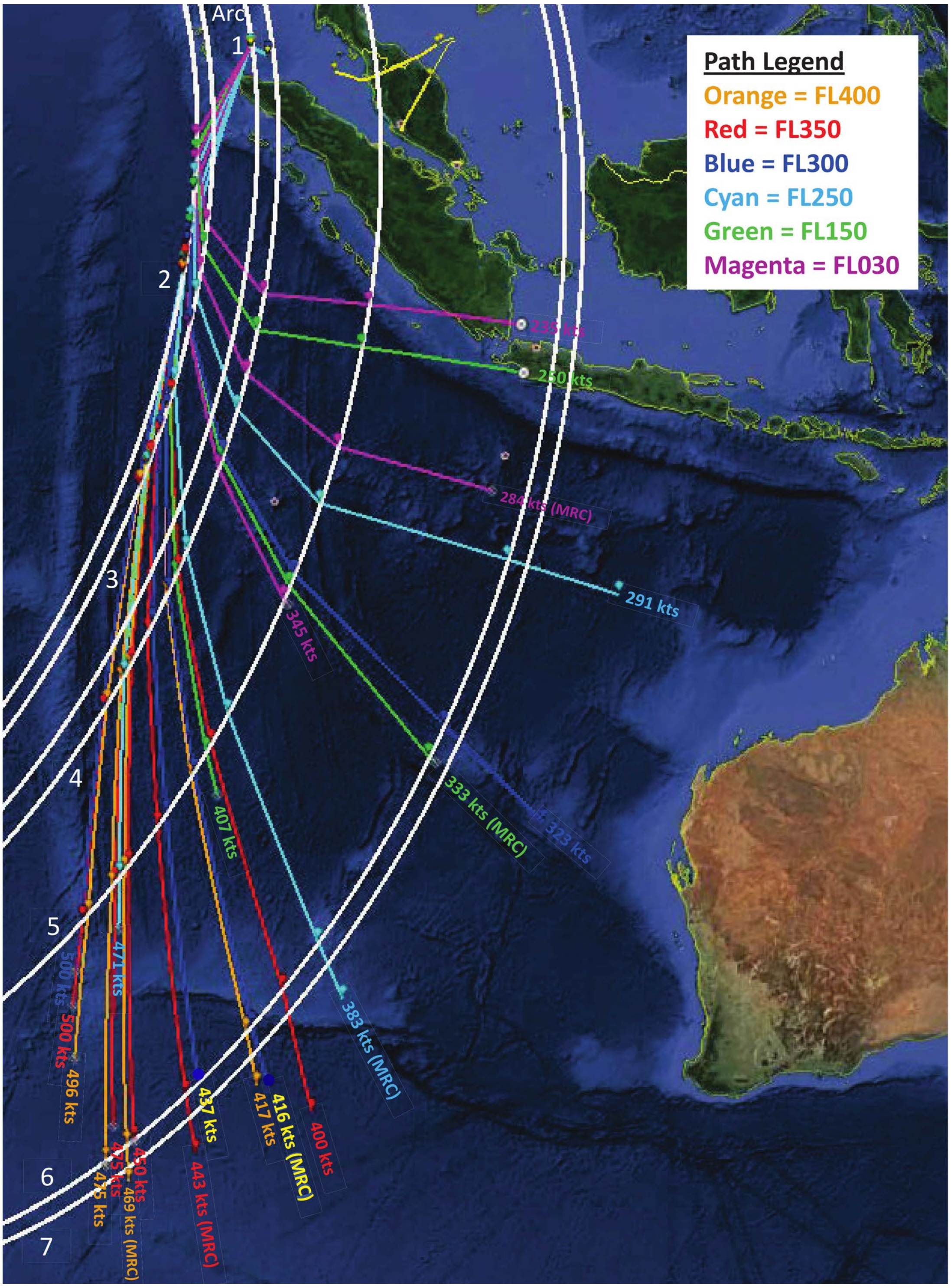

Figure 55 : Boeing calculated possible Flight Paths (Fig. 3 of [25])

Note: The blue paths TAS have been underlined in yellow for better contrast in the picture

The question addressed here is “how does our trajectory compare with these flight paths?”

Our trajectory is levelled at FL300, the average true air speed TAS is 431kt at ISA of the day (ISA+12) and the total distance flown from 18h28:06 (Arc1-Boeing) is 2522Nm. Thus, we focus our attention on the data given by Boeing for this flight level.

In Table 18 a line has been inserted including a flight path at TAS 431kt using the same computation from Boeing for determining the flight time and range (underlined in Red).

Table 18: Flight paths range including our trajectory

Flight Level	True Airspeed (knots)	Mach (ISA standard) (*=MRC)	Time (hours)	Range (Nm)
FL300	500	0.848	4.5	2270
FL300	437	0.742	5.7	2523
FL300	431	0.706 *(ISA +12)*	5.9	2544
FL300	416	0.706*	6.1	2552
FL300	323	0.548	6.8	2181

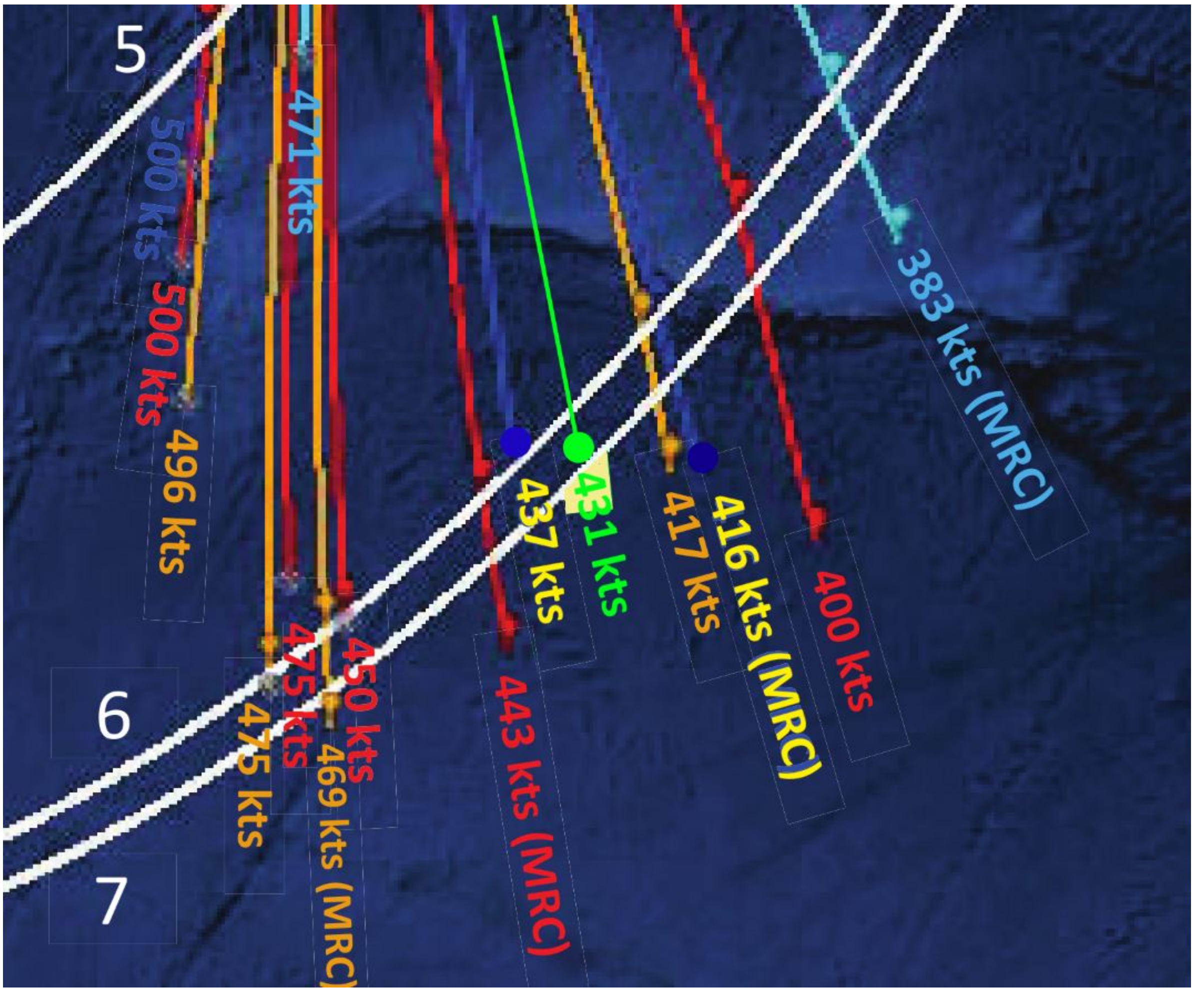

Figure 56: Range of our trajectory (Green) compared with Boeing possible paths at FL300

In interpolating the range and time in Table 18 with the ISA of the day (in average ISA+12°) we should match the corrected range of 2544Nm which is illustrated in Green in Figure 56. But actually, the path of our trajectory is 2522Nm long and was flown during 5.825 hours from 18h28:06 UTC.

The shortfall of 22Nm results most likely from the drag of the deployed RAT leading to a fuel overconsumption. From ARC1-Boeing at 18h28:06 UTC, we estimate this overconsumption at about ~300kg i.e. 0.9% of the fuel consumed during this southern leg.

Figure 57 illustrates a deployed RAT configuration where the turbine and its hatch are clearly justifying some fuel overconsumption.

Figure 57: Ram Air Turbine (RAT) and its hatch have been deployed

8 Annex 1: Variant 2 of the End of the Flight

At 00h19:29 UTC, arc 7 exists because the SATCOM of the aircraft sent a burst requesting a logon to the Inmarsat network. This provided the arc 7 BTO/BFO data. In the few seconds that followed, the logon procedure proceeded normally with the expected second burst from the SATCOM at 00h19:38 UTC but providing an unexpected measured BFO of -2Hz.

This BFO value is to be compared with the previous one equal to 182Hz. Professor Holland [12] analysed it and reported that in 9 seconds the aircraft could have accelerated because of a dive that increased its vertical speed from -4000fpm to -14500fpm. Subsequently, a lot of studies concluded that the aircraft was either in a free fall or in a high-speed vertical dive and smashed into the water … at the arc 7 or close to it.

If one considers a human presence in the cockpit, there is another possibility which is envisaged here and sketched in Figure 58. The small number of pieces of debris found and their type led to a conclusion that the aircraft did not violently crash into the water with a high speed. Otherwise, it would be similar to crashing into a concrete wall spreading thousands of pieces around. In our view, it is perfectly possible that after the start of the dive – it being voluntary or involuntary – the person in command recovered from this very quickly. The voluntary cut-off of the last running engine (the left one) and the management of the subsequent events in the cockpit might have triggered this temporary dive. For example, computations show that if the aircraft dived for 10 seconds shortly before the arc 7, the recovery manoeuvre sketched in Figure 58 would last 50 seconds with a flown distance of 6 Nm. Then a descent would take place similarly to the options described in Variant 1 and recalled in Figure 59.

The noticeable difference between the End of the Flight in Variants 1 and 2 is the estimation of the minimum and maximum distances flown by the aircraft. The minimum distance in Variant 1 would be ~45 Nm while the maximum would be ~67 Nm and ~42 Nm and ~59 Nm respectively in Variant 2 as posted in Figure 59.

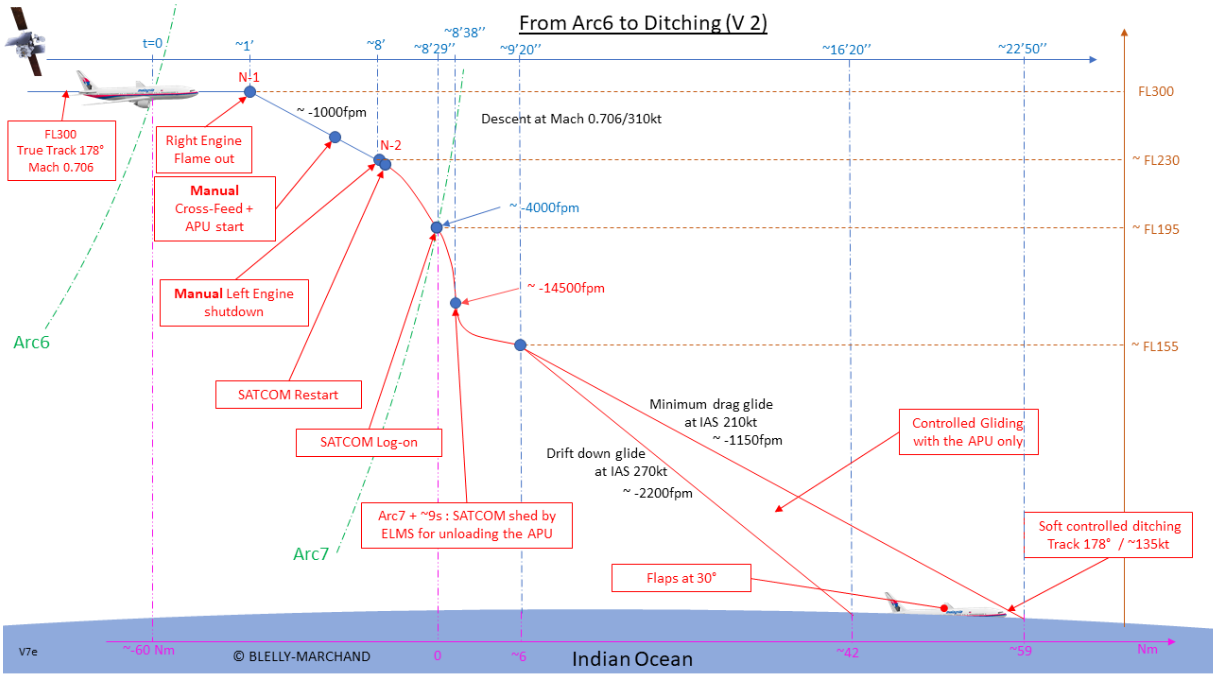

Figure 58: Variant 2 of the end of flight including a dive followed by a quick recovery (Blelly/Marchand)

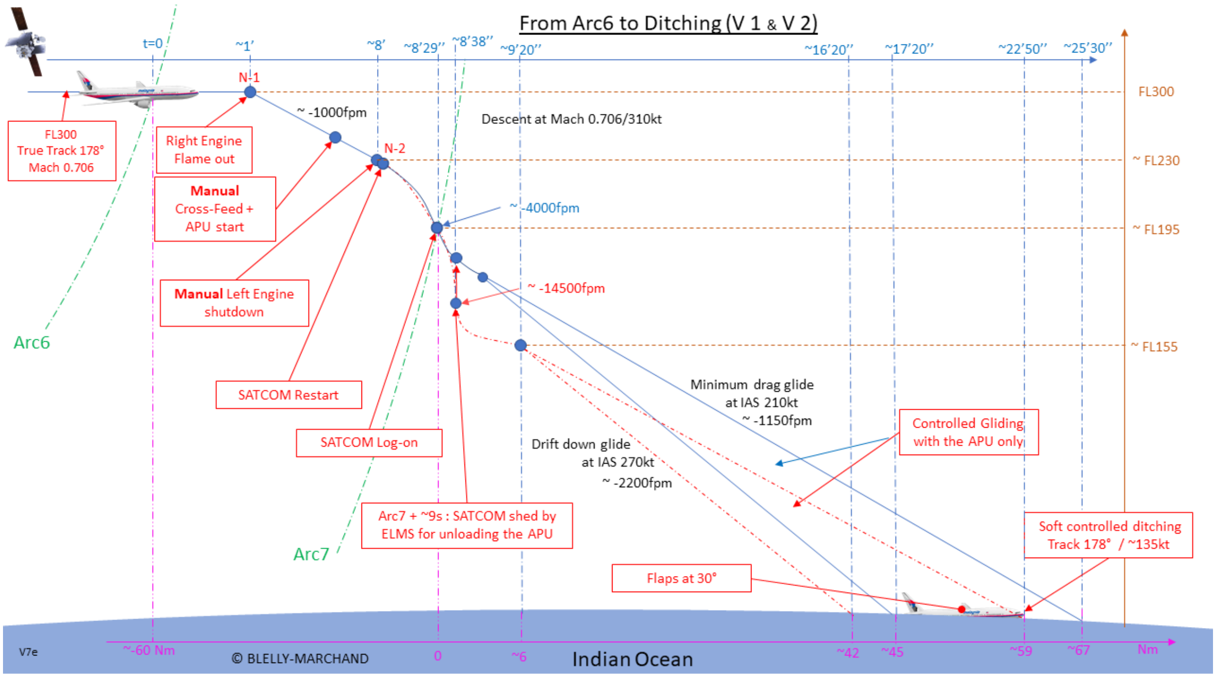

Figure 59: Synopsis of the End of Flight scenario (Variants 1 & 2)

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10 Abbreviations and Index

A/P	Auto-Pilot	
ACARS	Aircraft Communication, Addressing and Reporting System	Digital link system for the transmission of messages between aircraft and ground stations.
ADIZ	Air Defence Identification Zone	National area where military authorities request specific rules to be obeyed before entry.
ADS-B	Automatic Dependence Surveillance-Broadcast	System in which the aircraft broadcast their current navigational situation allowing the ATC and the other airspace users to be aware of the current situation of their surroundings.
AIS	Automatic Identification System	VHF automatic surveillance system for marine vessels (similar system to the airborne ADS-B)
APU	Auxiliary Power Unit	Turbine located at the rear of the aircraft providing electrical power and pneumatic power
ATC	Air Traffic Control	Authority in charge of the control of the air traffic in a specific airspace volume.
ATHR	auto throttle	Automatic system for maintaining speed
ATSB	Air Transport Safety Board	Australian department in charge of the investigation on safety issues in Australian air transport.
BFO	Burst Frequency Offset	The BFO is the recorded value of the difference between the received signal frequency and the nominal frequency at the GES. It is a function of the Doppler effect between the aircraft and the satellite.
BTO	Burst Time Offset	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 a measure of twice the distance of the aircraft from the satellite.
Data link reset		reset of the data link function via the Communication Manager. When airborne, it erases the flight and company data
DME	Distance Measuring Equipment	Radio Navigation system measuring the distance between the aircraft and the terrestrial transmitter
ELMS	Electrical Load Management System	System providing load management and protection to ensure power is available to critical and essential equipment. It manages the balance between the available electrical power and the demand from the electrical loads. It could shed loads as necessary.
FCOM	Flight Crew Operating Manual	Document incorporating aircraft manufacturer guidance on how to use the systems on board the aircraft
FIR	Flight Information Region	The world has been cut out into a set of geographical areas like a jigsaw puzzle. Each area is called a FIR where the Air Traffic Control is under the responsibility of one authority only.
FL	Flight Level	Standard definition of the altitude when an aircraft is above the transition level with the altimeter set to 1013hp.
FMC	Flight Management Computer	Onboard computer managing the flight parameters and keeping the aircraft within the flight envelop.

FMT	Final Major Turn	Manoeuvre including several turns performed by the aircraft to circumvent Sumatra in the north
FsX	MS Flight Simulator X	PC simulator software from Microsoft Corp. Version 10.
GDAS	Global Data Assimilation System	Meteorological data combined and provided by US official meteorological institutions. In this study, a posteriori measurement data is used and is referred to as "actual" meteorological, 'meteo' or 'met' data.
IAS	Indicated Air Speed	
IFE	In Flight Entertainment	Onboard system offering entertainment to passengers including telecommunications and cabin comfort
IFR	Instrument Flight Rules	
IG	Independent Group	A group of experts who made secession from the ATSB because of a diverging opinion on where to search the wreckage and who are very active in studying the case.
ISA	International Standard Atmosphere	This standard is the foundation in building the reference atmosphere charts used in aeronautics. It always considers that the sea level temperature is 15°C.
kt	knot	Speed equals to 1 nautical mile per hour
LNAV	Lateral Navigation	Navigation function of the Auto Pilot with a specified precision
LRC	Long Range Cruise	This is the FMS mode which makes the aircraft fly a slightly shorter range than the maximum MRC at a more economical manner.
LSTPR	LaST Report Point	Virtual waypoint defined at the location of the last echo received by Butterworth radar
Mach		Speed of an aircraft relatively to the celerity of the sound. Usually used above flight level FL300.
MCDU	Multi-function Control Display Unit	Interface system for input and consultation of FMC information
MCP	Mode Control Panel	Panel to adjust settings for: speed, altitude, Rate of climb/descent for the A/P etc.
MFD	Multi function Display	Interface to some aircraft management functions
MRC	Maximum Range Cruise.	This is the FMS mode which makes the aircraft fly the longest range. Sometime it is called also the mode with Cost Index = 0.
ND	navigation display	Display for monitoring and controlling the navigation
Nm	Nautical Mile	Distance of 1852m
OCXO	Oscillator Cristal Oven	System maintaining the temperature of the oscillator for ensuring the required stable frequency
PFD	Primary Flight Display	Pilot's primary reference display for flight information
PIC	Pilot In Command	Usual term to designate the person currently piloting the aircraft and in full command of it.
Prepar3D		PC Simulator software from Lockheed-Martin.
PSR	Primary Surveillance Radar	Non-cooperative Radar system which sends radio pulses and listens for received echoes. This information is translated into a raw video 'blip' or processed 'plot' on the controller radar screen (no exchange of info with the aircraft).
QNH	Geographic Altitude Indication	The pressure set on the subscale of the altimeter so that the instrument indicates its heights above sea level

R&R	Rolls-Royce	MH370 engines manufacturer
RAT	Ram Air Turbine	Small windmill turbine generating electricity and pneumatic power as the last resort in emergency. It deploys underneath the aircraft's body.
SDU	Satellite Data Unit	Satellite communication system onboard the aircraft
SSR	Secondary Surveillance Radar	Cooperative Radar system which interrogates an aircraft transponder that collects and responds with current aircraft navigational parameters depending on its operating Mode (A, C, S).
TAS	True Air Speed	Speed of the aircraft relative to the surrounding air
True Track		Navigation function disregarding the magnetic declination
UTC	Universal Time Coordinated	Greenwich (UK) time taken as the universal reference.
VOR	VHF Omni Range	Radio Navigation system indicating the bearing of the terrestrial transmitter