An Analysis of MH370's Flight Path Between Waypoint IGARI and the top of the Malacca Strait, a Review of Potential Vulnerabilities Specific to Airplane 9M-MRO and a Hypothesis Regarding Possible In Flight Events and an End-of-Flight Scenario

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Introduction

The purpose of this paper is to outline the findings of research into the flight path of Malaysia Airlines flight MH370 between waypoints IGARI and the top of the Malacca Strait and into potential vulnerabilities of the operating airplane, B777-200ER Registration 9M-MRO. Some of the findings support a hypothesis as to the cause of the loss of Malaysia Airlines flight MH370. Other findings contradict or undermine elements of the theory that deliberate and malicious direct action by a member of the flight crew, a "rogue pilot", was responsible for the disappearance of MH370.

Summary of Findings

1. There is no evidence to support the contentions that MH370 flew anything other than a direct route to Penang subsequent to the initial deviation from its planned flight path just past IGARI.
2. 9M-MRO, the Malaysia Airlines' B777 that operated as MH370, was at a significantly increased risk of experiencing a windshield heater fire or failure.
3. The crew oxygen system mask hoses on 9M-MRO were replaced seven weeks before the airplane flew as MH370 and there is evidence to suggest that the replacement task may have been rushed.
4. The initial deviation from the flight plan just past IGARI was consistent with the response to an inflight emergency such as a windshield heater fire.
5. A windshield heater fire and the probable crew response can explain the loss of communications with air traffic control, the loss of the transponder signal, the failure to descend and the interruption to the satellite communications.
6. Manoeuvring of the airplane immediately subsequent to the 18:25 UTC (02:25 MYT) log-on - the first ping - may have been consistent with a deliberate loiter.

Discussion

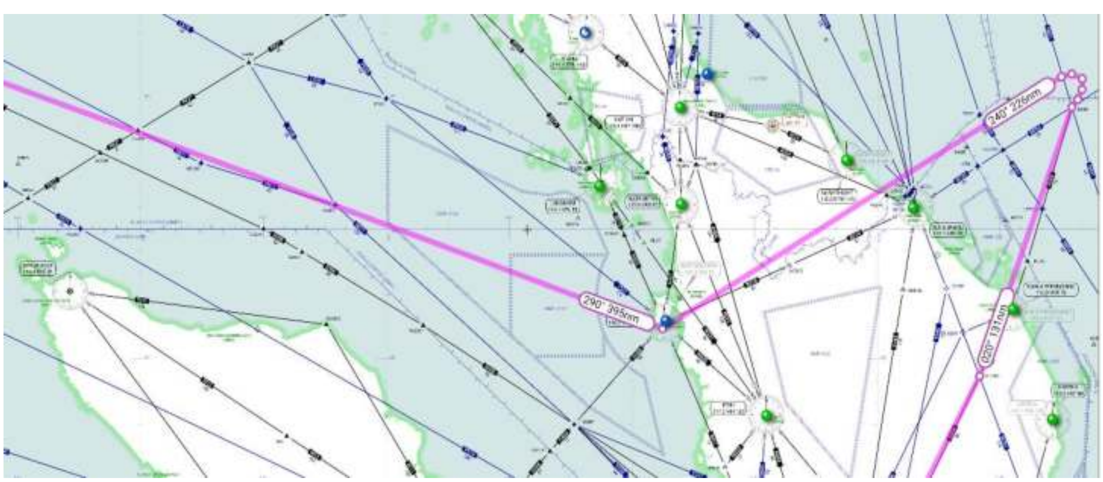
1. There is no evidence to support the contentions that MH370 flew anything other than a direct route to Penang subsequent to the initial deviation from its planned flight path just past IGARI.

Considerable misinformation abounds regarding the course that MH370 flew after turning back towards the Malay Peninsula. This misinformation together with associated misrepresentations have, to a large extent, guided thinking towards the "rogue pilot" theory.

There is a common misconception that MH370 flew along air space boundaries and navigated from one waypoint to another after departing from its planned flight path. This is not supported by the evidence as detailed in the Factual Information Report (FIR) released by the Malaysian ICAO Annex 13 Safety Investigation Team in 2015. [1] Many people believe that MH370 was tracked continuously on primary radar from when it turned back just past waypoint IGARI to when it was lost from radar at the top of the Strait of Malacca. That is not the case.

The inferred 750 odd kilometer flight path of MH370 after the turn back just past IGARI until radar contact is lost north west of MEKAR is based on seven separate primary military radar traces and five complementary primary civilian radar traces. [2] The longest continuous radar trace by the same radar station was the final 120 kilometers over the Malacca Strait from near VAMPI to past MEKAR. The only waypoint that MH370 ***may*** have overflown was VAMPI. As detailed in the FIR, MH370 flew about 16 kilometers to the north of MEKAR (although contrary to what is stated, MH370 most certainly did not join Airway RNAV Route N571; if it had of it would have tracked directly to MEKAR from VAMPI). [3] Radar contact was lost well before the airplane approached NILAM however a track from VAMPI to 16 kilometers north of MEKAR will pass about 12 kilometers to the north of NILAM.

Further, and also contrary to popular belief, MH370 did not track or "zig zag" along air space boundaries. After departing from its planned flight path MH370 flew on a heading that took it over, not along, a stretch of about 120 kilometers of the Bangkok (Thailand)-Kuala Lumpur (Malaysia) airspace boundary that traces the Golong River. Subsequently, MH370 remained firmly in the Kuala Lumpur FIR (Malaysian airspace) at all times until it was lost from radar.



Map 1 Probable flight path of MH370 south-west over the Malay Peninsula and north-west up the Malacca Strait.

Map 1 illustrates the very simple course that MH370 flew; an initial right turn at IGARI towards BITOD followed almost immediately by a left turn back towards Penang on a heading of 240°. Then from south of Penang a right turn to 290°; this track would take MH370 over VAMPI and to the north of MEKAR.

In short, the evidence indicates that MH370 ***may*** have tracked via one waypoint, VAMPI and I would content that this was coincidental with a simple course of 290° from just south of Penang.

Importantly, the flight path above does not require programming into the Flight Management System computer (in fact it would be quite laborious to do so), it can be flown very simply using the basic Mode Control Panel (MCP) autopilot function in Heading or Track Select/Hold.

There have also been a range of misrepresentations about the altitudes flown by MH370 after the turn, ranging from the physically impossible climb to 45,000 feet to a low level, radar-evading run at 5,000 feet across the Malay Peninsula. Of course, none of that is true.

To determine what is true we again go to the primary radar data. Of the various primary radar traces only three contain altitude data [4]:

1. 17:30:35 - 17:35 UTC (01:30:35 - 01:35 MYT), the radar return was at a registered height of 35,700 ft.

2. 17:36 - 17:36:40 UTC (01:36 - 01:36:40), the radar return was at a registered height of between 31,100 and 33,000 ft.

3. 17:39:59 UTC (01:39:59 MYT) , the radar return was at a registered height of 32,800 ft.

Allowing for the vagaries of primary radar with regards to determining altitude, that data suggests an altitude, or band of altitudes in a tight range, at or just below the previously established cruise of 35,000 feet.

Going beyond the radar altitude data, if we assume some consistency with regards to MH370's altitude and air speed from when it turned back until when it disappeared off radar, then we can use the distance flown and the time taken to fly it to do some calculations. Given the known weather conditions, a constant true air speed of 498 knots satisfies the time and distance involved. Based on the known conditions if we convert a TAS of 498 knots to a Mach number we get M = 0.840 at FL340 (34,000 feet). M0.84 is not only the last reported speed for MH370 prior to the loss of the transponder signal it is also the typical cruising speed for a B777- 200ER. Moreover, if you compare M0.84 at FL340 to the actual radar traces with regards to distance and time you also get a very good fit. [5]

After the initial turn back there were no en route deviations, no zigzagging, no tracking along airspace boundaries, no significant changes of altitude apart from the initial descent to FL340 (the correct flight level for the westerly heading), and no changes to speed. In short, there were no attempts to evade radar detection or confuse observers.

2. 9M-MRO was at a significantly increased risk of experiencing a windshield heater fire or failure.

The Boeing B757, B767 and B777 all use the same forward windshields; there are two per airplane - left (Captain's) and right (First Officer's). They are manufactured by PPG Aerospace Transparencies of Huntsville, Alabama in the United States.

As illustrated at Figure 1, the windshield is made up of two inner panes of Herculite (chemically strengthened) glass and an outer pane of tempered glass bound together with urethane interlayers. On either side of the middle pane of Herculite and adjacent to the inner and outer panes are layers of Nesatron film. Nesatron is transparent but electrically conductive and heats up when a current is passed through it - the layers of Nesatron are the windshield heaters. The inner heater prevents fogging of the inner pane and the outer heater prevents both icing and contracting of the outer pane due to exposure to sub-zero air temperatures at altitude. If the outer pane wasn't heated it would suffer a "thermal break" and shatter which would then expose the middle pane.

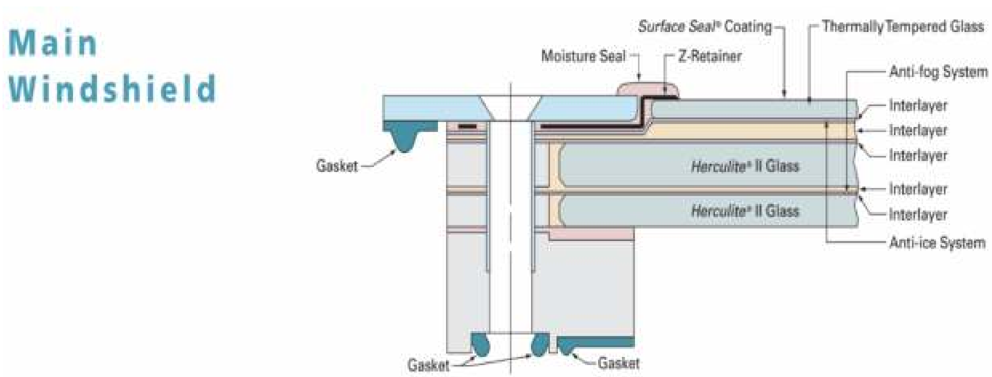


Figure 1 Cross-section view of construction of B777 forward windshield

In 2007, the cost of each windshield was around $US100,000.

In the late 1990s and early 2000s, Boeing started to experience problems with windshield heaters either failing or shorting and catching on fire. The problems were encountered initially on the B757 and B767 but eventually the problem manifested itself in the B777 fleet as well. [6] On 17 October 2002, an Air France B777 flying as flight AF062 from Paris to Los Angeles experienced a fire in the immediate area surrounding the windshield heater of the Captain's windshield. It took two fire extinguishers to put the fire out. The outer pane had cracked in a number of places. The crew initiated an emergency diversion and completed a successful landing at Churchill Airport, Canada. [7]

Ten months after the Air France AF062 incident, on 24 July 2003, an Alitalia B777 flying as flight AZ610 from Rome to New York also had an inflight windshield fire that started with the Captain’s windshield heater. The fire was extinguished but the outer pane of the Captain's windshield shattered and the crew initiated an emergency diversion to Shannon International Airport, Ireland. [8]

In an attempt to address the problem Boeing had PPG redesign the windshield heater terminal connections, replacing the original screw-in connections with pin-and-plug connectors. In April 2004, Boeing issued a number of service bulletins for the various airplane models impacted - Service Bulletin 777-30-0012 related to the B777 windshield heaters. [9] The bulletin recommended that airlines inspect the electrical connections of the windshield heaters and adjust the connections if necessary or replace the entire windshield assembly with the new design with the improved electrical connections. The bulletin covered all 440-odd B777-200/300 aircraft produced up until 2004. Aircraft built after that time were fitted with the new windshields during production.

It was not until 2007, after investigating American Airlines flight AA1477, a B757 that had declared an emergency on departure from the Dallas-Fort Worth International Airport because of smoke and a fire near the Captain's windshield heater terminal that the US National Transport Safety Board issued Safety Recommendation A-07-050. [10] That recommendation asked that Boeing and the Federal Aviation Administration require operators to replace the windshield terminal blocks rather than just inspecting them. However, the following year when the FAA issued Airworthiness Directive FAA–2008–0274, which covered B757, B767 and B777 airplanes, it only required operators to comply with Boeing's Service Bulletin(s) with regards to the inspections and adjustments; replacement of the windshields was not required. [11]

Boeing's service bulletins and the FAA's directive were temporarily effective – the incidence of windshield heater related issues fell to zero in the Boeing B777 fleet. But then in 2011, the problem re-surfaced, with two incidents involving B777s in 7 months. On 5 September 2011, an Air France B777 performing flight AF900 from Paris Charles de Gaulle to Yaounde, Cameroon was en route at FL350 about 270 kilometers south of Paris when the crew experienced a windshield heater failure that led to windshield cracking. [12] Then on 13 April 2012, an Alitalia B777 flying as flight AZ8320 from Rome to Dubai suffered cracking to the First Officer's windshield when the heater failed. [13]

There were also renewed problems with the windshield heaters on B757 and B767. These included a 2008 incident involving an American Airlines B757 operating as flight AA1738 where the inner pane on the First Officer's windshield shattered spraying him with shards of glass (NTSB Identification: ENG08IA011) [14] and a 2010 incident involving a United Airlines B757 operating as flight UA027 (NTSB Identification: ENG10IA029) [15] where the Captain's windshield heater caught fire - the Captain emptied two extinguishers onto the fire to put it out, in the process he had his oxygen mask torn from his face twice while retrieving fire extinguishers (the hoses simply aren't long enough for the wearer to move far from their seat with the mask on).

There were *at least* 39 B757, B767 and B777 windshield heater related incidents between 2002 and 2015, eight involving B777s. [16] I say "at least" because, alarmingly, not all incidents are reported through official channels. In 2012 Boeing conceded that there had been 39 incidents but a review of NASA's Aviation Safety Reporting System database (the ASRS is an external to "official" channels, confidential, voluntary safety reporting system open to flight crew, cabin crew and ground staff) shows a number of incidents that do not tally with NTSB records (a matter that the NTSB acknowledges). The chain of correspondence between the NTSB and the FAA while all of this was unfolding highlights the NTSB's palpable frustration with the slowness of the FAA's initial response and the lack of firm direction regarding windshield replacement.

A complete list of B777 windshield heater incidents is attached at Appendix 1. An analysis of those incidents is instructive. The airplane involved in the first incident, Air France F-GSPZ, was production line number 401; the Alitalia B777 involved in the second incident (I-DISU) was number 425. When windshield heater fires re-emerged, the Air France (F-GSPY) and Alitalia (EI-ISB) B777s were line numbers 395 and 426 respectively. All four airplanes – **395**, **401**, **425** and **426** – came off the Boeing production line in a nine month period from late March to mid-December 2002. [17] Together, that small cohort represents half of all the B777s that have ever experienced windshield heater related incidents and 80% of the B777s that had experienced windshield heater related incidents at the time that MH370 flew.

There was also a 30 July 2008 incident involving an Emirates Boeing B777, registration A6-EMS operating as flight EK006 from London to Dubai where the crew reported smoke in the cockpit and carried out an emergency landing at Budapest Ferihegy airport [18] but I have been unable to confirm that the source of the smoke was a windshield heater. A6-EMS was line number **408**. [17]

An inferential statistical analysis of the confirmed windshield heater related incidents involving B777s up to March 2014 (the time that B777 9M-MRO flew as flight MH370) highlights that 80% of the incidents occurred in less than 4% of the fleet. When adjusted for years of service, the rate of incidence of windshield heater fires/failures by years of service for B777s produced in 2002 is nearly 17 times higher than the incidence rate for the entire B777 fleet at that time and more than 100 times higher when compared to the remainder of the fleet (ie the fleet excluding the 2002 sub-group).

9M-MRO was manufactured on 14 May 2002, production line number **404**. [17]

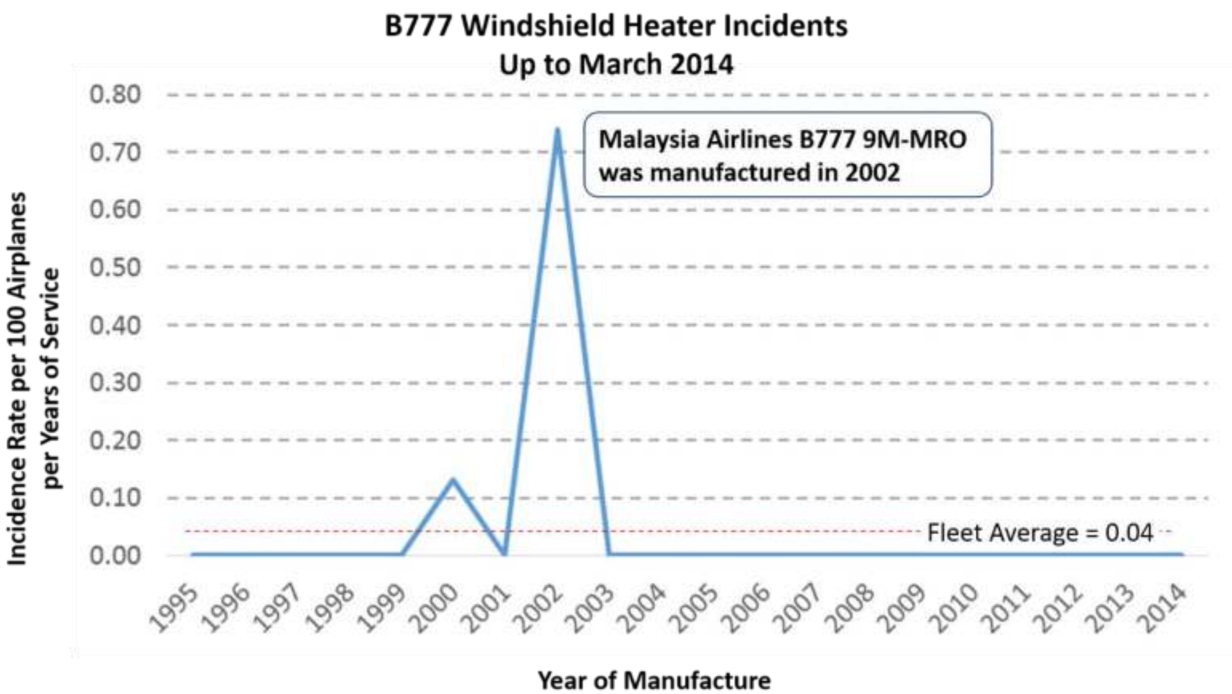


Figure 2 Incidence Rate of B777 Windshield Heater Incidents Up To March 2014 by Year of Manufacture

If Malaysia Airlines were complying with Airworthiness Directive FAA–2008–0274 and were following the Boeing phased-A check schedule, the flight compartment windows would have been inspected for condition in accordance with the Aircraft Maintenance Manual at every A2 Check. 9M-MRO's last A2 Check was 4 November 2013 and her next A2 Check would have fallen around the end of March-early April 2014. [19]

9M-MRO belonged to a cohort of B777s that were statistically significantly over-represented in windshield heater related incidents and it is probable that 9M-MRO's windshield heaters were inspected for condition some 4 months before it flew as MH370.

3. The crew oxygen system mask hoses on 9M-MRO were replaced seven weeks before the airplane flew as MH370 and there is evidence to suggest that the replacement task may have been rushed..

The crew oxygen system provides pressurised oxygen to four masks on the flight deck for use in the event of an emergency. Malaysia Airlines B777s are fitted with two cylinders that hold 3150 litres of oxygen each at 1850 psi. This is sufficient capacity to provide 100% pressurised oxygen on demand to two flight crew for 13.5 hours. [20]

Oxygen is drawn off from the system as part of the daily maintenance check; typically this check consists of a 5 second pressure check per mask. Additionally, before each flight, flight crew members check the flow of oxygen to their mask and the function of their mask microphone; these checks are combined into one 5 second test - the mask microphone is selected to INT (for intercom) and the oxygen flow test button is depressed, the oxygen flow can be heard on the flight deck speakers. Further, on the start of the first engine, 25 seconds of oxygen is automatically bled off so that the airplane's sensors can confirm both flow and pressure.

The following information has been sourced from the Factual Information Report, FAA Airworthiness Directives, Boeing Service Bulletins and the operational records for 9M-MRO:

- On 14 January 2014, the crew oxygen system was serviced. [21]

- On 17 January 2014, maintenance work was carried out on the crew oxygen system. That work was associated with an FAA Air Worthiness Directive, FAA AD 2012-13-05 (Replacement of Low Pressure Oxygen hose). [22] According to the relevant Boeing Service Bulletin, the replacement job consists of 17.75 task hours and takes 11.2 hours elapsed time for two technicians to complete. As the elapsed time does not include time for set-up, work breaks, clean-up or inspection it can reasonably be assumed that a two man crew would need at least 12 – 12.5 hours to complete the task. All the work is carried out on the flight deck on the low pressure side of the crew oxygen system and concludes with a simple flow check at the end of the job. The First Officer's seat need to be removed to access the flight deck oxygen system connections. [23]

- 9M-MRO came out of an A4 Check on 16 January and was scheduled to fly from Kuala Lumpur to Melbourne on 17 January 2014 as MH149 departing at 11:45pm MYT. [24] Thus, there was an operational requirement to have 9M-MRO out of maintenance and back on the line by no later than around 8.30-9.00pm local time. Work on the AD task would have occupied much of the day and early evening of 17 January. Given the requirement to first remove and lastly replace the First Officer's seat, the task is not one that can be easily rushed or curtailed

- FAA AD 2012-13-05 had to be completed before the mandatory completion date of 12 February 2014. [25] 17 January represented the last scheduled opportunity for the AD to be completed on 9M-MRO before the mandatory completion date.

- On 20 January 2014, three days after the work was performed, the First Officer's seat's forward/aft power adjustment was reported as inoperative. [26]

- On 7 March 2014, the afternoon prior to flying as MH370, the crew oxygen system pressure read 1120 psi and was topped up to 1800 psi. [21]

- Between 14 January and 7 March 9M-MRO flew 100 flights and accumulated around 550 airframe hours. [24]

The facts that the maintenance crew had to complete the AD task on 17 January and that operational requirements that day meant that they were afforded virtually no extra time to complete the task in the event of unforeseen delays or difficulties would have generated considerable work pressure. The subsequent failure of the First Officer's seat's power adjustment only days after the work had been completed may have been the result of the seat being hurriedly and improperly replaced. Based on the above I'm led to believe that the work associated with AD 2012-13-05 was rushed and that there is a possibility that the new hoses for the crew masks may have been improperly fitted.

Dangers associated with oxygen-enriched atmospheres

While oxygen itself is not flammable when the concentration of oxygen in the atmosphere rises by just 2%, from the usual 21% to 23%, the chemistry of fire changes and it changes dramatically; materials that do not normally burn become flammable and normally flammable materials ignite at lower temperatures and burn faster and hotter. Fires in oxygen-enriched atmospheres are extraordinarily difficult to extinguish. [27]

Photograph 1 Damage to flight deck of EgyptAir B777 registration SU-GBP, at Cairo International Airport, 29 July 2011.

Photograph 1 is of the flight deck of EgyptAir B777 registration SU-GBP that suffered an oxygen fire whilst on the ground at Cairo International Airport on 29 July 2011. [28] It took less than 4 minutes for the fire to cause that damage. (As a matter of happenstance, the work that was done on 9M-MRO's crew oxygen system under FAA AD 2012-13-05 was a result of the findings and recommendations arising from the EgyptAir B777 oxygen fire.)

A contributory factor, perhaps the major one, to an oxygen-enriched atmosphere may well have been a flight crew mask. The crew's initial reaction to a windshield issue or smoke, fire or fumes in the cockpit would be to don their oxygen masks, select 100% oxygen and select emergency mode on their mask. The combination of 100% oxygen and emergency mode ensures that oxygen is delivered continuously to the mask at a positive pressure to ambient; this is to ensure that smoke or fumes cannot be drawn into the mask.

The cockpit fire extinguisher is behind the Captain's seat and while it can be reached by the Captain while seated it is easier for the Captain to retrieve it and use it by getting out of his seat. However, doing so would tear the mask from the Captain's face in much the same fashion as the UA027 incident [15] mentioned in Section 2 or, if the hose hadn't been fitted properly, it may have become disconnected from its mount. If the mask came off, 100% oxygen would flow into the flight deck at the rate of 30 litres per minute at around 14-15 psi. However, if the hose had been disconnected from its mount, 100% oxygen would flow into the flight deck at the rate of more than 30 litres per second at 70 psi. In either case, the air flow on the flight deck is such that oxygen venting from the mask or its hose would most likely be drawn towards the forward instrument panel and the fire.

If the low pressure oxygen hose for the Captain's mask had become disconnected from its mount, the very rapid flow of 100% oxygen into the flight deck would bring the atmosphere to a 23% concentration of oxygen in about 20-30 seconds. Once this level of oxygenation was reached a windshield heater fire would flare violently and propagate rapidly.

4. The initial deviation from the flight plan just past IGARI was consistent with the response to an inflight emergency such as a windshield heater fire.

In the event of an inflight emergency such as windshield cracking or a windshield heater fire, the crew would divert to the nearest airport. A list of the four nearest airports in terms of ETA can be quickly accessed via the Flight Management Computer (FMC). At IGARI the Alternate page on the FMC it would have displayed:

1.	WMKC	Kota Bharu.	89.8 nautical miles	13.1 minutes
2.	WMKN	Kuala Trengganu.	97.2 nautical miles	14.1 minutes
3.	VTSS	Songkhla.	190.4 nautical miles	24.8 minutes
4.	WMKD	Kuantan.	190.4 nautical miles	24.8 minutes

All four were closed at that time of the night. WMKP Penang (220.6 nautical miles and 28.4 minutes away) was the closest operating airport to MH370 when it initiated a turnback. MH370's track back to Penang is offset to the south and it appears to align with a track towards KENDI, 11 nautical miles south-west of Penang. KENDI is the Intermediate Fix, a navigational point, for Penang's Instrument Landing System approach path ILS 04 and would be the logical place to track to for a landing on Runway 04.

While Kota Bharu is not a 24 hour airport and was closed when MH370 was flying it was the closest airport. A diversion to Penang, would have taken MH370 past Kota Bharu therefore providing an option if the emergency progressed rapidly to the point where an immediate landing was required.

MH370's change of direction back towards Penang on a heading of about 240° from just past IGARI was entirely consistent with a response to an inflight emergency.

5. A windshield heater fire and the probable crew response can explain the loss of communications with air traffic control, the loss of the transponder signal, the failure to descend and the interruption to the satellite communications link.

The circuit breakers in airplanes are thermal-magnetic; they are designed to respond to the heat generated by an electrical overload or the magnetic flux associated with a short circuit. Because they are sensitive to heat, external heat will trip a thermal-magnetic circuit breaker. [29]

There are two P11 overhead circuit breaker panels on the flight deck that hold circuit breakers for important aircraft equipment and systems. Heat rises and, in the case of a windshield heater fire, would roll across the flight deck ceiling and over the circuit breaker panels. The heat would naturally be more intense on the side of the fire (left for the Captain's windshield and right for the First Officer's windshield) particularly if it were being fed from an oxygen source on the same side. Heat from a windshield heater fire, particularly if it was in an oxygen-enriched atmosphere, may have started tripping some of the lower rated thermal-magnetic circuit breakers in the overhead panels.

Loss of Communications With Air Traffic Control

There are three VHF radios on the B777; left, centre and right. Each radio has its own Radio Tuning Panel. In normal operations VHF L is used to communicate with air traffic control, VHF C is used as a transmission path by ACARS (on MH370 ACARS was using the SATCOM to transmit) and VHF R is used to monitor 121.5 MHz, the civilian aviation emergency frequency (also known as "guard").

The circuit breakers for the Left and Centre VHF radios (COMM VHF L and COMM VHF C) are both rated at 10 amps and are both located on left overhead panel, in positions C8 and G8 respectively. If heat tripped COMM VHF L the radio normally used to communicate with air traffic control would lose power; if heat tripped COMM VHF C the radio used by ACARS would lose power.

Loss of Transponder Signal

There are two transponders on the B777; left and right. In normal operations one transponder is active and the other is in standby mode. If the active transponder fails there is no automatic fail-over to the standby transponder, it needs to be selected manually. I have not been able to determine what Malaysia Airlines' procedures are for selecting the active transponder when crew are undergoing training but under normal circumstances the left transponder is active and the right is on standby.

The right and left transponder circuit breakers are rated at only 5 amps. Further, the left transponder circuit breaker (ATC L) is located at the A3 position on the left panel, placing it closest (bar two) to the potential heat source, the Captain's windshield. If heat tripped ATC L the transponder would lose power and stop transmitting.

Failure to descend

The autothrottle is comprised of two Thrust Management Computing Systems (TMCSs) commanding two autothrottle servo motors (ASMs), one for the thrust lever for each engine. The right and left ASM circuit breakers (A/T SERVO L and A/T SERVO R) are rated at only 2.5 amps and the A/T SERVO L circuit breaker is located at the F5 position on the left overhead panel, placing it proximal to the potential heat source, the Captain's windshield.

If heat tripped the A/T SERVO L circuit breaker then the Left ASM would become unpowered; this asymmetry is sensed and the autothrottle disengages. (*It is worth noting that if every circuit breaker on the left overhead panel were tripped by heat the autopilot would remain engaged.)*

The autothrottle can be re-engaged by selecting the failed side's (in this case, the left) A/T ARM switch to OFF but this requires that the pilot realises that the autothrottle has disengaged; an "AUTOTHROTTLE L" EICAS message would have been displayed and there is an audible beep to draw the pilot's attention to EICAS. However, the autothrottle EICAS would have been just one of a slew of messages generated as circuit breakers tripped and could have been easily missed. The other visual cue would be the lack of an autothrottle mode indication on the Flight Mode Annunciator at the top of the pilots' Primary Flight Displays. Ordinarily, it would typically display "SPD" or "THR" but is blank when the autothrottle is disengaged. Again, this is an indication that could be easily missed.

The normal response to the onset of an inflight emergency that may require a landing, such as smoke or fumes being detected, is to determine the nearest suitable airport and initiate a diversion towards it; an immediate descent is not required. Certain very serious inflight emergencies, such as loss of cabin pressure, or developing/escalating emergencies, such as smoke that persists or a fire that cannot be positively confirmed to be completely extinguished, require a rapid descent to 10,000 feet (or the lowest safe altitude as permitted by local terrain). On a B777 such a descent would ordinarily be commanded using the MCP Flight Level Change (FLCH) autopilot function; the pilot simply selects lower altitude on the MCP altitude selector, then presses the FLCH button. In response the autothrottle will reduce thrust to idle and the aircraft will descend at its current speed until it approaches the selected altitude at which time the autothrottle will increase thrust and the autopilot will pitch the nose up to resume level flight.

The autopilot usually operates in what is known as "path-on-elevator" mode; the elevators are used to maintain the flight path while the autothrottle controls the speed. However, FLCH uses "speed-on-elevator" mode; in this mode the elevators are used to control speed and the autothrottle controls the flight path.

If the autothrottle had disengaged then thrust would not be reduced when FLCH was engaged. In such an event the autopilot would still control the speed via the elevators, but the airplane will not descend (unless the throttles are manually retarded); speed will be maintained and the airplane will remain at or fairly close to the altitude it was previously maintaining.

It is not inconceivable that the crew missed the autothrottle disengaging, commanded a descent on the MCP using FLCH and were then too distracted to notice that the autothrottle had not retarded the thrust levers and that they were not descending. Such an event would not be without precedent. There have been at least two incidents involving B777s and autothrottle "mishaps". Asiana Airlines flight OZ214 [30] and Emirates flight EK521 [31] both came to grief when their respective crews failed to realise that the autothrottle had not responded in the expected manner; in neither case where the prevailing circumstances as demanding or as distracting as a flight deck fire.

It is also worth noting that the First Officer had less than 40 hours on the B777; the bulk of his flying experience was on the Airbus A330. The Airbus autothrust system differs from the Boeing autothrottle system in a number of ways. Amongst those differences is the lack of servo motors on the Airbus system; when the Airbus autothrust system is engaged the thrust levers for the engines are not physically moved to change the thrust setting. Accordingly, the lack of physical movement of the thrust levers when a descent was commanded could easily have gone unnoticed by the First Officer because it was not in his experience to expect to see the thrust levers move.

With the autopilot in "speed-on-elevator" mode and with a fixed thrust setting, minor fluctuations in altitude would have occurred but speed would be closely maintained. This is broadly consistent with the analysis of MH370's flight back across the Malay Peninsula where airspeed appears to be constant but altitude may have varied in a tight range.

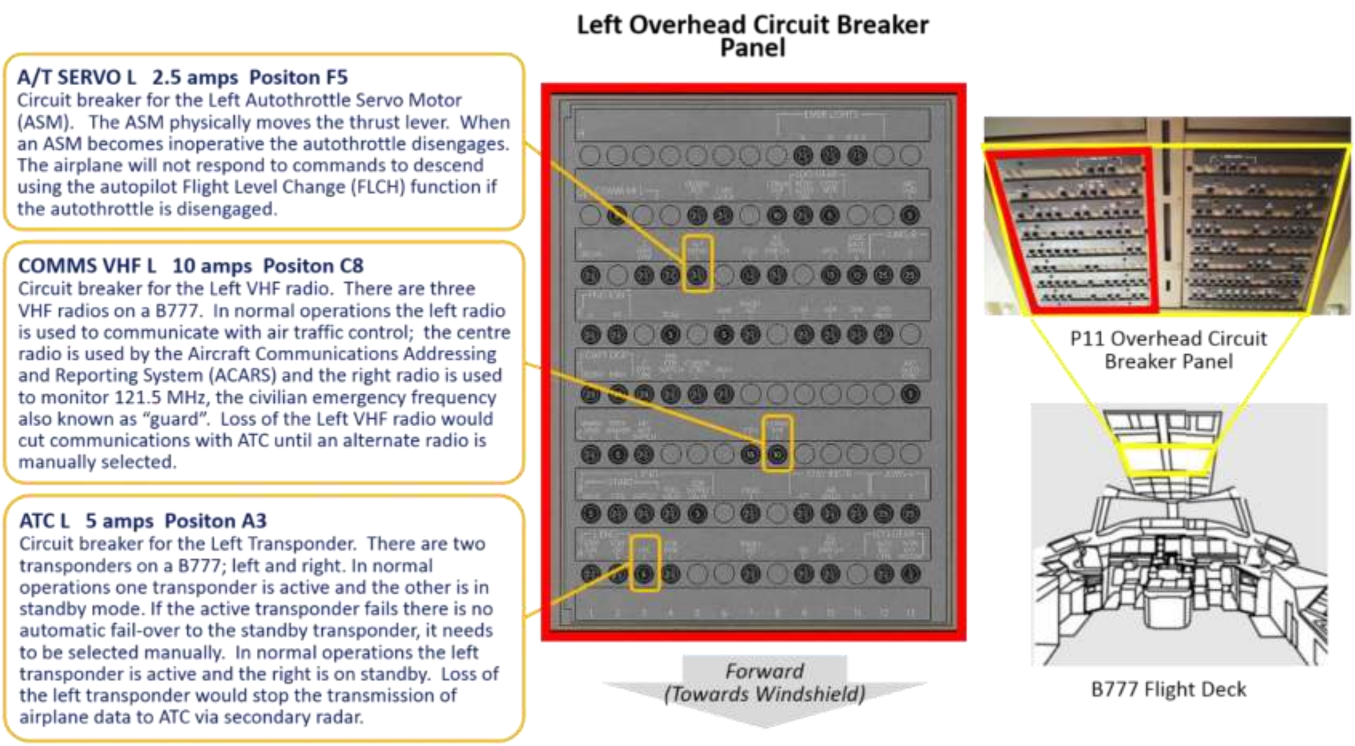


Figure 3 Key Circuit Breakers on the Left P11 Overhead Circuit Breaker Panel

Interruption to the satellite communications link

With regards to the failure of MH370's satellite communications, the Satellite Data Unit is powered by the Left Main AC bus. In the event of a fire, smoke or fumes in the cockpit, the B777 Quick Reference Handbook checklist states the objectives are;

- To remove power from the ignition source, and
- To land the airplane as soon as possible, if needed. [32]

The checklist states that if the source of the fire is obvious, power should be removed from any affected equipment. If the fire originated in the Captain's windshield heater the approach to removing power from it would be to first turn off the windshield heaters by selecting them to OFF on the overhead panel. In all prior windshield heater fire incidents turning off the heater has had no discernible effect on the fire. The next step in removing power from the affected equipment would be to manually open the relevant circuit breaker. However, the circuit breakers for the windshield heaters are not on the overhead panels on the flight deck, they are on the P110 power management panel in the Main Equipment Centre (MEC). Accordingly , the only remaining course of action immediately available to the crew to remove power from the Captain's windshield heater is to isolate the Left AC Transfer bus. This is accomplished by selecting the Left Bus Tie Breaker to ISLN, selecting the Left Backup Generator to OFF, and selecting the Left Generator to OFF. This action also isolates the Left Main AC Bus.

Isolating the Left Main AC Bus and the Left AC Transfer Bus is a significant step and would only be undertaken in extraordinarily desperate circumstances such as a rapidly propagating fire on the flight deck. The action would have a number of unintended consequences, among those would be cutting power to the Satellite Data Unit which would in turn render the SATCOM completely inoperative.

Alternatively, the Left AC bus may have been isolated automatically by the airplane's electrical system. The Generator Control Units (GCUs) and Electrical Load Management System (ELMS) combine to manage the airplane's electrical system; the GCU provides the supply control and the ELMS provides the load protection. The GCUs in particular are sensitive to voltage and frequency faults. It is possible that the Left GCU responded to the voltage/frequency spike caused by the rapidly tripping circuit breakers on the left overhead panel by isolating the Left AC Bus.

6. Manoeuvring of the airplane immediately subsequent to the 18:25 UTC (02:25 MYT) log-on - the first ping - may have been consistent with a deliberate loiter.

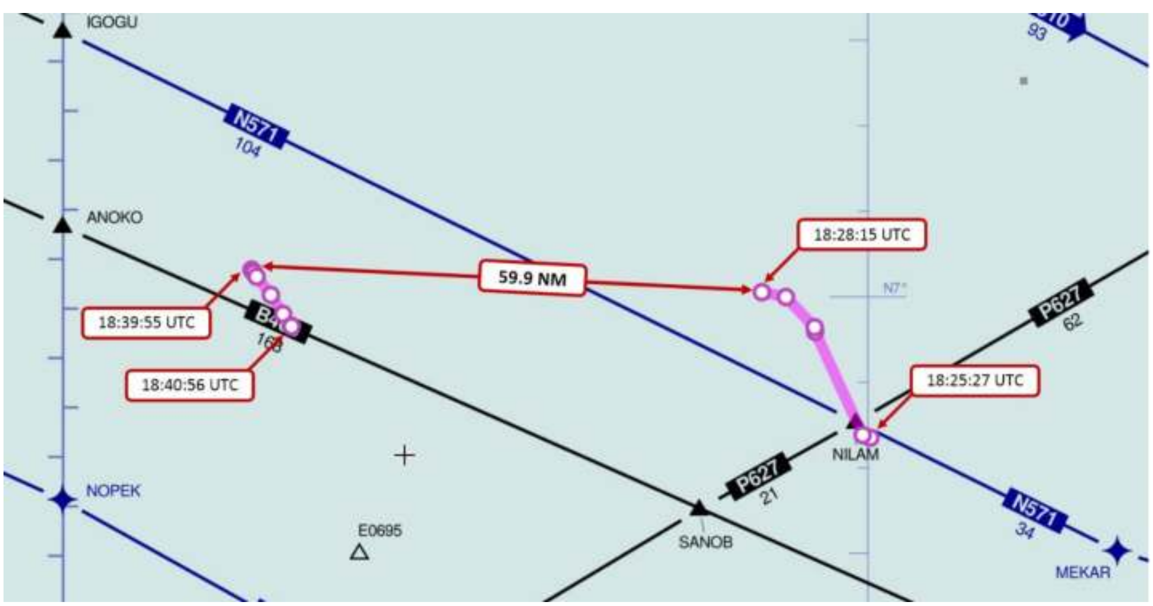
After being offline for about an hour, at 18:25:27 UTC (02:25:27 MYT) MH370's satellite communications (SATCOM) initiated a log-on to the Inmarsat satellite. The log-on process took 2 minutes and 47 seconds to complete and provided seven BTO/BFO data points. The seven complete data sets over a relatively short period of time allow for the airplane's position to be reasonably inferred. Based on those positions and knowing the time intervals, track and speed can also reasonably be inferred.

11 minutes and 40 seconds later at 18:39:55 UTC (02:39:55 MYT), an unanswered air-to-ground telephony call was placed to the airplane from the Malaysia Airlines Operations Centre. Over a period of 61 seconds 49 data points were recorded but only BFO data was captured (BTO data is not generated/captured for telephony). While the lack of BTO data might ordinarily render inferring the airplane's position problematic in this instance, because of the short interval between data points, the airplane's position, track and speed have been inferred. [33]

The two sets of airplane positions between 18:25:27 - 18:28:14 UTC (02:25:27 -02:28:14 MYT) and between 18:39:55 - 18:40:56 UTC (02:39:55 – 02:40:56 MYT) are illustrated at Map 2.

Based on the time intervals and distance travelled, the ground speeds calculated for the airplane are 421 knots for the first section and 415 knots for the second section. Accordingly, it would not be unreasonable to infer that the airplane was flying at a relatively constant speed.

That being the case, the 59.9 nautical mile gap between the two segments presents a problem. For the airplane to have taken 11 minutes 40 seconds to traverse the gap directly it would have had to fly at an improbably slow 308 knots.

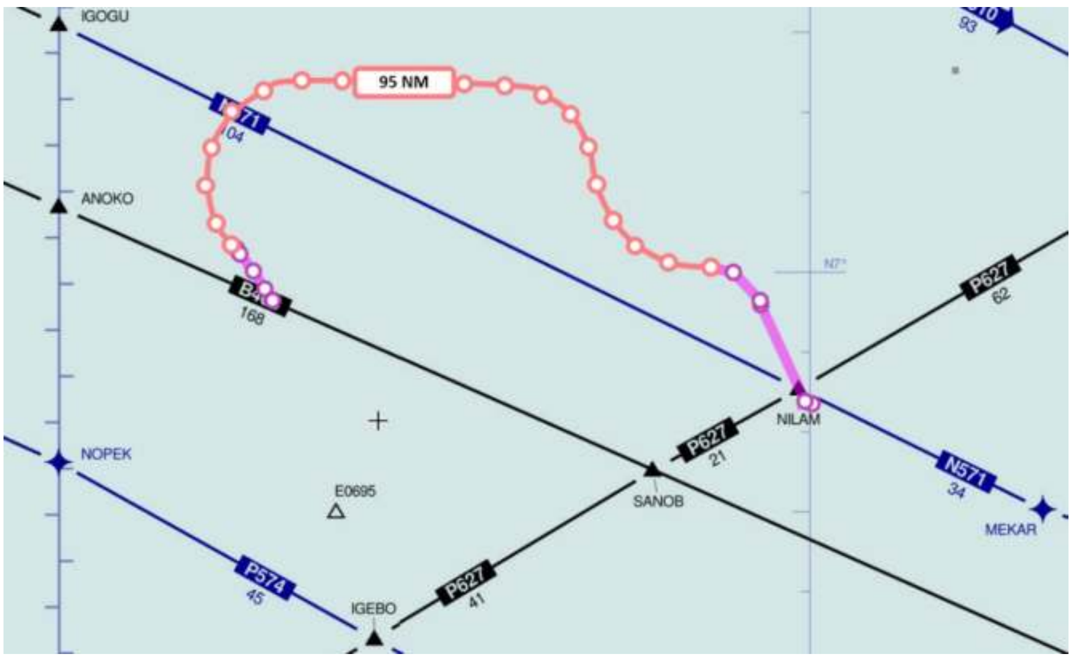


Map 2 MH370's positions between 18:25:27 - 18:28:14 UTC (02:25:27 -02:28:14 MYT) and between 18:39:55 - 18:40:56 UTC (02:39:55 – 02:40:56 MYT)

Possible Solutions

A wide variety of heading/altitude/airspeed changes can satisfy the problem of tracking from 7°0'33" N 95°47'29" E on an initial heading of 281° and arriving at 7°3'12" N 94°47'15" E on a heading of 145° after 11 minutes and 40 seconds. However if we assume a constant airspeed and no changes of altitude and work with standard 15° bank limited turns then the number of possible solutions is significantly reduced. One such solution is illustrated at Map 3.

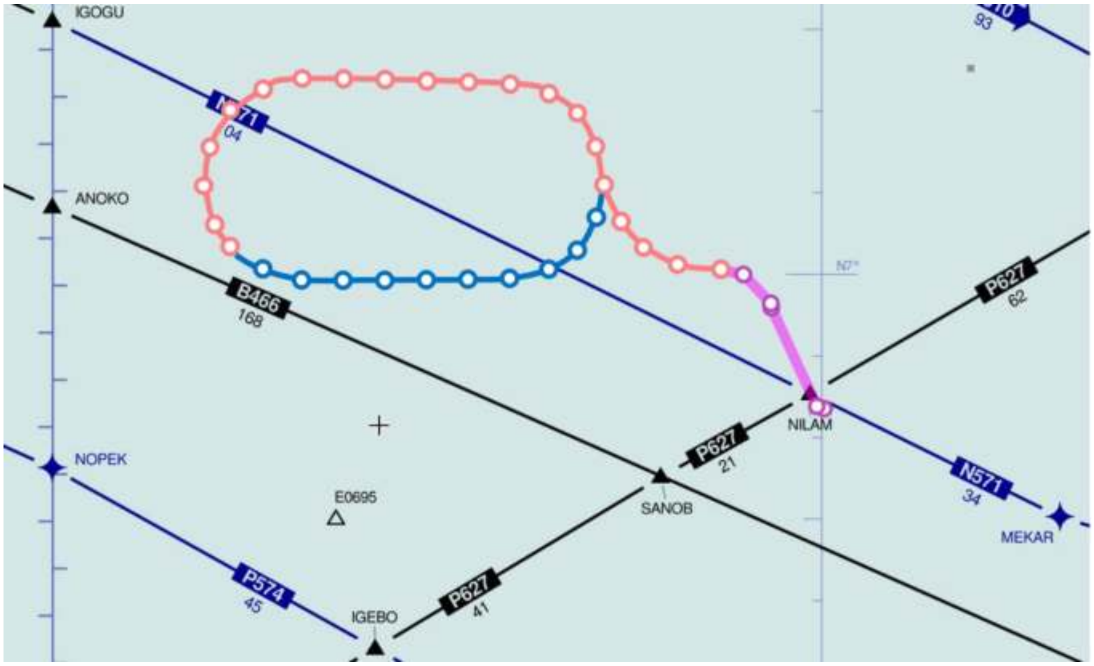
This track consists of a 90° turn to starboard followed by a 90° turn to port, tracking along a heading of roughly 280° for some 25 nautical miles followed by a 90° turn back to port and ending with a further 45° turn to port. All turns have a radius of about 12.8 nautical miles - the turning radius of a Boeing B777 at cruising speed with bank limited to 15° in nil wind. The total distance flown is about 95 nautical miles giving an average ground speed of 426 knots, which is broadly consistent with the entry and exit speeds.



Map 3 Possible solution for transiting the gap using standard 15° bank limited turns

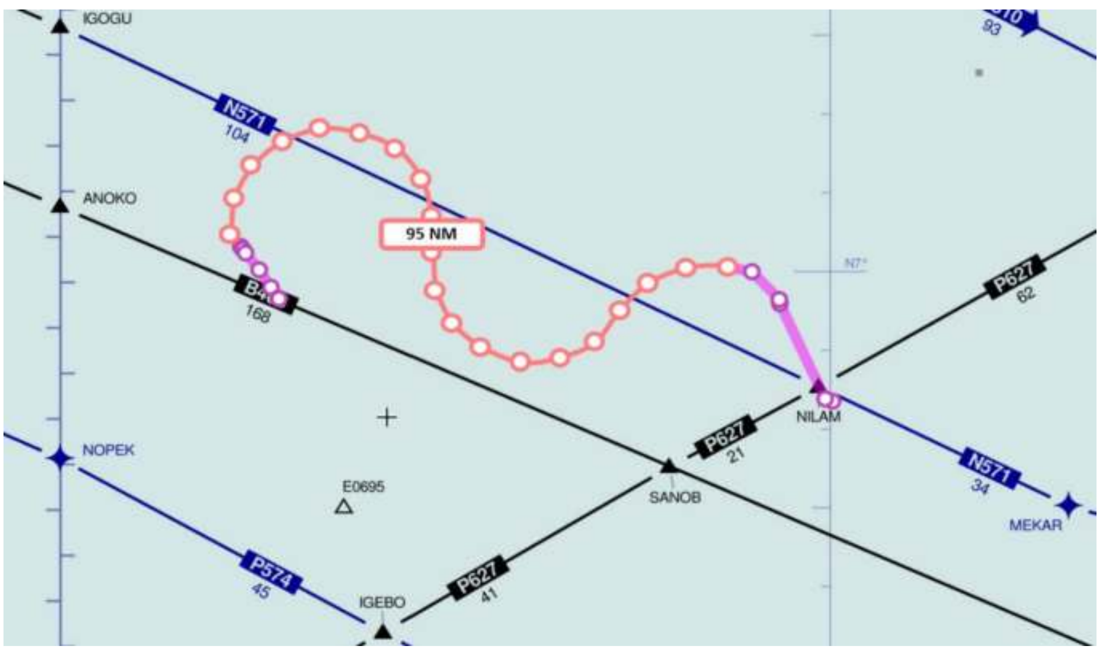
The hypothesised track is the first half of a standard racetrack pattern, as illustrated at Map 4. The track could be flown using the MCP autopilot in Heading Select (HDG SEL) or Track Select (TRK SEL) mode using no instruments (roll out to wings level would indicate that the airplane had settled on the selected heading) except for a watch or time piece. A watch is required to time the straight legs of the pattern.

The pattern was entered by flying North 000° off the track away from Penang then West 270° and then North 000°. The holding pattern itself may well have been a simple, symmetrical series of 2.5 minute manoeuvres; two 90° turns in one direction (eg North 000° then West 270°) each taking 2.5 minutes to complete, followed by a 2.5 minute straight leg followed by two 90° turns in the opposite direction (eg South 180° then East 090°) followed by another 2.5 minute straight leg giving a 15 minute repeatable pattern. The pattern can be flown using the autopilot MCP HDG SEL or TRK SEL function and a watch..



Map 4 The complete hypothesised Racetrack loiter manoeuvre

An alternative track to the racetrack pattern is illustrated below.

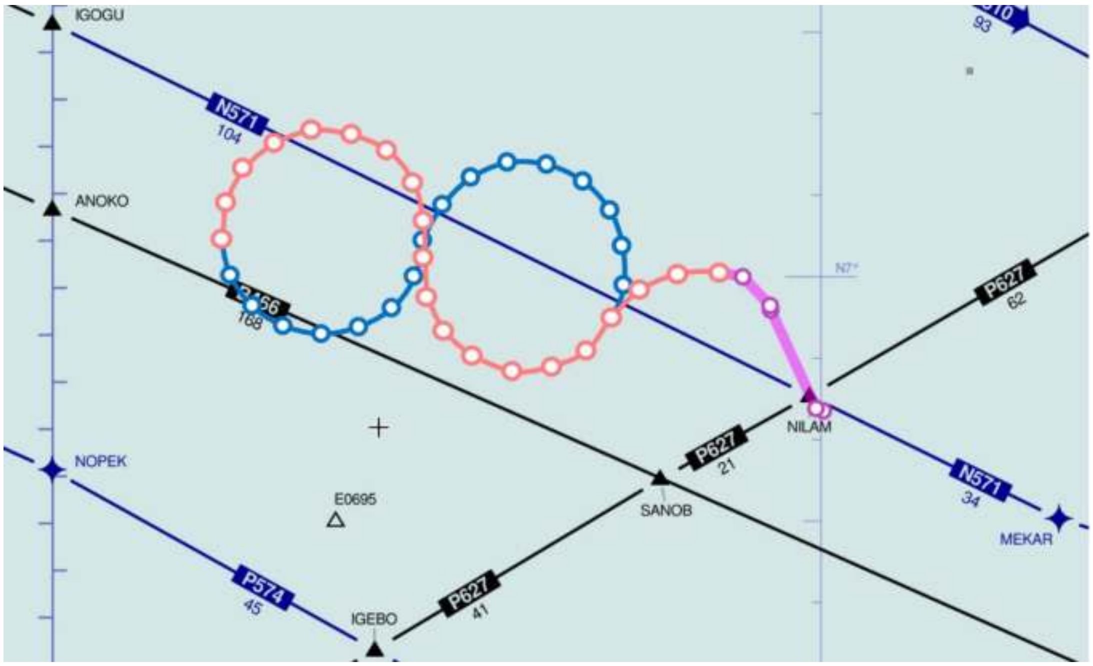


Map 5 Alternative possible solution for transiting the gap using standard 15° bank limited turns

The track consists of a 45° turn to port followed by a 90° turn to starboard followed by a 180° turn back to port. All turns have a radius of about 12.8 nautical miles. The total distance flown is again about 95 nautical miles giving an average ground speed of 426 knots, which is again broadly consistent with the entry and exit speeds.

This track could be flown using the MCP autopilot in HDG SEL or TRK SEL mode using no instruments; a watch with a seconds hand/display may have proved useful but would not be essential as there are no straight legs in this pattern. While figure 8 pattern is not an orthodox general aviation manoeuvre it is familiar to pilots of radio-controlled model airplanes (the Captain was known to be a radio controlled airplane enthusiast).

The hypothesised track represents the first half of a Figure 8 manoeuvre, as illustrated below.



Map 6 The complete hypothesised Figure 8 loiter manoeuvre

Possible Purpose

Regardless of the pattern flown - Racetrack or Figure 8 - it is not unreasonable to assume that the intent was to loiter the airplane at that location. Both the time and location of the manoeuvre are noteworthy. The loiter manoeuvre was initiated:

- 30 minutes after the airplane settled on its course away from Penang,
-
- With a visual reference to Banda Aceh at the north-west tip of Indonesia, and
- very shortly after the SATCOM rebooted.

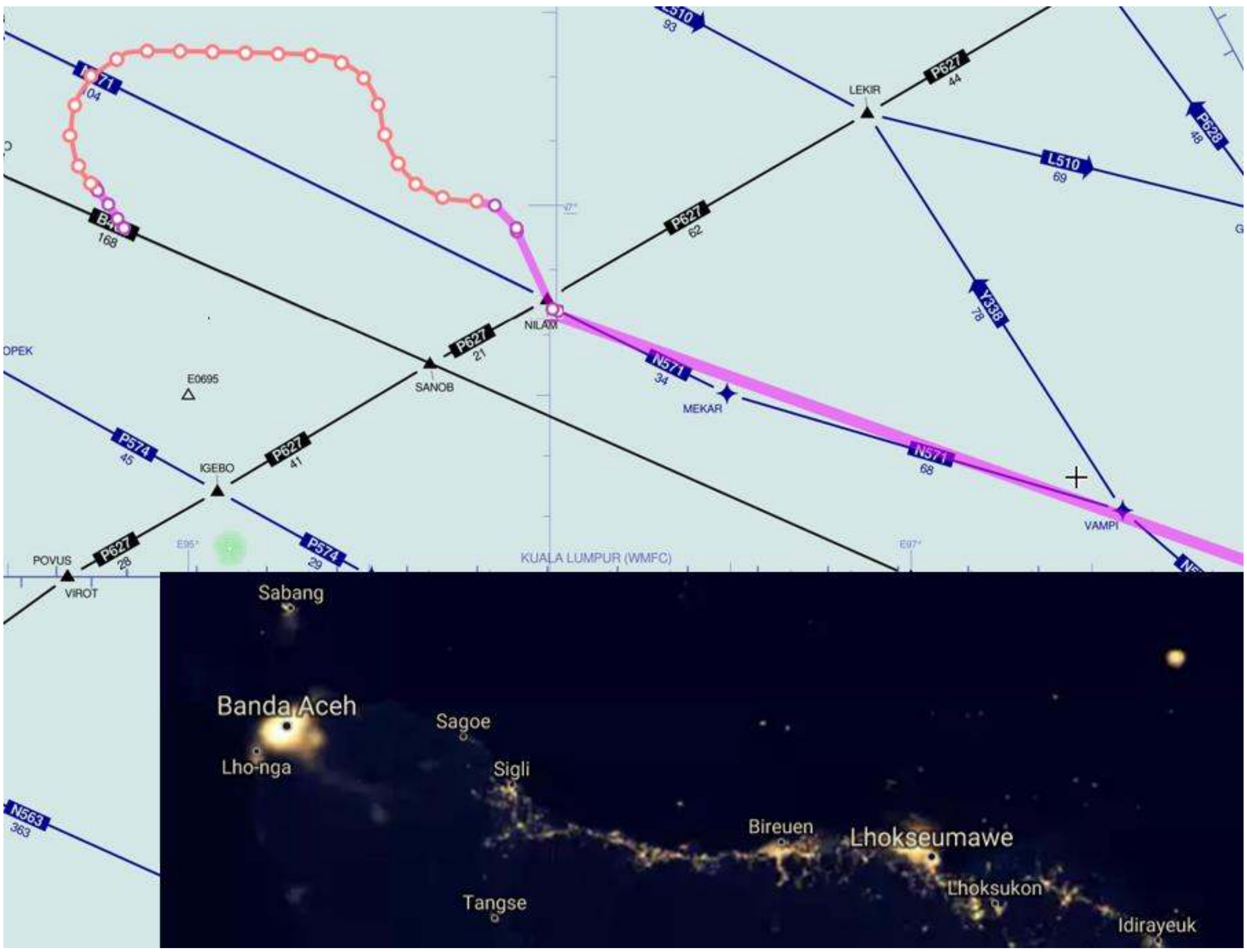
From the flight deck, there is only one way to remove power from the SATCOM Satellite Data Unit (SDU) in such a fashion that it can be subsequently restored; that is by isolating the Left AC Bus. There are two alternate methods of removing power from the SDU but both require leaving the flight deck. Accordingly, it might be reasonable to assume that the SATCOM rebooted subsequent to the Left AC Bus being reconnected.

Reconnecting power to the SDU around 18:25 UTC would have required a manual intervention. It is impossible to reconcile such an action with the “rogue pilot” theory. However, resetting the electrical buses or reconnecting the Left AC Bus are actions consistent with a crew attempting to restore communications and/or flight control functions.

The SATCOM rebooting concurrently with the airplane commencing what appears to be a holding pattern is not likely to be coincidental. Those actions are consistent with a crew attempting to recover the airplane.

Based on an interpretation of primary radar data presented by Victor Iannello in his 18 August 2015 paper *Some Observations on the Radar Data for MH370* [5] it appears that the approach to the manoeuvre was a track running from south of Penang through a point north of waypoint MEKAR to a point just south of NILAM; effectively a simple direct track on about 290°.

There is no compelling evidence that the airplane was being navigated in any sophisticated fashion and it was not tracking via waypoints. When the SATCOM log-on process first started Banda Aceh would have been clearly visible at about 7° forward of abeam. The map below, with the Indonesian coastline at night overlaid, shows the points at which the manoeuver commenced and completed with reference to Banda Aceh.



Map 7 The location of the hypothesised loiter manoeuvre showing its relationship to Banda Aceh (shown as visible at night).

Possible Explanation for Timing, Location and Track of Hypothesised Loiter Manoeuvre.

It is difficult to reconcile the events between 18:25 - 18:40 UTC (02:25 - 02:40 MYT) with the theory that deliberate and malicious direct action by a member of the crew, a "rogue pilot", was responsible for the disappearance of MH370. The "rogue pilot" theorists generally emphasise the technical prowess of the perpetrator in sending the airplane electronically dark and the desire to fly the airplane as far into the Southern Indian Ocean as possible. Reconnecting power to a communications device followed by a deliberate loiter are not only inconsistent with the objectives of stealth and maximum range, those actions are patently antithetical.

I have previously contended that the power to the SATCOM may have been disconnected inadvertently by the crew isolating the Left AC Bus in response to an electrical fire on the flight deck. One unintended consequence of that action would be to disengage the autothrottle which in turn precluded a descent using the MCP autopilot FLCH function. Reconnecting the bus may therefore have been an attempt to restore full autothrottle function. Further, power to the Centre VHF radio and the Centre Radio Tuning Panel would have also been disconnected when the Left AC Bus was isolated, reconnecting the bus may have also been part of an attempt to restore communications.

In a fire damaged airplane wholly reliant on the autopilot remaining engaged for safe flight, reconnecting the Left AC Bus would not be without some risks. Accordingly, it might be expected that such an action would be performed only once the airplane was safely away from populated areas such as Penang and the heavily trafficked shipping lanes of the Strait of Malacca in the event the autopilot disengaged. In the absence of data from the airplane's navigation system, such a safe location might be estimated by timing the flight away from Penang for 30 minutes and with visual reference to the Indonesian coastline, in particular Banda Aceh. A loiter manoeuvre such as that hypothesised above would be logically consistent with an attempt to restore autoflight function and/or communications while remaining proximal to Penang.

A possible sequence of events might therefore have been:

1. Navigate MH370 away from Penang on a simple heading of 290° using MCP HDG SEL or TRK SEL.

2. Time the flight away from Penang for 30 minutes to arrive in a safe location using Banda Aceh as a visual reference.

3. Attempt to restore the autothrottle/communications by reconnecting the Left AC Bus.

4. Initiate a loiter manoeuvre using a visual reference point such as Banda Aceh so as to remain proximal to Penang.

Hypothesis

The following is entirely speculation on my part but it is guided to a large degree by research and precedent accidents. It provides an internally consistent narrative that offers possible and plausible explanations for all observed events; it explains the evidence but that does not mean that it is supported by the evidence. As yet there is no evidence that MH370 suffered a windshield heater fire.

Windshield Heater Fire and Crew's Initial Response

As alluded to previously, I believe that MH370 suffered a windshield heater related incident involving the Captain's windshield shortly before arriving at waypoint IGARI. At the first sign of smoke, a burning smell or a fire, the crew's initial reaction would have been to don their oxygen masks. In keeping with prior windshield heater fire incidents the fire most likely would have broken out around the frame of the Captain's windshield.

After donning his oxygen mask, the Captain's would then have ordered the First Officer to identify the nearest airport and initiate a diversion. When the First Officer called up the Alternate page on the FMC it would have listed:

1. WMKC Kota Bharu. 89.8 nautical miles 13.1 minutes
2. WMKN Kuala Trengganu. 97.2 nautical miles 14.1 minutes
3. VTSS Songkhla. 190.4 nautical miles 24.8 minutes
4. WMKD Kuantan. 190.4 nautical miles 24.8 minutes

All four airports were closed at that time of the night so there would almost certainly have been some initial confusion/discussion regarding the choice of diversion before settling on WMKP Penang which was some 220.6 nautical miles and 28.2 minutes away.

The delay in selecting Penang as the diversion may well account for the initial right turn; as the airplane approached IGARI, the Flight Management System would have commanded a right turn to 059° to track towards their next waypoint, BITOD. Having decided on Penang the First Officer would have almost certainly commanded the diversion using the autoflight Lateral Navigation (LNAV) mode to track direct to KENDI (the intermediate fix for an instrument approach to land on Penang's Runway 04). Upon the First Officer executing the diversion command, the airplane would have stopped the right turn towards BITOD and then turned left back towards KENDI and Penang.

I suspect that the Captain got out of his seat to retrieve the cockpit fire extinguisher and fight the fire (a small fire burning directly in front of him may have provided an additional incentive for him to leave his seat). In order to reach the fire extinguisher the Captain would have either had to take his mask off or have it torn off his face or torn from its mount when the hose reached full extension. (All of those possible circumstances result in 100% oxygen venting onto the flight deck, only the rate of venting varies.)

In any event, the Captain would have then either:

- donned the Portable Breathing Equipment (PBE) – a smoke hood with its own 15 minute supply of pressurized oxygen - which was stowed right beside the fire extinguisher and, while somewhat cumbersome, was designed for use in just such a situation, or

- donned one of the observer's oxygen masks at the rear of the flight deck.

If the Captain had donned the PBE he was then out of communication with the First Officer as the PBE is not connected to the airplane's communication system; this would have left the First Officer to work the Smoke, Fire or Fumes checklist. Having identified the source of the fire as the Captain's windshield the First Officer would have first turned the windshield heat off on the overhead panel; in keeping with other windshield heater fires, this action would have had no effect.

A distress call is a memory item, it does not appear on the checklist. Further, as the Captain had been handling the radios for the flight up till this point, making a radio call may not have been front of mind for the First Officer.

Given the evidence that the crew oxygen system was leaking I suspect that one or more of the mask hoses had been incorrectly or poorly fitted when they were replaced on 17 January 2014. This suspicion leads me to believe that when the Captain's mask hose reached full extension, the hose became physically detached from its mount. This would have caused oxygen to begin flowing onto the flight deck at the rate of 30 litres per second. Apart from rapidly oxygenating the cockpit atmosphere, the venting would also have rapidly depleted the oxygen supply for the crew oxygen system; total depletion would occur in about three minutes.

Within 20-30 seconds of the Captain's mask hose disconnecting the oxygen concentration of the flight deck atmosphere would reach 23%; this would cause the fire to flare violently sending a blast of heat across the flight deck ceiling. It is worth noting that the stowage box for the Captain's oxygen mask is oriented to facilitate a clean extraction of the mask; as such it is angled up, back and in. The oxygen mask hose connects into the bottom of the stowage box. If the Captain's oxygen mask hose disconnected from its fitting at the base of the stowage box the resulting venting would be directed up, back and in, in the direction of the left overhead panels. The wave of intense heat would have started tripping circuit breakers, including those for the left transponder, the left autothrottle servo motor and the left and centre VHF radios. The rapidly tripping breakers would have generated a slew of EICAS messages, further distracting an already busy First Officer. Additionally, the violent flaring of the fire may well have injured either or both the pilots. The loss of the left transponder would terminate transmission of airplane data on S-band via secondary surveillance radar; the loss of the left VHF radio meant that the active radio was dead; and the loss of the left ASM would disengage the autothrottle.

One of two events then followed; either

- the Generator Control Unit and Electrical Load Management System responded to the voltage/frequency spike caused by the rapidly tripping circuit breakers on the left overhead panel by isolating the Left AC Bus, or

- in response to the worsening emergency the flight crew isolated the Left AC Bus in a desperate and creative attempt to remove power from the source of the fire.

In either case, another slew of EICAS messages would have been generated and power to the SATCOM would have been cut.

Around this time the First Officer would have almost certainly commanded a descent to 10,000 feet using MCP FLCH however, with the autothrottle disengaged, the airplane would not have responded. It is likely that at this point the First Officer would also have made a distress call but the active VHF radio was now dead.

Depressurisation event

With the concentration of oxygen on the flight deck now continuing to increase, the fire would have propagated rapidly and violently, possibly forcing one or both pilots from the flight deck. However, the fire would have only burned for a couple of minutes before one of two hitherto unprecedented events occurred; either:

- the Captain's windshield would have failed, or
- the oxygen-fed fire would have burned through the fuselage.

While there has not yet been an instance of a windshield failing in flight due to fire, there have been cases where the airplane has started to depressurise subsequent to the windshield cracking as a result of the failure of the windshield heater. Despite Boeing's requirement that the windshield must withstand a differential pressure load of 11.8 psi for at least 15 minutes with all panes of glass fractured on 3 July 2012, an Air France B777-200, registration F-GSPL on route AF085, flying from San Francisco to Paris at FL370 declared an emergency over Hudson's Bay. [34] The windshield heater had failed, multiple panes had cracked and the airplane could not maintain pressurisation.

Moreover, the Boeing requirement assumes that while the panes may have cracked, the various urethane interlayers remain intact and undamaged. A fire burning along one edge of the windshield assembly would significantly soften and weaken the interlayers. It is instructive that the oxygen-fed fire that damaged the flight deck of EgyptAir B777 registration SU-GBP was sufficiently hot to cause the inner pane of the First Officer's windshield to deform (melt) and separate from the frame. Accordingly, it is not beyond the realms of possibility that the windshield may have failed partially along the lower frame adjacent to the windshield heater terminal block.

However, while also unprecedented for an airplane in flight at cruise altitude, the alternative, a hull burn-through, was probably more likely.

Photograph 2 shows the damage caused to the forward starboard fuselage of EgyptAir B777 registration SU-GBP that suffered an oxygen fire whilst on the ground at Cairo International Airport on 29 July 2011. It took only a few minutes for the fire to burn two holes - one 76 centimeters by 41 centimeters, the other 25 centimeters by 10 centimeters – through the fuselage adjacent to the First Officer's oxygen mask stowage box. The metal tubing visible towards the bottom of the larger hole (inset) is the stainless steel oxygen supply tubing for the crew oxygen system that carries compressed oxygen from the storage bottles in the MEC to the crew mask hoses.

Photograph 2 Damage to forward starboard fuselage of EgyptAir B777 registration SU-GBP, at Cairo International Airport, 29 July 2011.

While the damage to SU-GBP's hull is significant in flight at cruising speed and altitude three factors combine to make such extensive damage highly unlikely. Aluminium alloys are used extensively in the manufacture of the surfaces for airplane fuselages, wings and empennages. While the aluminium alloys used in airplane construction (Al 2024(2XXX)-T3, -T42, -T36 alloys are used for the fuselage of the B777 [35]) have a relatively low melting point – in the range of 500°C - 655°C (930°F - 1210°F) – no inflight fire at cruise altitude and speed has yet managed to cause a hull burn through despite fires reaching temperatures of around 660°C (1220°F). This outcome is largely because of the combination of three factors:

1. The relatively high specific heat capacity of aluminium alloys,

2. the relatively high thermal conductivity of aluminium alloys, and

3. the aerodynamic cooling effect of sub-zero air passing rapidly over the skin of the airplane.

The specific heat capacity of aluminium alloys (816 - 1050 J/kg - °K) is approximately twice that of steel. This means that it takes twice as much heat energy to raise the temperature of aluminium by one degree as compared to a similar mass of steel. Accordingly, in any fire, aluminium alloys are relatively slower to heat. [36]

The thermal conductivity of aluminium and its alloys is 88 - 251 W/m - °K, which is several times the value for steels (11 - 63 W/m - °K). Thus, heat from a localised source will be distributed along an aluminium structure in an efficient manner. This is effective in preventing localised "hot spots". [36]

The fact that aluminium alloys are relatively slow to heat and distribute heat efficiently have combined with the aerodynamic cooling effect of the rapid passage (around 480 knots) of cold air (around -50°C) at cruising altitudes to prevent hull burn throughs in two very notable aviation accidents;

- The loss of South African Airways Flight 295, a Boeing 747 combi named "Helderberg", that suffered an inflight fire in the cargo area on a flight from Taiwan to South Africa and crashed into the Indian Ocean east of Mauritius on 28 November 1987 [37]; and

- The loss of Swissair Flight 111, a McDonnell Douglas MD-11, that suffered an inflight fire in the ceiling space above the flight deck while on a flight from New York to Geneva and crashed into the Atlantic Ocean at the entrance to St Margarets Bay, Nova Scotia on 2 September 1998. [38]

In both cases fires burned as hot as 700°C (1290°F) adjacent to the skin of the fuselage without burning through. The FAA has conducted a number of studies and estimates that the combined cooling effect of the three factors reduces the temperature of the exposed airplane skin by about 260°C (500°F) and thus prevents the aluminium alloys reaching melting point. [39]

However, an oxygen-fed fire would have burned at around 1200°C – 1400°C (2190°F - 2550°F), more than twice as hot as the fires that brought down the *Helderberg* and Swissair 111 and those studied by the FAA. A 1200°C fire burning close the skin of the airplane would have quickly overcome the cooling effects and have sufficiently heated a section of the fuselage such that it reached melting point and failed under the force exerted outwards by the cabin pressure inside the airplane. The thermal conductivity of aluminium alloy would mean that the area of fuselage that reached melting point would be somewhat larger than just the localised hot spot immediately adjacent to the heat source. However, because the fire would have been extinguished almost immediately by the rapid cooling caused by the cabin air escaping, the size of the burn through would be much smaller than either of the two burn throughs on EgyptAir B777 SU-GBP.

It is difficult to conceive what a hull burn through at 35,000 feet would look like to an observer on the ground but one might reasonably conclude that it might be described as a "burning object". That was oil rig worker Mike McKay's description of what he saw from the deck of an oil rig off the coast of South Vietnam. McKay's observed a "burning object" low on the horizon and subsequently disappearing below the horizon at around the time MH370 was turning back towards Penang. The direction that McKay nominated is generally consistent with where MH370 would have appeared and, given the distance involved, the airplane would have been quite low to horizon.

In either case, a partial windshield failure or, more probably, a hull burn-through, a rapid depressurisation would follow. The rapid outflow of air and the sudden cooling caused by the depressurisation would have extinguished the fire. Around the same time as the depressurisation event, the crew oxygen system would have been completely depleted of oxygen. If the flight deck door was closed the sudden change in pressure would cause it to unlatch and the rapidly escalating pressure differential between the flight deck and the main cabin would force it to open - this safety feature is designed to prevent the bulkhead between the flight deck and the main cabin from collapsing in the event of a flight deck depressurisation.

The basic autopilot function is highly protected and runs on redundant systems and would have completed the left turn and kept MH370 tracking towards Penang on 240°.

Figure 4 illustrates the sequence and timing of both observed and hypothesised events during the crucial three and half minute period from when the Captain replied to Kuala Lumpur Area Control Centre (ACC) "*Good night, Malaysian Three Seven Zero*" to the hypothesised depressurisation event and serves to highlight the rapid onset of events. (A more complete and detailed timeline is included at Appendix 1 MH370 – Timeline of Actual and Hypothesised Events)

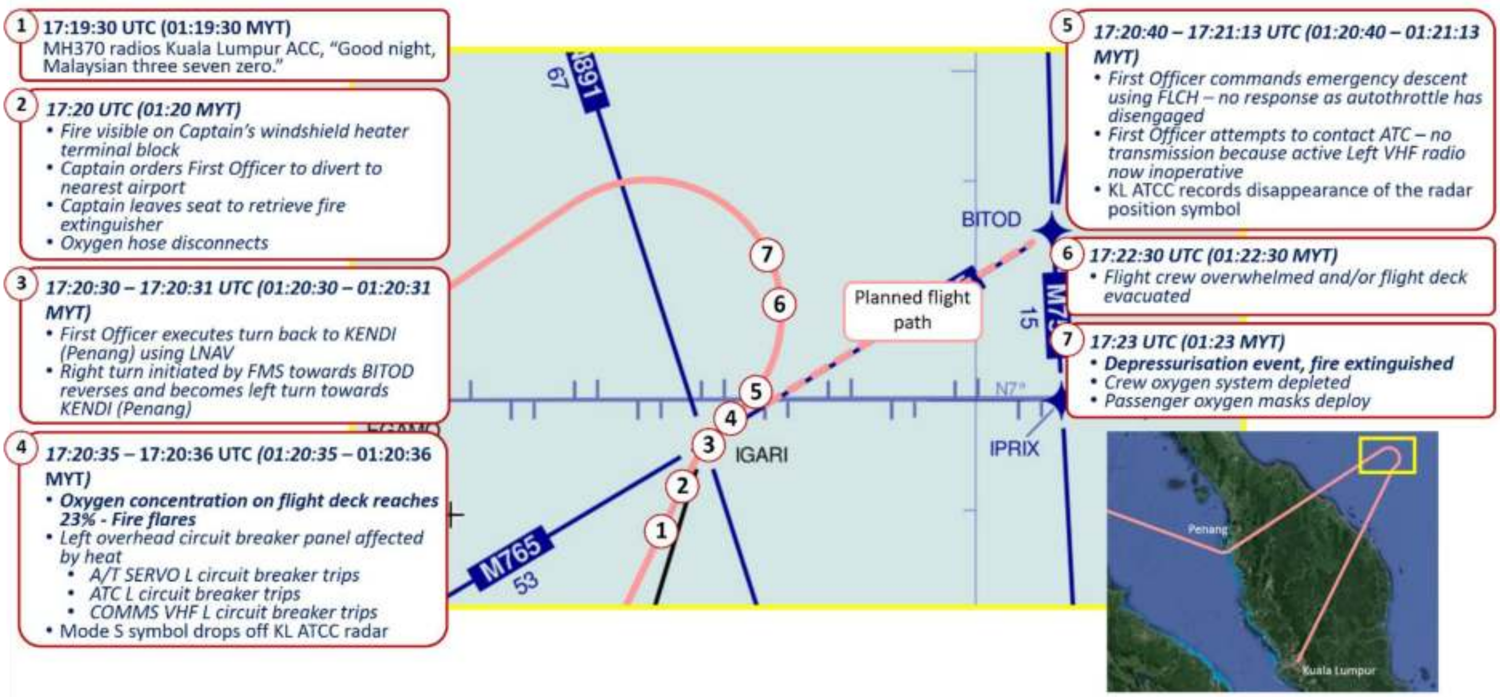


Figure 4 Timeline of Actual (normal typeface) and Hypothesised (in italics) Events during the critical 3.5 minutes between 17:19:30 UTC – 17:23:00 UTC (01:19:30 MYT – 01:23:00 MYT)

Immediately upon depressurising the passenger oxygen masks in the main cabin would have deployed. The passenger oxygen system uses chemical oxygen generators and continuous flow masks that have inhalation and exhalation check valves. Because the inhalation check valves on the masks dilute the supplied oxygen with the ambient atmosphere, at 34,000 feet the passenger oxygen generators cannot provide sufficient partial pressure of oxygen in the lungs to maintain consciousness without considerable conscious respiratory effort. [40] People unfamiliar with hypoxia would have simply lost consciousness and died after 20-22 minutes when the oxygen generators burned out [41]. A flight or cabin crew member may have recognised the early symptoms of hypoxia and started deep, forceful breathing and remained conscious. The PBE, which provides unpressurised but undiluted 100% oxygen to the wearer, would have offered the best chance of remaining conscious after the depressurisation.

Damage to the flight deck

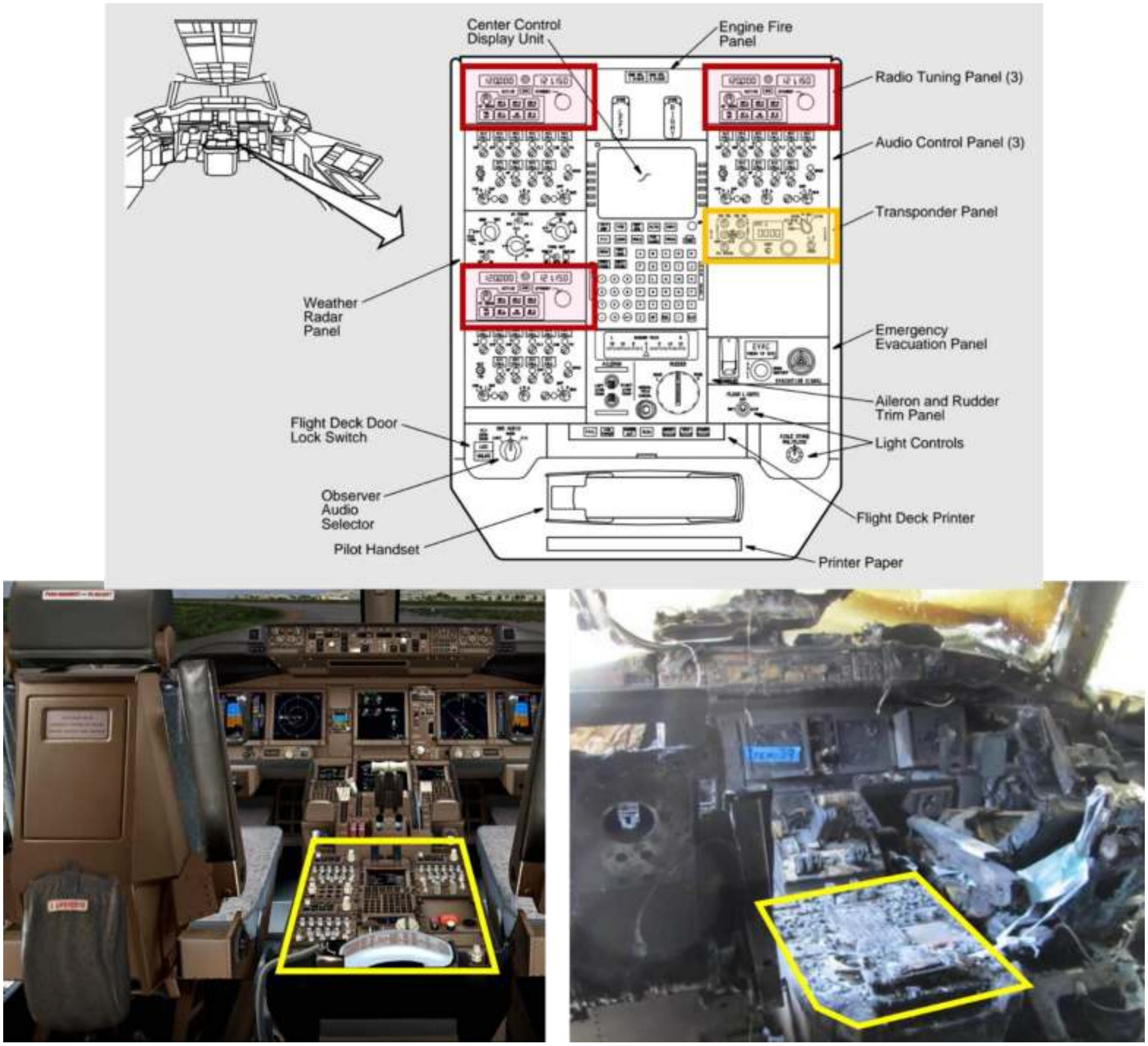


Figure 5 *Location and configuration of the Aft Aisle Stand Panel (top) highlighting location of the three Radio Tuning Panels (red) and Transponder Panel (orange), together with photographs of pristine flight deck and fire damaged flight deck of EgyptAir B777 registration SU-GBP highlighting the panel (yellow).*

The fire damage to the flight deck would have been something akin to EgyptAir B777 SU-GBP with the additional problems of being both noisy and cold (probably around -20°C; the main cabin, being further removed from the source of the depressurisation, would have been less cold). The cockpit displays are liquid crystal and quite vulnerable to heat damage, in all likelihood they would have all been rendered unusable. There are no analogue back-up instruments on the B777 making instrument flying impossible. Moulded plastics such as keypads and switches together with oxygen masks and hoses, headsets and microphones would have been burned or melted.

In a quirk of design on the B777 all the audio, radio and transponder controls are mounted on the Aft Aisle Stand Panel, a 40 centimeter by 50 centimeter "centre console" located between the two pilots (see Figure 5). All the splendid redundancy associated with two transponders and five radios (three VHF and two HF) on the B777 comes together at this relatively compact single point of failure. On at least one occasion on a B777 a mishandled beverage spilled onto the Radio Tuning Panel has caused a significant communications failure. [42]

There would have been only very poor visibility from the cockpit - it would be almost impossible to look through the damaged windshield and all the other windows would have been covered with soot from the fire and would also be rapidly accumulating frost. Adding to the inhospitable environment was the lack of oxygen on the flight deck.

For someone to get back to the cockpit would have taken considerable effort as they would have needed to retrieve one of the portable walk-around oxygen bottles - one bottle would give them 15 minutes of oxygen - or one of the extra PBEs. Then they would need to brave the cold and the noise. Accordingly, I expect that excursions to the cockpit would have been brief.

Impact of burn through damage with fixed thrust setting

With the autothrottle disengaged the airplane would be flying with a fixed thrusting, essentially "inheriting" the thrust that was set at the time the FLCH function was engaged. This setting would be equivalent to the cruise thrust appropriate for the airplane weight and altitude at that time of the flight.

As mentioned previously, FLCH uses "speed-on-elevator" mode; in this mode the elevators are used to control speed and the autothrottle controls the flight path. The target speed is also "inherited"; it is whatever speed is showing in the MCP Mach/IAS window at the time FLCH is engaged. We know from the 17:07:48 UTC (01:07:48 MYT) ACARS transmission that MH370 was in an established cruise at FL350 at Mach 0.821 (CAS = 278.4 knots). [43] At the point at which the diversion was commenced the airplane was probably flying closer to M0.83 (IAS = 283 knots) and this speed would have been inherited as the target speed.

The hole in the side of the fuselage from the burn through would have generated some additional drag. With fixed thrust, this would have the effect of slowing the airplane down; how much the airplane was slowed would depend on the amount of drag and this in turn would depend on both the size and location of the burn through. Given that the size of the burn through would have been limited as previously explained, a slowing of 5-10 knots would not be an unreasonable estimate.

As the autopilot is now in "speed-on-elevator" mode it would seek to maintain its target speed by pitching the nose down. With cruise thrust set only a very small pitch down would be needed to pick up the required 5-10 knots. Consequently, the airplane would start a slow descent, perhaps something in the order of 20-30 feet per minute. As the airplane descended, a number of other factors would progressively come into play.
First, because the target speed is expressed as a fraction of the speed of sound (a Mach number) and the speed of sound is proportional to the square root of the absolute temperature, the target speed will slowly increase as the airplane descended into less cold air. The difference would be about 27 knots over 4,000 feet from FL350 to FL310. Accordingly, the airplane would speed up slowly from an IAS of around 283 knots at 35,000 feet to 310 knots at 31,000 feet. To achieve the slowly increasing target speed the autopilot would slowly increase the pitch down which in turn would slowly increase the rate of descent. If we assume an average rate of descent of 40 feet per minute, that 27 knot increase would occur over 100 minutes.

Second, as the airplane descended into denser air, the engines would produce more thrust. This increase in thrust would serve, in part, to offset the amount of pitch down required to match the target speed.

Third, the MCP target speed automatically changes from a Mach number to an IAS at 310 knots. Accordingly, when the airplane reached 310 knots at around FL310 its target speed would stabilise.

While all of these factors were playing out the airplane would be progressively getting lighter as it burned fuel. As the airplane got lighter it would have tended to fly faster. The autopilot would have responded to this by gradually pitching the nose up. Based on a fuel burn of some 43,800 kilograms between when the airplane became established cruise at FL350 at Mach 0.821 at 17:06:43 UTC (01:06:43 UTC) and fuel exhaustion at or around 00:17:29 UTC (08:17:29 MYT), an altitude increase of some 4,500 feet from 35,000 feet to 39,500 feet could be expected for a clean (ie no damage) airplane.

In the absence of understanding the size and location of the burn through, the net effect of all of these factors is difficult to determine but was most likely a gradual but slowly increasing descent with a slowly increasing airspeed for the first couple of hours down to around 31,000 feet, then a slowly decreasing rate of descent at 310 knots to a period of level flight followed by a gradual but slowly increasing ascent with a slowly decreasing airspeed before fuel exhaustion.

Turn away from Penang

I believe that at least one of the flight crew survived the fire and depressurisation event, possibly because they had donned the cockpit PBE, possibly because they were out of the cockpit retrieving an extra fire extinguisher when depressurisation event occurred, possibly both. There is a possibility that the surviving pilot was badly injured and may have been evacuated from the flight deck the assistance of another survivor, possibly a cabin crew member.

Upon re-entering the flight deck for the first time, the surviving crew would have had a lot to process in somewhat less than ideal conditions. They would have come to the realisation that they had no means of communication; the active VHF radio was dead and the radio communication panel keypads, microphones and headsets would have been burned or melted by the fire. MH370 carried an Elta ADT406 portable emergency locator transmitter (ELT) in the forward cabin right hand coat closet [44] and the crew may have tried using it to send a distress signal. However, the handheld ELT is not designed for use inside the airplane; the airplane fuselage would act like a Faraday cage and shield the signal so trying to get line of sight to a satellite through a window would be highly problematic. Moreover, the battery would have been short-lived given the freezing temperature (the batteries are not rated to function in temperatures below -20°C). [45] They may have tried mobile phones but given their altitude and average maximum cell tower ranges of 35 kilometers any connection would have been fleeting at best and the batteries would have also quickly succumbed to the cold.

The crew would have also realised that the airplane had not descended or, at least, that it had not descended appreciably from its previous cruise altitude. However, determining the airplane's altitude and rate of descent would have been rendered almost impossible given the circumstances. First and most obviously, there were no instruments to confirm altitude, attitude or vertical speed. Second, the visibility through the flight deck forward windshields and side windows would have been marginal and it was a moonless night; that effectively eliminates the ability to determine altitude or a pitch down visually. The visibility issue would have been further compounded by the problem that the crew would have had nowhere to sit as it is most probable that the Captain's and First Officer's seats would have been destroyed by the fire is a similar fashion to those in the EgyptAir B777 ground fire. Accordingly, the orientation of the crew's eyes to the windshield and nose would probably have been elevated compared to normal and this may have, in turn, created the illusion that the airplane had pitched nose down.

If there was, as I suspect, a small burn through of the hull, the flight deck would have been quite noisy; that eliminates the possibility of determining that the engines had been retarded to flight idle aurally. Further, with the airplane in speed-on-elevator mode, a fixed thrust setting and a small hull burn through, the autopilot would have commanded a very shallow descent in order to hold airspeed. Under the circumstances, it is not difficult to envisage the crew convincing themselves that the airplane was nose down and descending.

The physical condition of the surviving crew would have also served to compound all of the foregoing factors further. The heat associated with an oxygen fed fire is extraordinary and I doubt that anyone could have made it off the flight deck without being burned. Accordingly, I suspect that either or both of the flight crew were injured, perhaps badly. On top of that they would have almost certainly have been suffering from some cognitive impairment from hypoxia; the portable bottles are not designed to maintain consciousness for extended periods at 35,000 feet. Under this combination of circumstances it is not difficult to conceive of a situation where the crew could not comprehend that the airplane was not descending rapidly enough and that the lack of an effective descent did not manifest itself as their primary problem.

Even if the failure to descend had manifested itself the crew would have quickly realised that there was no reasonable chance of manually flying the airplane; they had no instruments, it was night, there was no moon, visibility through the fire and smoke damaged windshields and windows was poor and they could only occupy the cockpit for short periods of time and only then with the aid of a portable oxygen bottle. Any attempt to take manual control of the airplane would almost invariably end with loss of control due to disorientation and there could be no guarantee that they could re-engage the autopilot if they disengaged it.

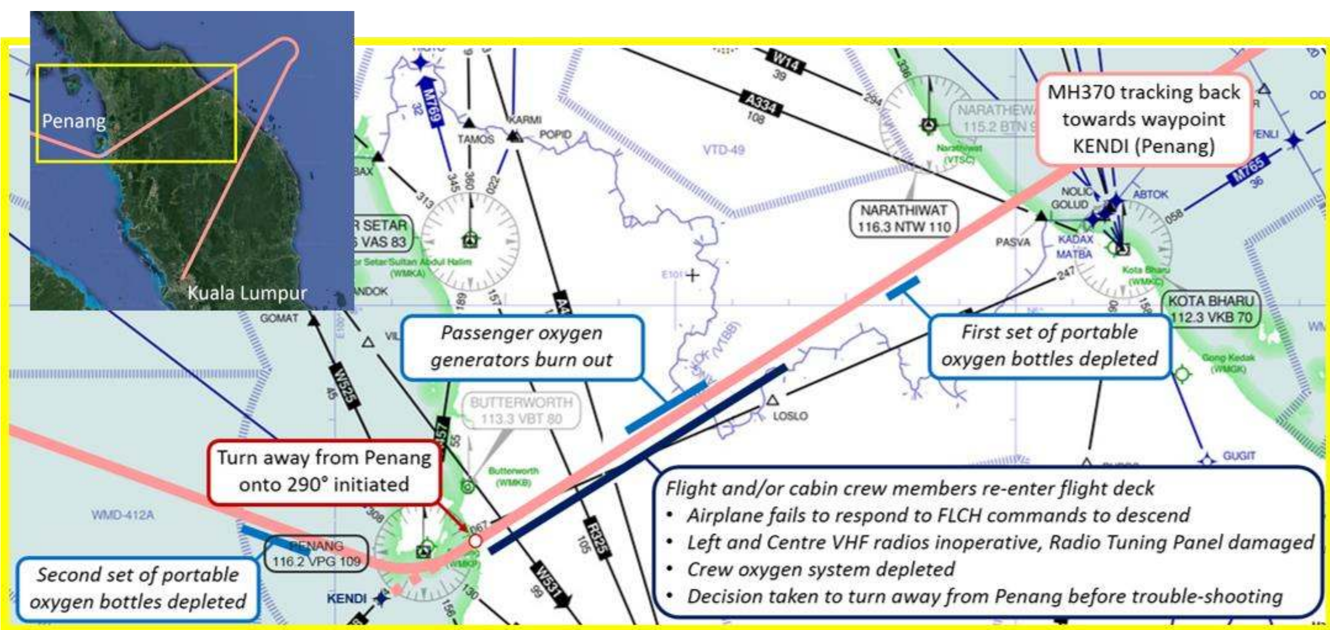


Figure 6 The transit of the Malay Peninsula and the turn-away from Penang

I suspect that the most pressing issue would have been the complete exhaustion of the crew oxygen system. If the surviving crew's plan had been to use a portable oxygen bottle to make their way back to the flight deck and then revert to using the crew oxygen system, that plan would now need to be radically amended.

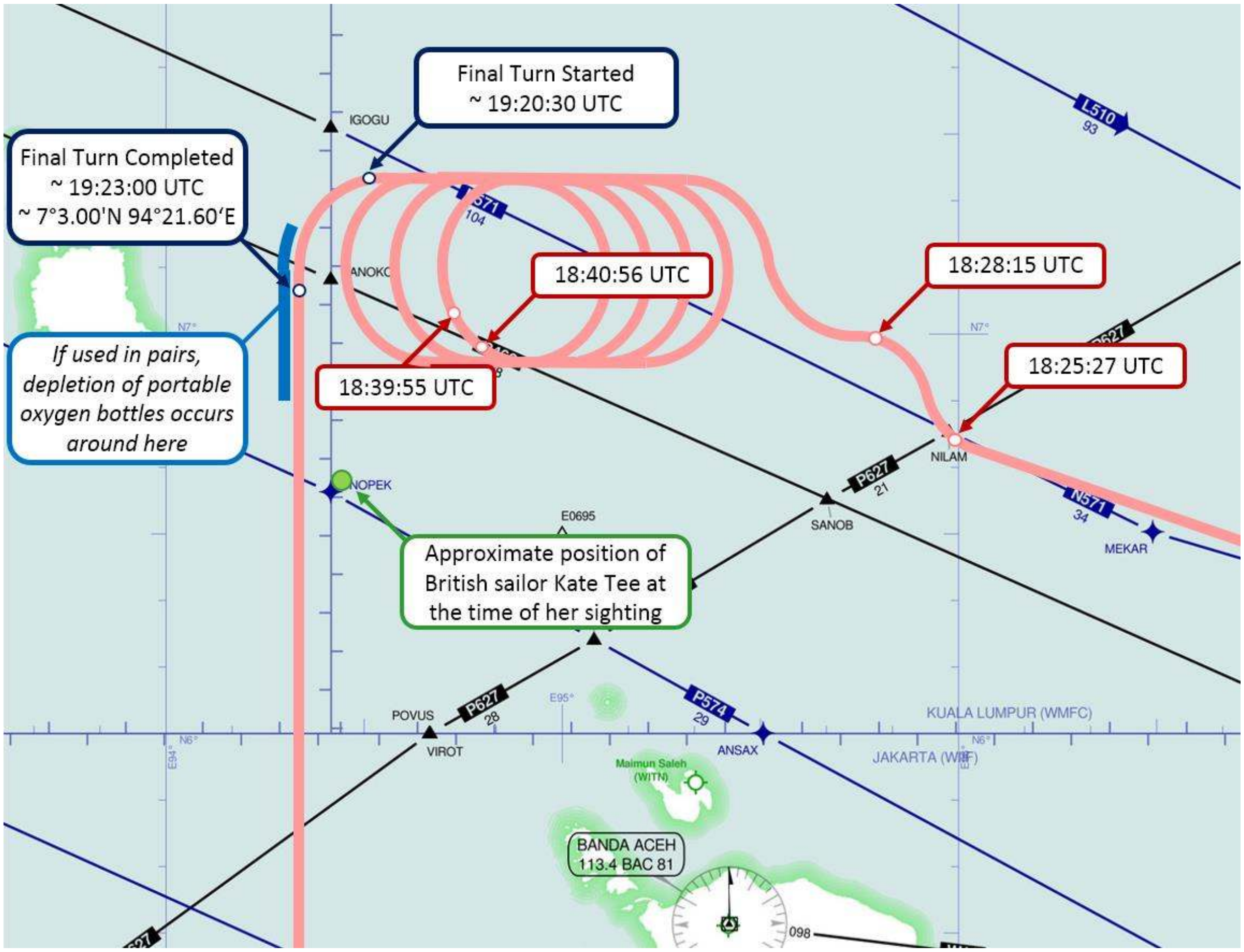
The combination of the extent of the damage and the lack of a long term oxygen supply on the flight deck would mean that the surviving crew did not have a lot of time to assess their situation much less attempt to rectify it. The emergence of Penang off the starboard wing would have perhaps been the first clear indication of their actual location. With their time on the flight deck limited they would have to conceive a plan quickly. To their right was the island of Penang, population 1.65 million. Immediately ahead and stretching 900 kilometers from the north-west to the south-east was the world's second busiest shipping lane, the Strait of Malacca, the conduit for trade from Europe and the Middle East to South East Asia. There would have been ships - tankers, chemical ships, container ships, bulk carriers and cruise liners - about every 5-6 kilometers along the Strait. 20 minutes further ahead lay nearly five million people, the inhabitants of Indonesia's North Sumatra province and that country's third largest city, Medan.

Given the situation I believe that the surviving crew then elected to do what many crews in stricken airplanes have done in the past; steer it clear of populated areas before attempting any troubleshooting. Accordingly, with only a few minutes of oxygen remaining in their portable oxygen bottles, they utilized the MCP autopilot TRK SEL or HDG SEL function and turned up the Strait of Malacca on the simple course of 290°, running parallel to but to the north of the shipping lane. The distance flown up the Strait, some 425 kilometers over about 30 minutes, may well have been a function of the crews need to source and position additional portable oxygen bottles before returning to the flight deck.

Loiter and final turn south

It appears that the airplane flew for 30 minutes away from Penang and then entered a loiter where there was a visual reference to Banda Aceh. Having that visual reference was the best safeguard against becoming spatially disoriented and losing control should the autopilot disengage.

At this time the pilot would have attempted to re-establish communications and/or to regain some additional flight functions such as the autothrottle; this may have entailed reconnecting the Left AC Bus, resetting the Right AC Bus or both. Reconnecting the Left AC Bus would have had the effect of reconnecting power to the SATCOM which then rebooted and started the sequence of satellite handshakes that allowed MH370 to be eventually tracked to the Southern Indian Ocean. In order to maximize the chance of their being spotted by other traffic or a Royal Malaysia Air Force fighter I expect that the crew most likely turned the landing lights on (the landing lights may explain British sailor, Kate Tee's account of seeing "… *just a plane glowing orange and surrounded by an orange glow like a halo*." [46] flying from north to south to the west of her position near approximately 6° 37.7' N, 94° 26.4' E although Ms Tee's account has been varied and inconsistent).



Map 8 Hypothesised manoeuvers at the top of the Malacca Strait showing westerly drift and a final turn south onto a track of 180° near 7°3.00' N 94°21.60' E at around 19:23:00 UTC (03:20:00 MYT).

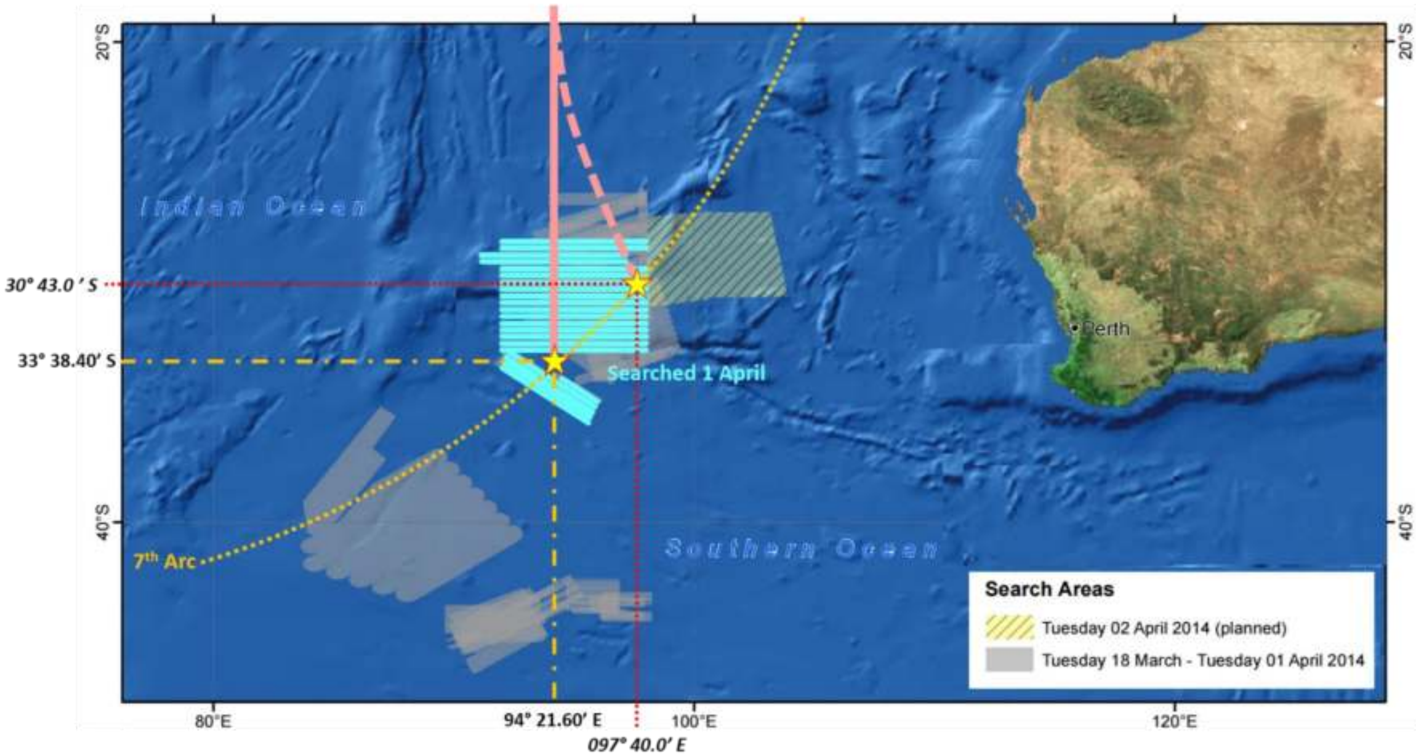
By the time the loiter was commenced the remaining crew would have been exposed to -20°C temperatures for over an hour and would have been starting to suffer from hypothermia. As previously discussed, the surviving crew would almost certainly have been suffering from some degree of cognitive impairment due to hypoxia.

Given the suite of circumstances discussed previously regarding their inability to discern the altitude, attitude and rate of descent, I don't think that it is difficult to envisage the crew convincing themselves that the airplane was nose down and descending slowly and that all they needed to do was maintain a loiter pattern. If there were two surviving crew members then at the point they commenced their loiter they would have used more than half of the stock of portable "walk-around" oxygen bottles; another pair of bottles would be depleted in the time taken to execute each loiter manoeuvre.

In any event, I believe that the final turn did not commence until around 19:20:30 UTC (03:20:30 MYT) and that the airplane rolled out onto a track of 180° somewhere near 7°3.00' N 94°21.60' E at around 19:23:00 UTC (03:20:00 MYT). This is some 52 minutes later than the time used by the ATSB for their modelling. I have arrived at this time for the final turn based on the time taken to complete the loiter pattern illustrated above and the fact that it is roughly coincidental with the time at which the eighth or, if used in pairs by two survivors, *the last* portable oxygen bottle would have been depleted.

End-of-flight

Moving to the end of flight, two impact sites are possible depending on which MCP autopilot mode was engaged – TRK SEL or HDG SEL. TRK SEL corrects for wind/drift and ensures that the airplane flies along the track selected whereas HDG SEL simply ensures that the nose of the airplane is pointed at the selected heading. Under normal circumstances HDG SEL would be the more commonly used MCP mode.



Map 9 Probable impact areas based on final turn south (180°) at the top of the Malacca Strait from near 7°3.00' N 94°21.60' E at around 19:23:00 UTC (03:20:00 MYT) using Track Select (solid path) and Heading Select (dashed path).

TRK SEL yields a straight flight path south that terminates on the 7th arc near 33°38.40' S 94°21.60' E. On the other hand, HDG SEL gives rise to a flight path that curves away to the east under the influence of the prevailing westerly winds and terminates with fuel exhaustion beyond the 7th arc. However, I have plotted the intersection of the flight path with the 7th arc to be near 30°43’ S 097°40’ E. The two possible impact sites are nearly 480 kilometers apart.

Flight path modelling against satellite data

As illustrated at Figures 7 and 8, when the two flight paths are modelled against the actual BTO and BFO readings using Barry Martin’s (Independent Group) BSM7.9.4 flight path model [47] (Barry has pointed out that this somewhat older model contains some minor errors with regards to magnetic declination) TRK SEL produces an extraordinarily good fit to both BTO and BFO, far better than the results for the more commonly used HDG SEL. Based on the modelling I tend to prefer 33°38.40' S 94°21.60' E as the more likely crash site but I cannot discount 30°43’ S 097°40’ E on the basis that HDG SEL is the more commonly used MCP mode. I expect that the sunken wreckage of MH370 will be found within 50 kilometers of either of those two locations – a search area of some 15,750 square kilometers.

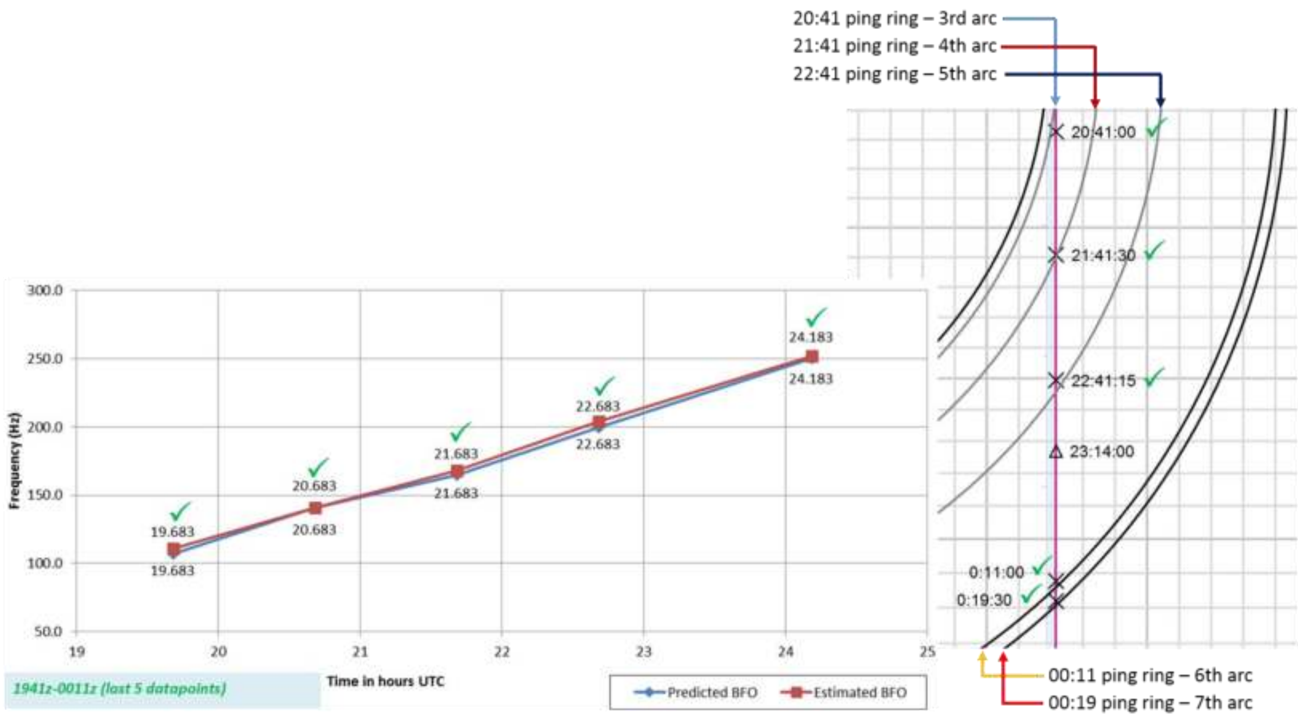


Figure 7 Modelled BTO and BFO outcomes for final southern leg using TRK SEL showing very good fits to both BFO and BTO data

33°38.40' S 94°21.60' E is about 695 kilometers north east of the ATSB hot spot and just inside the 120,000 square kilometer search area (roughly 50% of a 50 kilometer radius search area has already been searched, the remainder, mainly to the north, has not). The ATSB modelling assumed an undamaged, intact airplane with an operational autothrottle flying in economy cruise mode and favours flight paths to the 7th arc that are longer (ie an impact site that is to the south-west along the 7th arc). Factoring in the additional drag from a burn through makes shorter paths that use more fuel over the same period of time more likely. A southerly track on 180° gives a total flying distance from IGARI to fuel exhaustion that is 190 kilometers (or roughly 4%) shorter than that modelled as most likely by the ATSB.

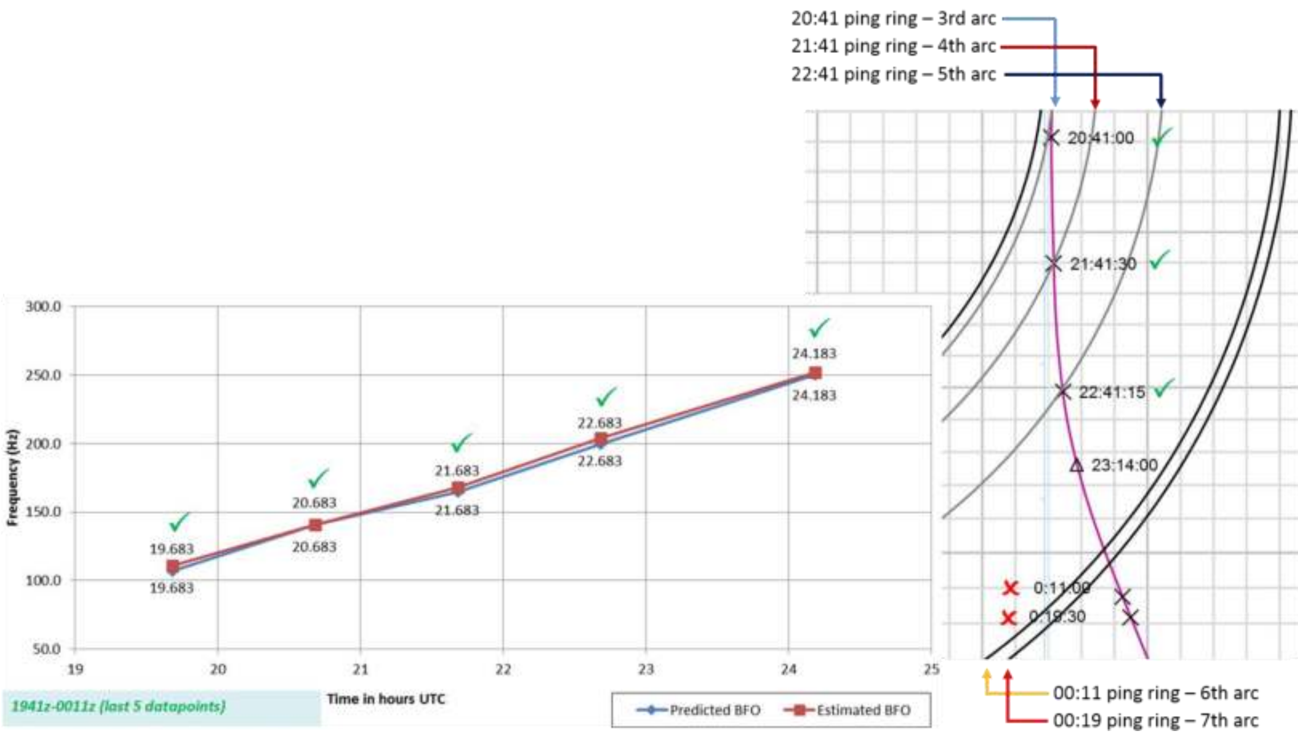


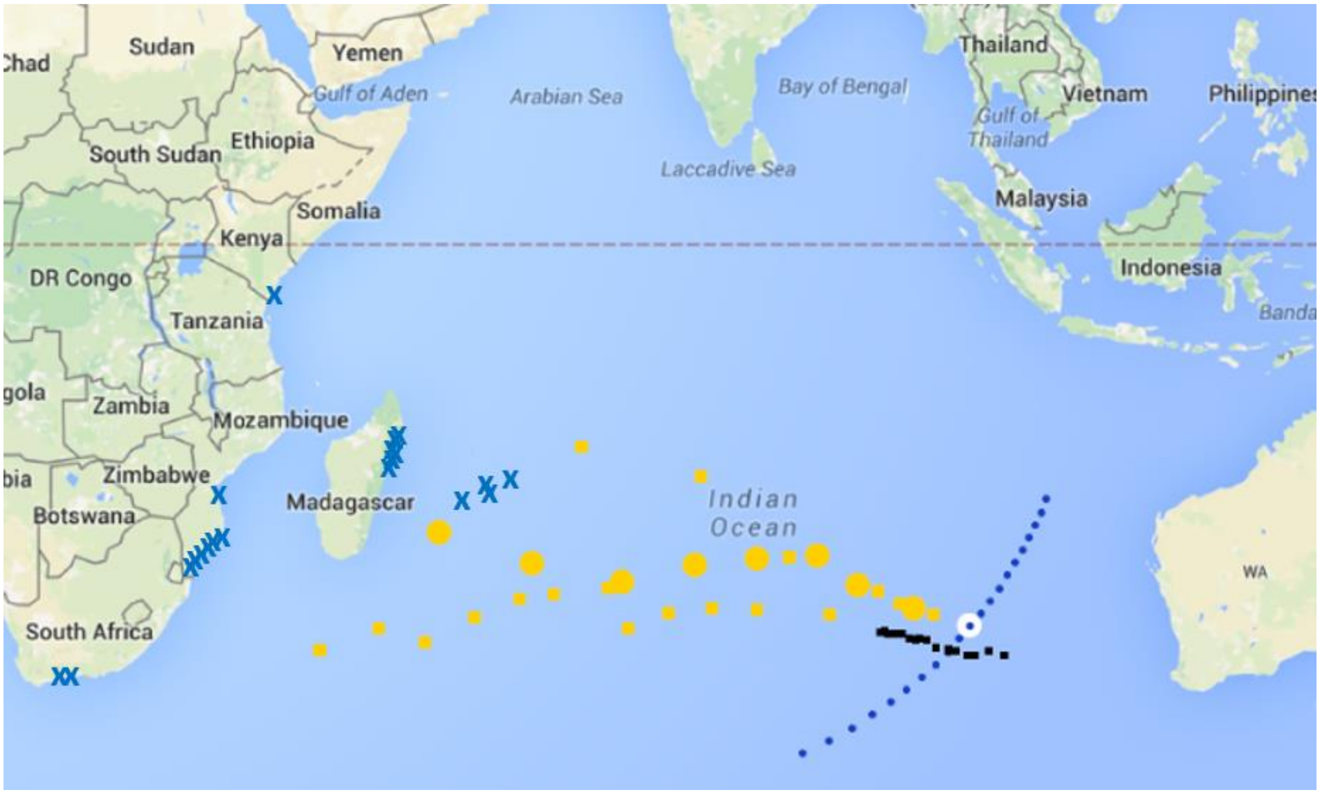
Figure 8 Modelled BTO and BFO outcomes for final southern leg using HDG SEL showing very good fit to BFO but less good fit to BTO data

Impact points modelled against drift analysis

Independent Group member Richard Godfrey recently published a paper *The Probable End Point of MH370* [48] in which he uses the extensive drifter data from the Global Drifter Program to develop a comprehensive drift model. Richard set about organising and analysing the position, speed, direction, and water temperature data measured by the drifters at 6-hour intervals; he then groups the data by position and calendar month. Richard uses the derived factors to estimate the trajectory of debris originating from the 7th arc in March 2014. His analysis highlights the considerable dispersion of debris released from the same starting position along the 7th arc and he is able to relate predicted water temperature history of the debris to the observed barnacle populations on the debris. As stated in his paper, Richard states that:

> "*The drift analysis also explains the reason why MH370 floating debris originating around 30°S near the 7th Arc could end up in Reunion and South Africa with barnacles via tracks that pass through sea water between 19°C and 25°C and end up in Madagascar, Mozambique and Tanzania without barnacles via tracks that pass through sea water above 25°C.*"

Importantly, Richard's analysis and modelling "… *appears to support a probable end point of MH370 around 30°S near the 7th Arc.*" Accordingly, drift modelling is broadly supportive of the HDG SEL impact point at 30°43' S 097°40' E and it does not exclude the TRK SEL impact point, 33°38.40' S 94°21.60' E.



Map 10 Drift modelling from an Impact on the 7th arc at latitude 30°S.

Crosses mark the location of wreckage finds. The circles show the simulated path of floating debris by month; the colour of the circles indicates sea water temperatures; below 19°C are shown in white and between 19°C and 25°C are shown in orange. The 7th Arc is marked with dark blue dots and the undersea feature known as Broken Ridge is marked with black squares.

(Reproduced (with additional information) from The probable End Point of MH370, Richard Godfrey, 12 February 2017)

Concluding observations

The TRK SEL impact point at 33°38.40' S 94°21.60' E is interesting in another regard; as illustrated on Map 9 it sits right in a gap in the aerial search zone of 1 April 2014, not that a failure to plug that gap would have mattered. By the time airplanes were deployed to that area on 1-2 April, more than three weeks after the crash, any floating debris field from either hypothesised crash site would have drifted sufficiently west-north-west to have fallen well outside of the aerial search zones.

On 2 April the search was moved to the north east of the 30°43’ S 097°40’ E site. Then, on 4 April 2014 all the search assets were redirected about 1,500 kilometers to the north chasing what turned out to spurious underwater acoustic signals.

With regards to the work of the ATSB’s First Principles Review [49], the area surrounding the 33°38.40' S 94°21.60' E (TRK SEL) impact site falls in the new 25,000 square kilometer prospective area (as previously stated, roughly 50% of the associated 50 kilometer radius search area falls in the already searched 120,000 square kilometer search zone). However, the 30°43’ S 097°40’ E (HDG SEL) impact site sits about 250 kilometers outside and to the north-east of the new prospective area.

Appendix 1

Boeing B777 Windshield Heater Incidents

Incidents prior to MH370

1. 17 October 2002, Air France Flight 062 from Paris to Los Angeles experienced a windshield heater fire on the Captain's windshield. The crew initiated an emergency descent and completed a successful landing at Churchill Airport, Canada.

   Airplane details:
   Manufacturer’s Serial Number 32310
   Line Number 401
   Operator Air France
   First flight 24/04/2002
   Registration F-GSPZ

2. 24 July 2003, an Alitalia Boeing 777 en route from Rome to New York experienced a fire at the captain's windshield heater. The crew initiated an emergency descent and completed a successful landing at Shannon International Airport, Ireland.

   Airplane details:
   Manufacturer’s Serial Number 32858
   Line Number 425
   Operator Alitalia
   First flight 04/12/2002
   Registration I-DISU

3. 5 September 2011, an Air France flight AF-900 from Paris Charles de Gaulle to Yaounde, Cameroon was en route at FL350 when the windshield heater failed and the windshield started cracking. The crew initiated a rapid descent and returned to Charles de Gaulle Airport.

   Airplane details:
   Manufacturer’s Serial Number 32305
   Line Number 395
   Operator Air France
   First flight 25/03/2002
   Registration F-GSPY

4. 13 April 2012, Alitalia flight AZ-8320 flying from Rome to Dubai at FL370 declared an emergency near Athens. The first officer's windshield heater had failed and his windscreen had cracked. The crew descended rapidly and diverted to Athens.

   Airplane details:
   Manufacturer’s Serial Number 32859
   Line Number 426
   Operator Alitalia
   First flight 18/12/2002
   Registration EI-ISB

5. 3 July, 2012, Air France flight AF-85 flying from San Francisco to Paris at FL370 declared an emergency over Hudson's Bay. The windscreen had cracked and the crew reported problems maintaining pressurization in the cabin. The crew descended to 10,000 feet and diverted to Montreal.

   Airplane details:
   Manufacturer's Serial Number 30457
   Line Number 284
   Operator Air France
   First flight 12/06/2000
   Registration F-GSPL

Incidents after MH370

6. 20 September 2014, Singapore Airlines flight SQ-324 from Singapore to Amsterdam, was en route at FL380 about 15nm southwest of Prague when the windshield heater failed and the windshield cracked. The aircraft descended and continued to Amsterdam.

   Airplane details:
   Manufacturer's Serial Number 28526
   Line Number 355
   Operator Singapore Airlines
   First flight 31/07/2001
   Registration 9V-SVC

7. 29 July 2015, Virgin Australia flight VA-8 from Los Angeles to Brisbane had just levelled off at FL300 when the crew reported the left hand windshield heater had failed and the left hand windshield had cracked. The crew descended to 10,000 feet dumped fuel and returned to Los Angeles.

   Airplane details:
   Manufacturer's Serial Number 37939
   Line Number 764
   Operator Virgin Australia
   First flight 10/02/2009
   Registration VH-VPE

8. 5 August 2015, United Boeing flight UA-200 from Guam to Honolulu was en route at FL370 about 900nm east of Guam when the crew decided to return to Guam due to a whistling emanating from the windshield that made communication in the cockpit difficult. The windshield heater had failed and the windshield had started to crack.

   Airplane details:
   Manufacturer's Serial Number 30218
   Line Number 293
   Operator United Airlines
   First flight 18/07/2000
   Registration N212UA

Possible Boeing B777 Windshield Heater Incident

30 July 2008, Emirates Boeing flight EK006 from London to Dubai was flying in Romanian airspace when the crew reported smoke from an unidentified source in the cockpit. The crew carried out an emergency landing at Budapest Ferihegy airport.

Airplane details:
Manufacturer's Serial Number 29067
Line Number 408
Operator Emirates
First flight 14/06/2002
Registration A6-EMS

Appendix 2

MH370 – Timeline of Actual and Hypothesised Events

Event Time UTC	Actual/Observed Event	Source	Hypothesised Event	Transponder	VHF	SATCOM	ACARS	IFE
14:50	Captain signs in	Factual Information Report, p 1						
15:15	First Officer signs in	Factual Information Report, p 1						
15:55:57	SATCOM initiates a normal Log On Renewal with a valid Flight ID.	Factual Information Report, p 54				✓		
16:27	Cleared to push back	Factual Information Report, p 1			✓			
16:40	Cleared for take-off	Factual Information Report, p 1			✓			
16:42	Take off from 32R	Factual Information Report, p 1						
16:42:04	IFE SMS e-mail application sends a normal beginning-of flight message with correct flight ID, origin and destination airports.	Factual Information Report, p 54				✓		✓
16:43	Cleared to FL180, direct to IGARI	Factual Information Report, APPENDIX 1.18D, p 10 of 14		✓	✓			
16:47	Cleared to FL250	Factual Information Report, APPENDIX 1.18E, p 10 of 29		✓	✓			
16:50	Cleared to FL350	Factual Information Report, APPENDIX 1.18E, p 11 of 29		✓	✓			
17:01	Captain advises FL350 reached	Factual Information Report, APPENDIX 1.18E, p 17 of 29		✓	✓			
17:07:48	ACARS transmission, HDG 027, FL350, Mach 0.821	Factual Information Report, p 46				✓	✓	
17:19:26	KL instructs "Malaysian Three Seven Zero contact Ho Chi Minh one two zero decimal niner good night."	Factual Information Report, APPENDIX 1.18E, p 27 of 29			✓			
17:19:30	MH370 replies "Good night, Malaysian three seven zero."	Factual Information Report, APPENDIX 1.18E, p 27 of 29			✓			

Event Time UTC	Actual/Observed Event	Source	Hypothesised Event	Transponder	VHF	SATCOM	ACARS	IFE
After 17:19:30			*First indication of fire, crew don oxygen masks*					
17:20			• *Fire visible on Captain's windshield heater terminal block* • *Captain orders First Officer to divert to nearest airport* • *Captain leaves seat to retrieve fire extinguisher* • *Oxygen hose disconnects*					
17:20.30			*First Officer executes turn back to Penang (KENDI) using LNAV*					
17:20:31	At IGARI	Factual Information Report, p 2	*Right turn initiated by FMS towards BITOD reverses and becomes left turn towards KENDI (Penang)*					

17:20:35			• *Oxygen concentration on flight deck reaches 23%*
			• ***Fire flares***
			• *Left overhead circuit breaker panel affected by heat*
			  • *A/T SERVO L circuit breaker trips*
			  • *ATC L circuit breaker trips*
			  • *COMMS VHF L circuit breaker trips*
				X	*X*			

17:20:36	Mode S symbol drops off KL ATCC radar	Factual Information Report, p 2		**X**				

Event Time UTC	**Actual/Observed Event**	**Source**	**Hypothesised Event**	**Transponder**	**VHF**	**SATCOM**	**ACARS**	**IFE**
17:20.40			• *First Officer commands emergency descent using FLCH – airplane fails to descend because autothrottle disengaged* • *First Officer attempts to contact ATC – no transmission because Left VHF radio now inoperative*		*X*			
17:21			*Left AC Bus isolated, SATCOM loses power*			*X*		
17:21:13	• KL ATCC records disappearance of the radar position symbol • Right turn followed by left turn towards Penang (Note: right turn would have probably commenced around 17:20:31 a few miles short of IGARI)	• Factual Information Report, p 2 • Factual Information Report, p 2 and p 7		**X**				
17:22:30			• *Crew overwhelmed or flight deck evacuated* • *Expected ACARS transmission of WINDOW HEAT L FWD and EQPT COOLING OVRD advisories – NO TRANSMISSION*			*X*	*X*	
17:23			• ***Depressurisation event, fire extinguished*** • *Crew oxygen system depleted* • *Passenger oxygen masks deploy*					
17:25			• *First walk-around bottle(s) deployed* • *Cabin crew member retrieves flight crew from flight deck*					

Event Time UTC	**Actual/Observed Event**	**Source**	**Hypothesised Event**	**Transponder**	**VHF**	**SATCOM**	**ACARS**	**IFE**
17:37:22	Primary radar tracks crossing coast north of Kota Bharu	Factual Information Report, p 7						
17:37:48	Scheduled routine ACARS transmission – NO TRANSMISSION	Factual Information Report, p 1-2, p 46				**X**	**X**	
17:40			*First walk-around bottle(s) exhausted, second walk-around bottle(s) deployed*					
17:45			*Passenger oxygen generators begin to burn out*					
17:50			• *Flight and/or cabin crew members re-enter flight deck and assess situation* • *Airplane fails to respond to FLCH commands to descend* • *Left and Centre VHF radios inoperative and Radio Tuning Panel probably damaged* • *Decision taken to fly a safe distance from Penang before attempting trouble-shooting*					
17:52:35	6 nautical miles south of Penang	Factual Information Report, p 7						
17:53			*Right turn onto 290°*					
17:55			*Second walk-around bottle(s) exhausted, third walk-around bottle(s) deployed*					
18:03:41	MAS OPS GES-initiated DATA-2 ACARS transmission uplink – Not successful	Factual Information Report, p 54				**X**		
18:05:11	MAS OPS GES-initiated DATA-2 ACARS transmission uplink – Not successful	Factual Information Report, p 54				**X**		
18:13:00	Primary radar tracks passing VAMPI	Factual Information Report, p 7						

Event Time UTC	**Actual/Observed Event**	**Source**	**Hypothesised Event**	**Transponder**	**VHF**	**SATCOM**	**ACARS**	**IFE**
18:10			*Third walk-around bottle(s) exhausted, fourth walk-around bottle(s) deployed*					
18:21:50	Primary radar tracks passing north of MEKAR	Factual Information Report, p 7						
18:22:12	Last tracked by primary radar 10 nautical miles past MEKAR	Factual Information Report, p 7						
18:24			*31 minutes after turning right at Penang airplane commences manoeuvring, initially turning right to roughly 335°*					
18:24:27			*Left AC Bus reconnected*					
18:25			*Fourth walk-around bottle(s) exhausted, fifth walk-around bottle(s) deployed*					
18:25:27	1st handshake starts – log-on initiated by the aircraft	Factual Information Report, p 54				✓		
18:25:34	1st handshake – SATCOM Log-On, successfully completed, no flight ID	Factual Information Report, p 54				✓		
18:26			*Airplane continues manoeuvring, reversing right turn and turning left to roughly 281°*					
18:27:03	1st handshake – IFE sets up a Data-3 ground connection over SATCOM for an SMS/e-mail application	Factual Information Report, p 55				✓		✓
18:28:05	1st handshake completes – IFE sets up a Data-3 ground connection over SATCOM for a Built-In Test Equipment (BITE) application	Factual Information Report, p 55				✓		✓
18:39:52	Ground to Air Telephony Call from MAS OPS starts	Factual Information Report, p 55				✓		

Event Time UTC	**Actual/Observed Event**	**Source**	**Hypothesised Event**	**Transponder**	**VHF**	**SATCOM**	**ACARS**	**IFE**
18:40			• *Airplane now heading roughly 145°* • *Fifth walk-around bottle(s) exhausted, sixth walk-around bottle(s) deployed*					
18:40:56	Ground to Air Telephony Call from MAS OPS ends - unanswered	Factual Information Report, p 55				✓		
18:55			*Sixth walk-around bottle(s) exhausted, seventh walk-around bottle(s) deployed*					
19:10			*Seventh walk-around bottle(s) exhausted, eighth walk-around bottle deployed, if bottles used in pairs (ie two survivors) only one bottle remains*					
19:20:30			*Final turn commenced*					
19:23:00			*Final turn completed, roll out onto 180°M*					
19:25			*Eighth walk-around bottle exhausted, ninth walk-around bottle deployed, if used in pairs, last walk around bottle exhausted*					
19:41:00	2nd handshake– Log-On Interrogation by the Perth Ground Station with a response from the SATCOM					✓		
20:41:02	3rd handshake– Log-On Interrogation by the Perth Ground Station with a response from the SATCOM					✓		
21:41:24	4th handshake– Log-On Interrogation by the Perth Ground Station with a response from the SATCOM					✓		

Event Time UTC	Actual/Observed Event	Source	Hypothesised Event	Transponder	VHF	SATCOM	ACARS	IFE
22:41:19	5th handshake– Log-On Interrogation by the Perth Ground Station with a response from the SATCOM					✓		
23:13:58	Ground to Air Telephony Call from MAS OPS ends - unanswered	Factual Information Report, p 55-56				✓		
00:10:58	6th handshake– Log-On Interrogation by the Perth Ground Station with a response from the SATCOM	Factual Information Report, p 56				✓		
00:19:29	7th handshake starts – log-on initiated by the aircraft	Factual Information Report, p 56				✓		
00:19:37	7th handshake – SATCOM Log-On, successfully completed, no flight ID, No subsequent IFE Data-3 ground connection over SATCOM for SMS/e-mail application or BITE	Factual Information Report, p 56				✓		**X**

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