MH370 – CAPTION – A New Plausible Piloted Trajectory

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CAPTION[2]

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Executive Summary

CAPTION describes the reconstructed trajectory of flight MH370 based on two main assumptions: the aircraft was piloted until its end and that the hijackers' initial plan to land somewhere could not be executed as foreseen, thus making Learmonth in Australia an impossible target to reach.

New elements that have enabled an updated analysis include the release of civil radar data, the sailor Kate Tee's sighting and the unprecedented detailed conclusions that can be drawn from them and thirdly the results of seismic data analysis from Cocos Islands thus enabling potential additional waypoints to be considered with their time tag. The usage of a further series of real-time simulations has led to this new plausible piloted trajectory for the MH370.

This study presents also a new perspective on the electrical power management after the hijacking until its full restoration and demonstrates that for an experimented pilot a simple but realistic scenario including the RAT deployment is possible. This is supported by a detailed analysis of the Inmarsat data.

In addition, the use of simulations has allowed for a closer match to the real flight conditions, for example through the usage of actual meteorological data in the 4D interpolation modelling as direct inputs into the simulator in quasi real-time. It is important to highlight that the Flight Management System automation algorithms modelling is a proprietary system to the aircraft manufacturers. Therefore, the simulations were performed using an FsX-PMDG B777-200LR model which is the closest affordable existing model to the B777-200ER.

The new elements led to the identification of new scenarios on the aircraft behaviour, in particular after the hijacking around the IGARI waypoint. They are the basis for the identification of two additional waypoints namely NOPEK and Cocos Islands overflown within a relatively precise timing. In addition, they highlighted the probable presence of an ash cloud encountered during the journey which might have impacted the trajectory profile.

The series of simulations concluded that the trajectory:

- had repeated the same manoeuvre several times in order to mislead any potential surveillance of the flight i.e. exit radar coverage with a subsequent change to the flight direction, speed and/or altitude and
- had been flown at a constant altitude of ~23000ft from the Inmarsat Ping 2 (also called Arc-2) time tag until Ping 6 (or Arc-6) time tag.

[1] *With contributions from Philippe Gasser, CAPTION*
[2] *CAPTION Initiative, see* https://www.mh370-caption.net

Interestingly, the reconstructed trajectory includes two options to follow route T41 or route M641 after overflying Cocos Islands given the perfect match along these paths between the respective estimated Burst Time Offset (BTO) and Burst Frequency Offset (BFO) values and the Inmarsat BTO and BFO measured values published in [0].

From Cocos Islands, Route T41 is the path to Learmonth in the Australian Continent while route M641 is the path to Perth. The choice between the two options would certainly have been made based on the unknown initial plan and fuel consideration. Subsequently, CAPTION favours Learmonth (Route T41) as it could have just been reached, whilst Perth (Route M641) was out of reach at the Cocos Islands decision point.

The journey stopped short well before the respective targets. As assumed in the Malaysian official report [2], this is most probably due to the fuel exhaustion and the subsequent engines flame out. This was confirmed by the results of the fuel consumption computation performed in this study.

Finally, the identified End of Flight (EoF) zone is found along Arc-7. Assuming it was following route T41, the EoF would be located between ~15.7°S and ~17.5°S. Figure 1 illustrates the full trajectory with two extreme variants at the end of flight after Arc-6.

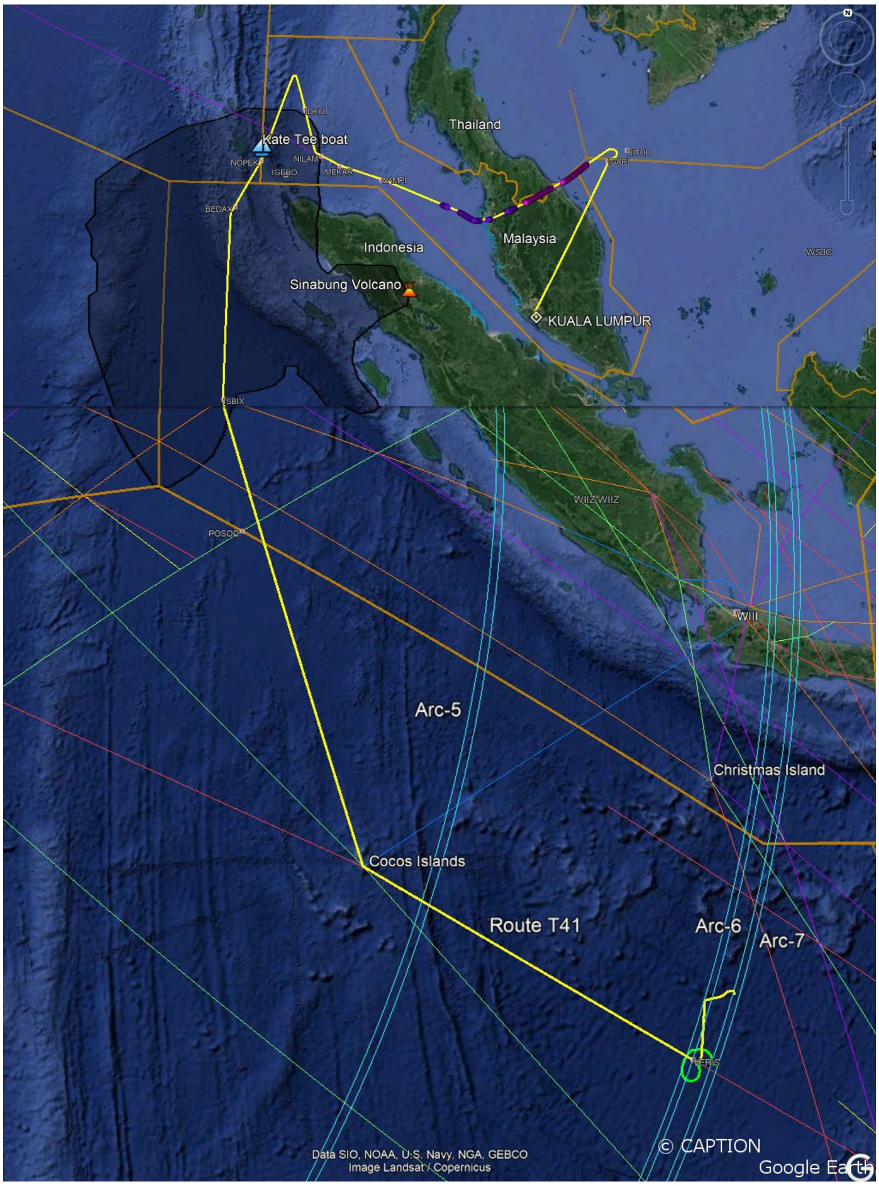

Figure 1: CAPTION reconstructed piloted trajectory including NOPEK and Cocos Islands waypoints

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Note: This document can be downloaded from [*https://www.mh370-caption.net/wp-content/uploads/MH370-PlausibleTrajectory-CAPTION.pdf*](https://www.mh370-caption.net/wp-content/uploads/MH370-PlausibleTrajectory-CAPTION.pdf)

1. Introduction

Since the first analysis that reconstructed a plausible fully piloted trajectory by CAPTIO in [1] and after the release of the Malaysian Final report [2], some complementary elements either became available or deserved deeper investigation. The present report provides new findings on these elements and proposes a new plausible piloted trajectory called CAPTION[3]. The new factual elements are:

1- The scenario of a manual switch-off of the transponder.

2- New radar data from civil surveillance systems of Kota Bharu and Penang publicly released by V. Iannello in [3].

3- A detailed analysis of the Inmarsat data in correlation with the electrical power status.

4- Sailor Kate Tee's eye sighting report in [4] to [12] and analysed in detail in Annex 2.

5- The Sinabung volcanic eruption and its ash cloud transportation as detailed in Annex 3.

6- Seismic (infrasound) data recorded at Cocos Islands as analysed by Ed Anderson in [13].

From the results of detailed analyses of the points listed above, a revised plausible piloted trajectory is reconstructed in using the full Inmarsat set of data, including those data that have often been ignored by publicly available studies so far. This trajectory also follows the assumption that the aircraft flew at a constant altitude between Arc2 and Arc6 minimising the number of changes of altitude.

In addition, a rationale is tentatively provided to explain some of the decisions possibly – and perhaps logically – made by the People in Command (PIC) during the flight. This includes their management of the electrical power.

Elements from the CAPTIO study in [1] that are still applicable will not be addressed again in this report, only new elements are presented as well as the complete CAPTION trajectory.

2. Objective

The objective of this study is to determine a plausible piloted trajectory based on new and/or revised pieces of information since the publication of the Malaysian final report. CAPTION is reconstructed keeping in mind the original objective of the PIC to land somewhere.

Each of the elements listed above will be considered in sequence with an innovative perspective. All the necessary information has been extracted from publicly available sources. Then, the resulting full set of elements will be used as the basis for the refinement of the revised CAPTION trajectory.

3. The transponder manual switch-off… and RAT deployment?

On his blog, V. Iannello provided a detailed description [14] of the active transponder manual switch-off. The described actions and their timings correspond to the sequence of manual actions leading to properly turn the transponder knob to the standby and do not correspond to a "hard" disconnection via a power cut.

This new element is demonstrating that the hijacking could have been done from the cockpit. The proper execution of putting the transponder on standby means that electrical power was still available until this moment at least.

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[3] www.mh370-caption.net

This means that the electrical power provided to the SATCOM - already analysed in a large number of publications - was most probably switched off at a later stage. Considering the various ways of cutting the power, there are two possible scenarios for doing so.

Scenario 1

The first scenario considers that the automation of the aircraft continued to be functional. It consists of isolating the left bus by switches on the overhead panel leaving the right bus powering the basic functions of the aircraft but no longer the SATCOM, provoking its subsequent hard logout. Under these circumstances the autopilot is still functional and provides lateral navigation (LNAV) and vertical navigation (VNAV) capabilities. Quasi-normal flight conditions would have been ensured during this leg.

But then, no convincing rationale can be found to explain why the electrical power was switched back on at the chosen moment. It was not necessary to put it back as the aircraft would be flying normally.

Scenario 2

The second scenario consists of providing to the PIC the conditions to continue the journey while managing both the cockpit and the cabin. A realistic hijack modu operandi is detailed in [30]. Scenario 2 includes disconnecting all electrical generators, i.e. the main generators (IDG), the backup generators and the auxiliary generator (APU), via the overhead panel switches and possibly isolating both electrical transfer buses. This is strongly supported a-posteriori by the occurrence of a subsequent power switch back on (cf key event 10) around 18:23:00 UTC which was well justified.

This voluntary power "outage" would have triggered the deployment of the RAM Air Turbine (RAT), which provides the minimum electrical and hydraulic power necessary for flying the aircraft[4]. This wind-mill generator does not supply power to the left bus which feeds the SATCOM equipment. The analysis of the rationale on this realistic scenario 2 and its potential consequences is provided in Annex 1.

The electrical power re-establishment at about the same time of the exit out of Western Hill radar coverage is not a coincidence and is convincingly justified by the hijacking scenario described in [30].

Annex 1 provides the detailed analysis of the Inmarsat data taking the electrical power status in perspective. The full set of relevant signal units exchanged between the aircraft and the ground have been put into context of the aircraft operation, of the PIC actions. Conclusions are drawn about the electrical power situation at each of these key moments.

A consequence of the (low) power supply by the RAT only is that the Auto-Pilot (A/P) functions were not available. Nevertheless, some navigation functionalities were still available, such as the left VOR radio navigation aid which have been probably used during the manual piloting inducing such peculiar characteristics of the trajectory along the border between Thailand and Malaysia and during the turn in the South of Penang. An additional element to consider is the execution of the sharp U-Turn performed in such a short time which is coherent with a manual manoeuvre.

Therefore, a manual piloting leg would have started somewhere after IGARI waypoint probably before the Major U-Turn-1 and continued when the aircraft had been stabilised on a quasi-direct heading to Kota Bharu. This manually flown leg would have lasted until the electrical power re-establishment. After this, A/P LNAV and VNAV functionalities would have become available again, allowing the control of the flight via waypoints with RNAV precision as in a normal flight.

We estimate that the power was switched off between the re-entry in the FIR Singapore and BASIR waypoint, as described in Annex 1 dedicated to the electrical power management.

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[4] *On 20th Dec. 2018, LA8084 flight from Sao Paulo to London landed at Belo Horizonte (distance ~90Nm) powered by the RAT only*

Thus, the probable Scenario 2 from IGARI to ping #1 (Arc-1) is as follows:

a) After overflying IGARI, the transponder was switched to standby manually

b) A sharp U-Turn was performed also manually

c) Shortly after the U-Turn back to Malaysia, the main sources of electrical power were disabled (IDG, Backup generators and the APU)

d) During the interim, the main battery supplied the necessary power

e) The RAT deployed and then provided the necessary standby electrical power after the power break.

f) The aircraft was piloted manually most probably using intermediate VOR radials. This is recognised as a possible procedure by pilots.

g) Around 18h22 UTC the IDGs were switched back on. After a power break, this powered the SDU up as well as the ACARS and the non-critical functions of the IFE. The electrical power was re-established at about the same time of exiting the Western Hill radar coverage. This was not a coincidence. This is convincingly justified by the hijacking modus operandi as described in [30].

h) Then a Reset Data Link command was executed via the Communication Master Manager page before the SDU could become operational. This switched the ACARS media to the default central VHF in data mode. This also reset the company and flight information to the default values, thus making the Flight ID not available anymore.

i) Quickly afterwards, the ACARS was switched to "Auto Message Off" to block any message transmission as the preceding Reset Data Link would have put it on.

j) The SDU reconnected to the Inmarsat network recognised only by the AES ID which is the standard protocol for all messages. But the Log-on request could not include the missing flight ID.

This kept the aircraft as most anonymous as possible… successfully …

4. New radar data from civil surveillance systems

On his blog, V. Iannello released radar digital data from civil surveillance systems from Kota Bharu and Penang [3]. This data clearly demonstrates that the aircraft flew above the border between Thailand and Malaysia with some oscillations in direction and speed.

Reading these data from an A/P perspective, one could infer that the a/c started by a direct path to KADAX waypoint, which is in the vicinity of Kota Bharu. Then it flew almost directly to ENDOR waypoint in the southeast of Penang Island, then it followed a northwest track to OPOVI waypoint and finally headed directly to MEKAR waypoint in the northwest of the Malacca Straight.

But, considering the shape of the trajectory provided by the radar data, which presents some irregularities in its path, it cannot be clearly established that it was flown with the A/P in LNAV control mode. Questions could be raised on why the aircraft FMS and A/P could not fly a smooth and well controlled path. In fact, this radar data is probably more compatible with a trajectory flown under manual control using VOR radials as navigation aids. Annex 1, based on [30], shows that the measured speed variation advocates more for still throttles rather than auto-controlled throttles. If engaged, the auto-throttle mode would have regulated the aircraft speed to the reference IAS which is not visible.

5. Sailor Kate Tee's eye sighting report

On her blog [7], sailor Kate Tee reported the eye sighting of a slow, low-flying aircraft during the night of the 8th of March 2014 Malaysian time (~19:19:00 UTC on March 7th). A detailed analysis is provided in Annex 2, including information directly provided by the sailor herself. It shows that her testimony is coherent and credible with an aircraft passing close to her boat. This study is based on the hypothesis that it was flight MH370. The timing and the bearings visually measured by the sailor are compatible with a trajectory using NOPEK waypoint as a target (cf Figure 2) with a slight turn at that point, followed by a direct leg to BEDAX waypoint.

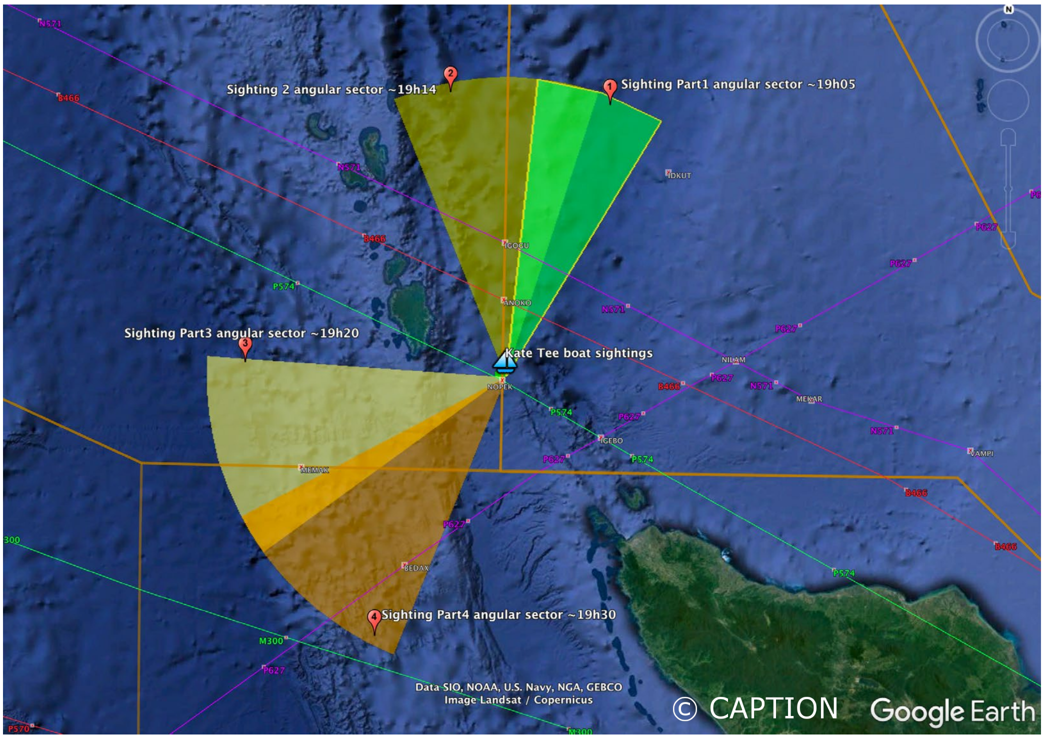

Figure 2: Kate Tee's eyes sighting sectors and corresponding timing

Verification has been performed to confirm that the estimated altitude, the sectors of viewing and the speed are acceptable characteristics of a fly-by close to Kate Tee's boat, either as a straight-line or as a two-segment broken-line trajectory.

Thus, **overflying NOPEK waypoint at ~19:19:30 UTC is a new key point taken into consideration for the determination of the new 4D piloted trajectory** presented below in this report**.**

In the selected trajectory below, the type of legs best suiting the overall path – in particular the segment between ~18h40 and ~19h19 UTC – is a two-leg broken line slightly turning at NOPEK waypoint and targeting BEDAX waypoint as the next report point. The family of such possible trajectories is illustrated by the Yellow sectors in Figure 3 for flying altitudes between 2000ft and 10000ft.

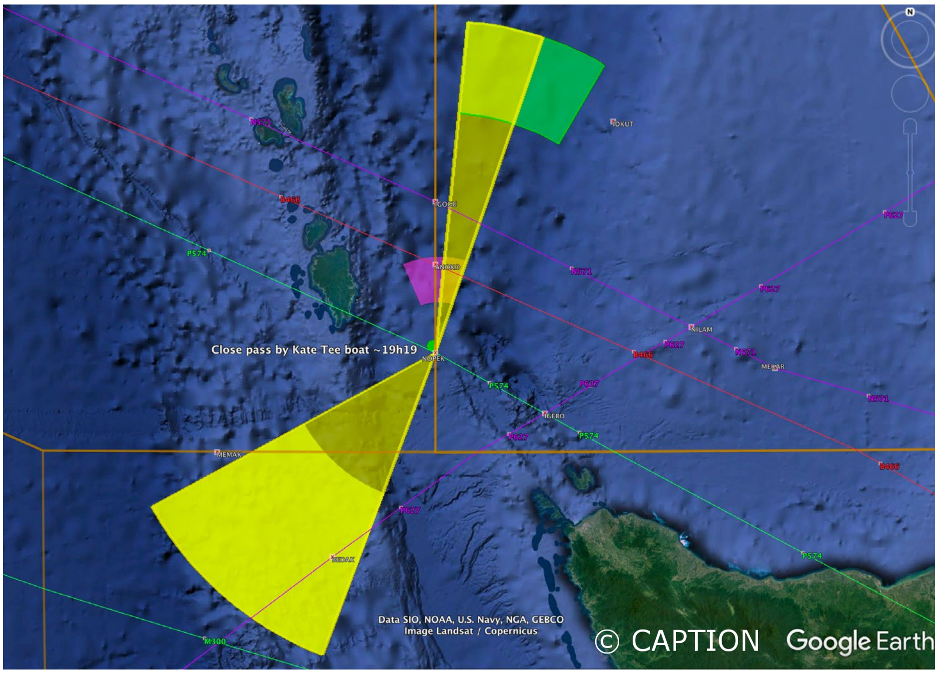

Figure 3: Family of possible 2-leg broken line paths at altitudes between 2000ft and 10000ft (Yellow area)

6. Mount Sinabung volcanic eruption and its ash cloud

Kate Tee reports that during her sighting the aircraft appeared to be surrounded by an orange glow. A possible interpretation is that this could have been caused by volcanic ashes. In fact, Volcanic Ash Advisories (VAA) concerning Mount Sinabung on the 7th and 8th of March are mentioned in the Malaysian Final report [2] section 1.7.2-3. Actually, the volcano had been continuously active following a significant eruption in January leading to a quasi-permanent release of thin particles until the beginning of March. Mount Sinabung volcanic eruption material and its ash cloud evolution have been analysed in detail in Annex 3, thanks to simulation runs of atmospheric propagation models from NOAA. It shows that ashes have spread from sea level up to a maximum altitude of 20000ft only and would have been in motion reaching Kate Tee's boat's location in a two-day journey. For these altitudes, Figure 4 sketches the geographical location of the ashes on 7th March at about 18:00UTC in perspective with the angular sector of Kate Tee's eye sightings.

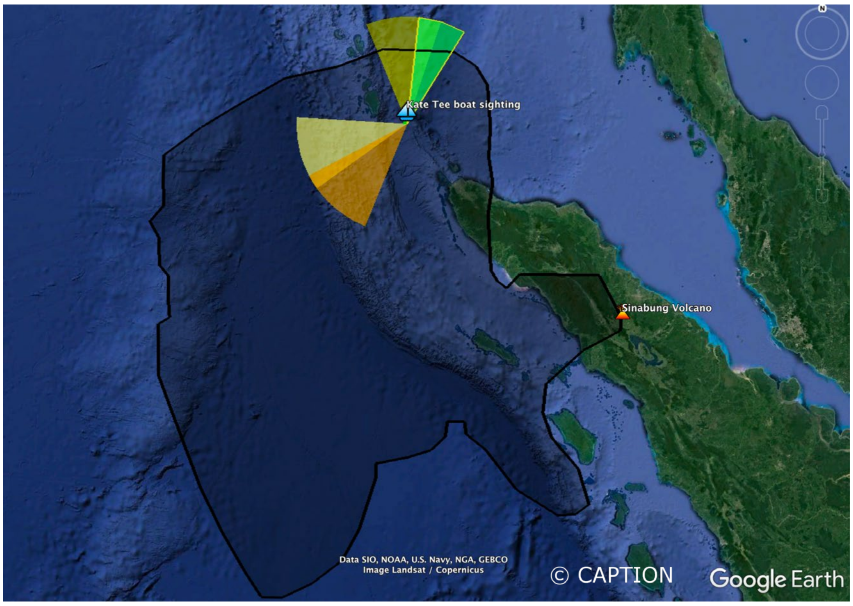

Figure 4: Ash cloud location relative to Kate Tee's boat at the time of the sighting

The conclusion is that **an ash cloud was most likely present in Kate Tee's boat's area and in a larger surrounding zone with a very high probability**. Our simulation could not take into account the accumulation from earlier days. Thus, our results are probably an underestimation of the true ash concentration. This matches her sighting testimony and could explain the visual orange glow phenomenon. In addition to this, the ash cloud's ceiling might also explain the trajectory profile in that area. In trying to avoid the ashes the aircraft descended at first and then subsequently flew above the cloud. This fits well with the found optimum flight level of 23000ft after waypoint BEDAX.

7. Seismic data recorded at Cocos Islands

On his blog [13], Ed Anderson published reports of studies on the possibility that infrasound and seismic detectors had captured **MH370 overflying Cocos Islands**. The analysis of the few publicly available screen shots of infrasound data from the IM.I06 array indicates that only one significant acoustic event took place between the times of the 4th and 5th Inmarsat pings. This has been analysed in more detail thanks to seismic data used as infrasound data and captured by II.COCO detector as part of the Global Seismograph Network IRIS/IDA. The time of occurrence of **this event is 22:22:22 UTC**. This is the time tag where the aircraft possibly passed above the seismic detector, which is located just beside the Cocos Islands runway as illustrated in Figure 5. The records seem to indicate that the incoming direction was probably from the northwest and the outgoing direction was towards the southeast.

Unfortunately, some of the existing extra infrasound data are not publicly available for such an analysis.

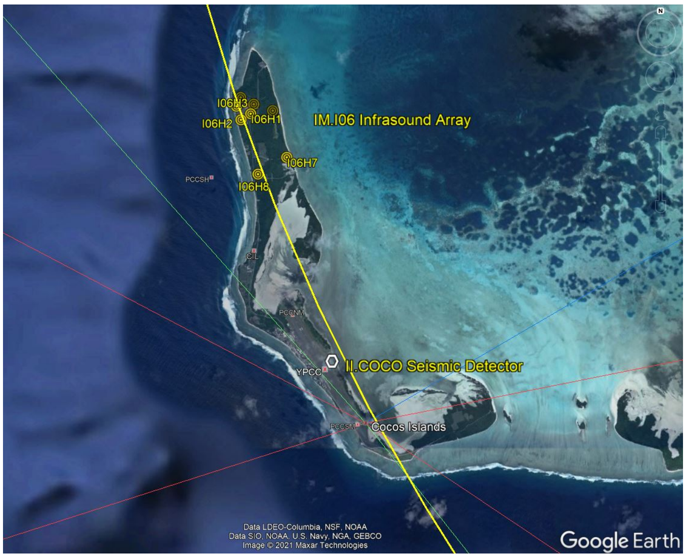

Figure 5: Location of the infrasound detectors array and seismic detector at Cocos Islands

8. CAPTION Reconstructed Trajectory

Considering these new elements with a fresh eye, is it possible to identify a simple trajectory reconciling all of them with the indisputable facts coming from the surveillance systems, the ACARS messages and the Inmarsat data as well as adequate FMS flight modes? The positive answer is illustrated in Figure 6 with its corresponding list of key events provided in Table 1 with two final leg options provided in complementing Table 2 and Table 3. This list of events starts at IGARI waypoint and finishes at the estimated end of the flight just after Inmarsat Arc-7, with two possible route options after overflying Kate Tee's boat and Cocos Islands.

The two route options have to be considered because their corresponding estimated BTO[5] and BFOs match very well with the Inmarsat Arc-5 and 2nd phone call attempt measured data. Arc-6 and Arc7 crossing points can also be properly selected to match Inmarsat data. Between the two route options, the one heading to Learmonth on the Australian continent is the one that best resists scrutiny.

The trade-off of altitude versus speed was analysed and simulated with our flight simulator with the conclusion that, matching the key events timing and maximising the range, the optimum altitude was ~23000ft under VNAV control.

We chose the approach of using flight simulations because the flight dynamics and actual meteo make theoretically computed average values too far from reality. The flight management system (FMS) automation model needs to "fly" the trajectory in an almost actual context in order to provide the best instantaneously induced flight parameters. In particular, the 4D interpolated quasi-real-time meteo data is key and was input to the simulator every five seconds.

At this stage a caveat must be made: our flight simulator includes a B777-200LR model and not a B777-200ER like the actual aircraft. The differences are threefold, the 9M-MRO B777-200ER includes:

a) Rolls-Royce engines instead of GE's,

b) a smaller wing area by 9m2 but includes winglets

c) a smaller weight (~7 tons less)

Nevertheless, the results of the simulation will form the baseline for the new trajectory determination. Thus, due to these small differences which have partial compensation effects, some imprecision will exist, for example, the actual levelled altitude which may not be exactly 23000ft but would not be far from it.

The final results are in accordance with the commonly accepted hypothesis that the engines provided their quasi-nominal thrust capability until the end. The fuel consumption computation of this study provides coherent results matching this assumption and estimates a near-total exhaustion of the fuel.

Nevertheless, the PIC decision taken at Cocos Islands, where they had the possibility of taking a direct route to Christmas Island, which they did not take, shows to have been risky. Referring to the temporary power supply regime by the RAT, or the battery discharge which led to losing some capabilities among which possibly a reliable fuel consumption prediction, they could have been misled on the value of the remaining fuel weight.

One could also think about a past similar situation when, in 1996, Ethiopian Airlines ET-961 hijackers naively thought they had enough fuel to complete their planned journey.

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[5] *Inmarsat Burst Time Offsets (BTO) and Burst Frequency Offsets (BFO) are defined and analysed in Inmarsat paper [20]*

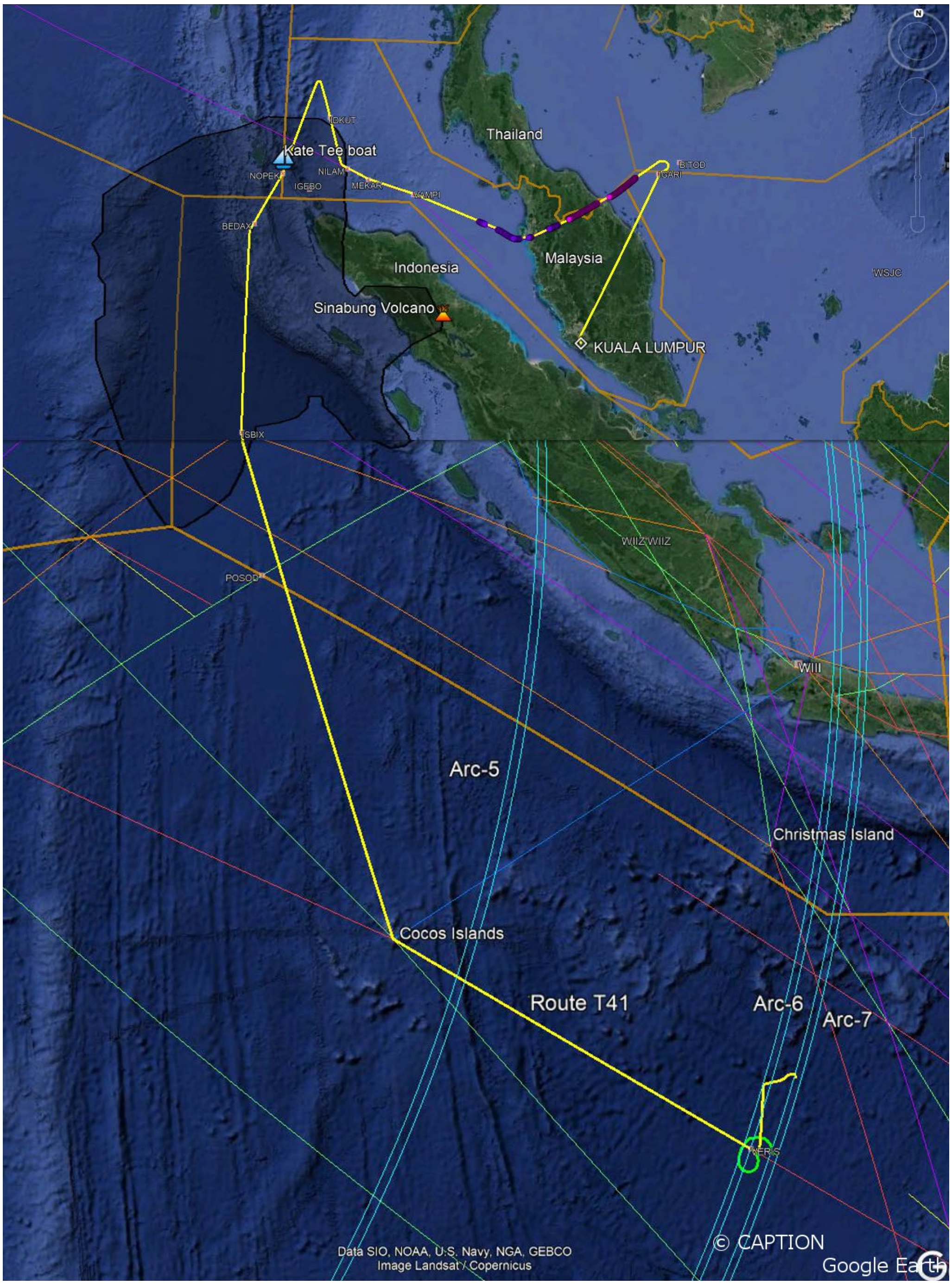

Figure 6: Full CAPTION Trajectory enhanced by the newly considered events

Table 1: CAPTION Trajectory key events with their time tag and location until Cocos Islands

Event	***Time***	***Latitude***	***Longitude***	***Altitude***	***Description***	***Track***	***Ground Speed***	***Vertical Speed***	***Est. BTO***	***Est. BFO***[6]	***Inmarsat BTO***	***Inmarsat BFO***
	UTC	°	°	ft		°	kt	fpm	µs	Hz	µs	Hz
1	17:21:13				Transponder manual switch-off from the cockpit							
2					180° U-Turn: could be with the A/P on or could be manual							
3					Electrical Power switch-off either: 1- In the cockpit by overhead panel switches 2- In the EEB by breakers opening							
4					RAM Air Turbine deployment leading to systems shedding							
5					Manual piloting starts (i.e. no more LNAV & VNAV functionalities)							
6					Direct to KADAX (near Khota Baru) using Nav Display waypoints as guidelines (cf radar data)							
7				~38500ft	Legs LOSLO, ENDOR, (South of Penang Island), OPOVI, VAMPI and MEKAR		~495kt					
8	17:52:27	~6Nm	South of	Penang	First officer mobile phone detected by a LBS (Localisation Base station) at Bandar Baru Farlim Penang.							
9	18:22:12				Exit from Western Hill radar coverage at 10 Nm after MEKAR on route N571							
10					Electrical power switched back on either: 1- to recover from the discharge of the battery and the loss of the ADIRU 2- to get LNAV and VNAV back before the discharge of the battery and the loss of the ADIRU							
11	18:25:27	6.778	95.931	38500	Arc-1: first Inmarsat Ping (logon request)	296.0	495	0	12520	142	12520	142
12	18:25:40	95.874	6.808	38500	Turn right to a northern direction (repeat same manoeuvre as at IGARI: exit radar coverage and significant change of heading). Emergency recovery?	296.0	495	0				

[6] *A bias of 150Hz is used for the BFO calculation*

13	18:27:04	6.964	95.795	38500	Arc-1.1 (from SITA log file) 2 possible explanations for the small RoC : 1- referring to Richard Godfrey [15]: BFO / Hertz increase in Turns (MH16 from Kuala Lumpur to Amsterdam 7th March 2014 BFO Analysis) up to 7.4Hz 2- As the aircraft is finishing its turn, it is the roll back to horizontal that makes the antenna speed ~120fpm	345.0	495	150	12470	168	12520	175
14	18:28:15	7.134	95.740	38500	Arc-1.2 (from SITA log file) start descent at -1000 fpm while under Sabang radar coverage. (ECON descent at IAS 240kt)	342.5	492	-1000	12460	142	12480	143
15	18:33:15	7.860	95.541	36500	Increase descent -3000fpm (with speed brakes to get quicker under 10000ft)	342.5		-3000				
16	18:35:25	8.005	95.504	28000	IDKUT waypoint	342.5	406	-3000				
17	18:39:58	8.400	95.392	16000	Start-Phone Call -1 attempt	342.5	347	-3000		89		88
18	18:40:33	8.462	95.372	15200	Phone Call 1 attempt	342.5	347	-3000		89		87
19	18:40:56	8.494	95.364	14000	End of Phone Call 1 attempt	342.5	335	-3000	~12450	89		89
20	~18:41:30				Exit from Sabang radar coverage at 10000ft							
21	~18:43:45	8.804	95.263	~5000-~10000	Bottom of Descent	342.5	277					
22	18:46:45	8.917	95.188	~5000-~10000	Major-Turn3 Left after descent. Repeat same manoeuvre for the third time as at IGARI and at 18:25:40: exit radar coverage and significant change of heading.	270	277					
23	~19:05:00	7.985	94.850	~5000-~10000	Entry into the ash cloud (estimated from sea level up to 20000ft)	198	~276					
24	~19:06:00			~5000-~10000	Start descent to 3000ft possibly for ash avoidance manoeuvre	198	~270					
25	19:19:00	6.634	94.428	3000	Passing close to Kate Tee's boat (~19:19:00)	198	262					
26	19:19:30	6.604	94.417	3000	NOPEK (Exiting Malaysian FIR)	208	269					
27	~19:30:10	5.871	94.042	3000	Start climb to 23000ft (VNAV ECON Climb) IAS 298/0.620M	208	270	~3500/~4500				
28	~19:36:00	5.364	93.788	20000	BEDAX	208	395	~4000				
29	~19:37:00	5.271	93.730	23000	ToC at 23000ft (then select mode: VNAV CRZ ECON) 268/0.619M	208	414	0				
30	~19:37:30	5.169	93.691	23000	Major-Turn4 before Direct to ISBIX	192	393	0				
31	19:41:03	4.783	93.690	23000	Arc-2	180	390	0	11540	111	11500	111

32	20:22:00	0.365	93.670	23000	ISBIX	180	386	0				
33	20:41:05	-1.611	94.163	23000	Arc-3	166	385	0	11730	147	11740	141
34	21:41:27	-7.832	95.716	23000	Arc-4	166	381	0	12790	169	12780	168
35	22:22:22	-12.201	96.840	23000	YPCC - Cocos Island	166	380					

At Cocos Islands a decision had to be made on the next leg. If the assumption is made that the PIC went on using documented waypoints, there are two suitable candidate routes i.e.T41 and M641 towards Learmonth and Perth respectively. At the current altitude and speed, they both post excellent compatibility with Inmarsat data at Arc-5 and at the phone call of 23:14 UTC. At this altitude of 23000ft and at the given ground speed of 380kt, route G200 to Christmas Island, to the North-East, does not match the BFO Inmarsat data. On the other hand, if the PIC stopped following waypoints then there would be a large family of possibilities.

How to decide between the two routes T41 and M641? If one assumes that the PIC did actually target an airport for landing, then the consideration of the remaining weight of fuel onboard and its corresponding maximum range will provide a way to choose. Our fuel computations and consumption simulations indicate that around ~10T of fuel would have remained at Cocos Islands. The distance between Cocos Islands and Learmonth is ~1160Nm while Cocos Islands are ~1600Mn away from Perth. The Flight Crew Operational Manual (FCOM) indicates that, with zero wind, Learmonth could have been potentially reachable with 14 tons while Perth would have needed at least 17.5 tons. Proceeding to Learmonth direction is also the choice by default because it is the shortest route to reach the Australian continent and could have been the target of the PIC's plan that could not be followed eventually.

Consequently, the logical choice would be to take route T41 towards Learmonth which will be the first to be analysed. But as the end of flight at Arc-6 and Arc-7 on route M641 posts interesting features, this one will be analysed also. Table 2 presents option 1 to Learmonth and Table 3 presents option 2 to Perth.

Option 1: Route T41 to Learmonth

Table 2: CAPTION Trajectory key events with their time tag and location on route T41 to Learmonth from Cocos Islands till the End of Flight (Option 1)

36	22:41:22	-13.214	98.415	23000	Arc-5	123.5	377	0	14590	206	14540	204
37	23:14:30	-15.115	101.440	23000	Phone Call from 23:14:01 to 23:15:02 BFO is 217Hz on average as provided by Inmarsat. From this point several alternate paths are possible without using waypoints	123.5	372	0		219	0	217
Southern option among the alternate paths:												
38	23:54:25	-17.270	105.001	23000	VERIS	123.5	362					
39	00:10:58	-15.813	105.307	23000	Arc-6	35	359	0	18020	251	18040	252
40	00:19:29	-15.711	106.108	5000	Arc-7: according to best BFOs	180	350	-3000	18400	180	18400	182
41	00:19:37	-15.332	106.290	0	SATCOM Log-On Completed – probably ditching at this Last point	175	150	-13600	18440	-1	18410	-2
Note					*Distance Cocos Islands to Learmonth= 1160Nm*							

Option 2: Route M641 to Perth

Table 3: CAPTION Trajectory key events with their time tag and location on route M641 to Perth from Cocos Islands till the End of Flight (Option 2)

42	22:41:22	-13.673	98.051	23000	Arc-5	141.3	377	0	14510	201	14540	204
43	23:14:30	-16.267	100.221	23000	Phone Call from 23:14:01 to 23:15:02 BFO is 217Hz on average as provided by Inmarsat.	141.5	372	0		217	0	217
44	00:10:58	-20.099	103.623	23000	Arc-6 close to route M641	60	359	0	18040	252	18040	252
45	00:19:29	-20.311	104.323	5000	Arc-7: according to best BFOs	180	350	-3200	18410	182	18400	182
46	00:19:37	-20.313	104.324	0	SATCOM Log-On Completed Ping 28 - Last point ditching	180	150	-14000	18410	-2	18410	-2
Note					*Distance Cocos Islands to Perth= 1600Nm*							

Section 10 provides details on each key event along with complementary information and/or its justification. The paragraph numbering follows the events numbering making the reading easier.

9. Key aspects of the identification of the trajectory

The reconstructed trajectory was built taking into account all the extra elements presented in Sections 3 to 7 which provide additional waypoints to consider with some indication of timings.

In addition, a large number of real-time simulations were performed taking into account the quasi-real meteorological conditions along the flight. Philippe Gasser, during the CAPTIO initiative, has developed a specific add-on software application feeding our FsX-PMDG simulator with the input of 4D-interpolated Nullschool meteo data [16] every 5 seconds.

During these simulations, several VNAV (Vertical Navigation) flying modes have been tested. Table 1 figures result from the best simulation which after Arc-1 used a sequence of three successive B777 flying modes best adapted for the corresponding phases of flight as the aircraft descended, climbed and flew level. From Arc-1.2 until the climb after flying by Kate Tee's boat the aircraft simulator automatically selected a 240kt Descent mode. The follow-up climb phase was flown in ECON Climb mode. And the long leg from the top of this climb just before Arc-2 until Arc-6 was flown in ECON Cruise mode at 23000ft. The cost index had been set to 0 after IGARI to maximise the range.

Thus, **there was NO MANUAL CHANGE OF SPEED from Arc-1**. The speed evolution came only from the FMS automation algorithms of the automatically selected flying modes as the FMS interprets by itself the pilot changes of altitude accordingly. Thus, from Arc-1 onwards the speed was continuously automatically controlled by the aircraft. Thus, from the top of the climb after BEDAX waypoint, the FMS automatically and continuously adjusted the speed slightly by few knots to take care of the continuous fuel weight decrease.

The CAPTION reconstructed trajectory BFOs in both options matches the available Inmarsat measured BFOs and BTO. The standard deviation of the BFO residuals (BFORs) is ~2.3Hz for both options. When considering the available extra BFOs (like those we named Arc-1.1 and Arc-1.2 for example), which are not usually considered by the other studies, the BFOR σ becomes ~3.5Hz.

For both route options, the computed fuel consumption results in a fuel weight value lower than the precision of the model meaning that at Arc-6 and Arc-7 the remaining fuel weight was close to zero. This result matches normal flight expectations with engines quasi-nominally performing as assumed in the official report [2]. **The end of flight was provoked by a sequential flame out of the engines due to fuel exhaustion in the vicinity of Arc-6.**

10. CAPTION key events detailed description

This section provides the rationale for each key event with complementary information and graphical illustrations when necessary. Let's remember that a large number of ground speed figures are not computed averages via the ratio distance over time, but they are provided by our simulator and come exclusively from the FMS automation itself using the input of the actual local meteo conditions provided every 5 seconds via 4D-interpolated Nullschool data publicly available in [16].

Let's analyse the key events one by one once the aircraft was levelled just after its top of climb and just after IGARI waypoint heading to BITOD waypoint as illustrated in Figure 7 by the yellow arrow. It was in a Singaporean control area delegated to Kuala Lumpur Air Traffic Control (ATC).

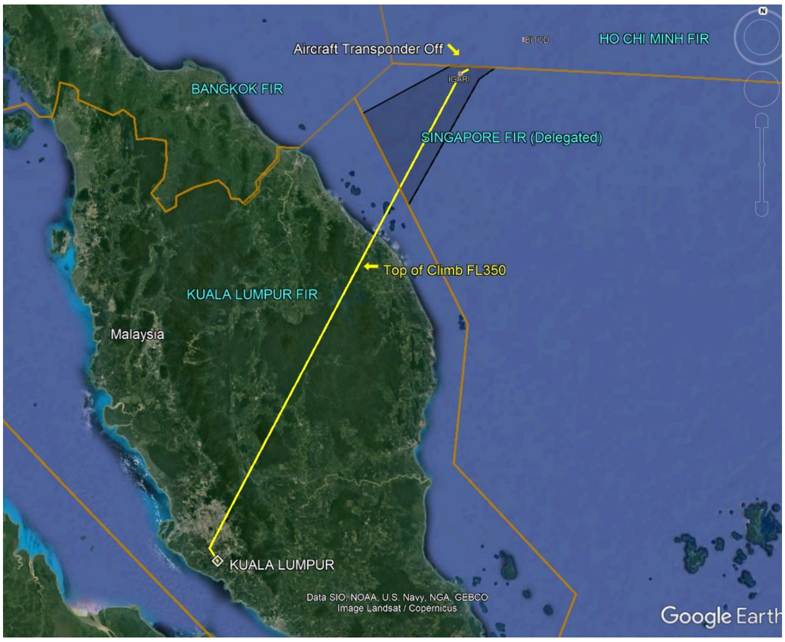

Figure 7: MH370 flight leg fully traced by ATC until its Secondary Radar label disappearance

10.1 Transponder switch-off

This refers to Section 3 "The transponder manual switch-off… and RAT deployment". It is most probable that this was done manually in the cockpit. Not only would this make the aircraft information disappear on the secondary radar ATC and military displays, but also mislead the military tracking algorithms which did not properly capture the U-turn in real-time. It took several days for the military to reconstruct the flight path and the 180° turn.

10.2 180° U-Turn after IGARI

Being "invisible" to the Civil ATC and "isolated" from the military, the aircraft performed a quick U-Turn. This was made at the boundary of the military radar coverage and in the Vietnamese ATC area. Military data shows a turn but this capture was an incomplete tracking as the ADS-B data disappeared. Thereafter, several disconnected legs needed several days to be identified and linked together.

The turn could have been performed via the auto-pilot as described by V. Iannello [3], but alternatively it could have been driven fully manually, as shown by our simulations. Both ways show similar characteristics of the U-Turn.

This was cleverly perpetrated at the limit of the radar coverage following a model repeated several times later: exit radar coverage, change direction (and possibly altitude) and re-enter the radar coverage "as a new flight" with no recent history for that radar (cf paragraphs 10.12 and 10.22).

10.3 Left Electrical Bus isolated or Electrical Power switch-off?

There is basically no doubt that some or all of the electrical power was switched-off voluntarily. The exact time when the Electrical Power switch-off occurred is unknown. But the absence of an ACARS routine message due at ~17h37 and the impossibility at 18:03 for a phone call from the ground to be forwarded to the AES provide an estimate of the last moment of the switch-off. The SATCOM did not transmit any data nor any signalling information between 17:07 and 18:03 which means that, at least, the left bus had been unpowered as there was no proper logoff from the AES which is powered by this bus.

There are two possibilities for performing such a switch-off: either in the cockpit by isolating the corresponding generators via switches on the overhead panel, or in the Electronic Equipment Bay via a manual hard disconnection of breakers of the left and right main transfer buses. The cockpit scenario is most probable since it has been demonstrated that the transponder was manually, properly switched off.

In the case of an action in the cockpit, two scenarios (or interpretations) are possible (cf Sect. 3):

1- The left bus only has been unpowered and the aircraft went on powered by the right bus and under the control of the auto-pilot (Scenario 1).

2- All the five generators have been isolated which is equivalent to a complete switch-off of the electrical power. Subsequently, this would have triggered the take-over by the Standby buses with the deployment of the RAT (Scenario 2).

More details on the electrical switch off cases have been provided in Annex 1 of the CAPTIO analysis report [1].

Both scenarios lead to the same trajectory and same timing. Our opinion is that Scenario 2 provides a convincing rationale for the power switches being back on later at ~18h23 UTC.

10.4 RAT deployment (scenario 2)

The RAM Air Turbine (RAT) automatically deploys as the ultimate electrical and hydraulic power supply before the battery. As a consequence of the limited power supplied by the RAT, the Electrical Management System had to perform some systems shedding in order to match the available energy supply (*note: it is not sure if shedding is still active in such a minimum power situation*).

In addition, a RAT critical feature is that it does not supply power for charging the main battery (cf FCOM). To the contrary, the battery energy contributes to power some of the equipment (*possibly under the EMS supervision, tbc*). Thus, it decreases and its voltage consequently i.e. from the nominal 27V down to approximately 13V. At this voltage level the battery stops supplying power.

Thus, after the U-Turn, the RAT and the main battery were most probably the only sources of electrical power.

10.5 Manual piloting (scenario 2)

Because of either a systems shedding or a pre-established degraded mode configuration, some functionalities ceased operating, in particular the auto-pilot functions like the LNAV and VNAV, forcing the PIC to pilot the aircraft manually. This is possible by using waypoints as simple guiding navigation targets displayed on the navigational display (ND) with the intentional path indicated in dotted lines. Once a waypoint is entered in the FMC, a purple direct route is displayed on the ND. The pilot needs only to adjust the heading to follow the provided purple line.

10.6 Direct to KADAX waypoint (near Khota Baru)

Considering the publicly available radar data, after the U-Turn the aircraft path followed a Direct to KADAX waypoint in the northwest of Khota Baru. The U-turn was a constant left turn to a south-westerly direction i.e. a 180° turn to the left to a track almost parallel to the boundary of Kuala Lumpur FIR and Bangkok FIR and back towards the Malaysian Peninsula, in the direction of the waypoint KADAX. It overflew this point before proceeding over the Malaysian inland.

10.7 Waypoints LOSLO, ENDOR, OPOVI, VAMPI and MEKAR

From KADAX waypoint to the south of Penang island (ENDOR and OPOVI) the flight path followed the FIR boundary between Bangkok FIR and Kuala Lumpur FIR first and Bangkok FIR afterwards. This was done on purpose so that the Air Traffic Management (ATM) controller on duty on each side of the boundary might have assumed that his or her counterpart controller was actually controlling the aircraft.

People in Command wanted the aircraft to be seen as flying a standard trajectory along waypoints and standard routes especially in such a sensitive area like the Malacca Straight monitored by Kuala Lumpur and Bangkok civil and military ACCs.

After Penang, the flight took the direction of waypoints VAMPI and MEKAR with a quasi-over-flight of Pulau Perak Island. At 18:03 UTC, a phone call attempt from the ground AOC did not go through.

These legs, including leg 10.6, are well-documented thanks to the civilian radar data of the approaches to Khota Baru aiport and to Penang airport as provided in [3] and illustrated in Figure 8.

Figure 8: Clever path in-between Malaysia and Thailand FIRs depicted by the civilian radar plots (Purple)

10.8 First officer mobile phone detected

When passing to the south of Penang Island between waypoints ENDOR and OPOVI, the first officer's mobile phone was detected by a Penang mobile phone terrestrial communications system at 17:52:27UTC. This provides a key point in two aspects: the geographic location and the timing. No clear interpretation so as to why only this gsm was detected and why other mobiles were not, such as the pilot's or the passengers' for example.

10.9 Exit from Western Hill radar coverage

The maximum detection range of the Western Hill Penang radar is ~255Nm. Nominally, the radar can only detect aircraft flying at altitude ~31000 ft and above, with a 5000 ft height precision. The range of the aircraft last detected spot is ~243NM which is consistent with the radar capability.

The aircraft disappeared from the military radar records of this radar at 18:22:12 UTC. The Last Radar Spot Position (LRSP) is at approximately10NM beyond MEKAR waypoint in the northwest direction on route N571 i.e. ~(6.5770N, 96.3423E) along the corresponding track of 296°. This is illustrated in Figure 9.

According to the latest estimation, when exiting the radar coverage, the aircraft is supposed to have flown at ~38500ft with a ground speed of around ~495kt.

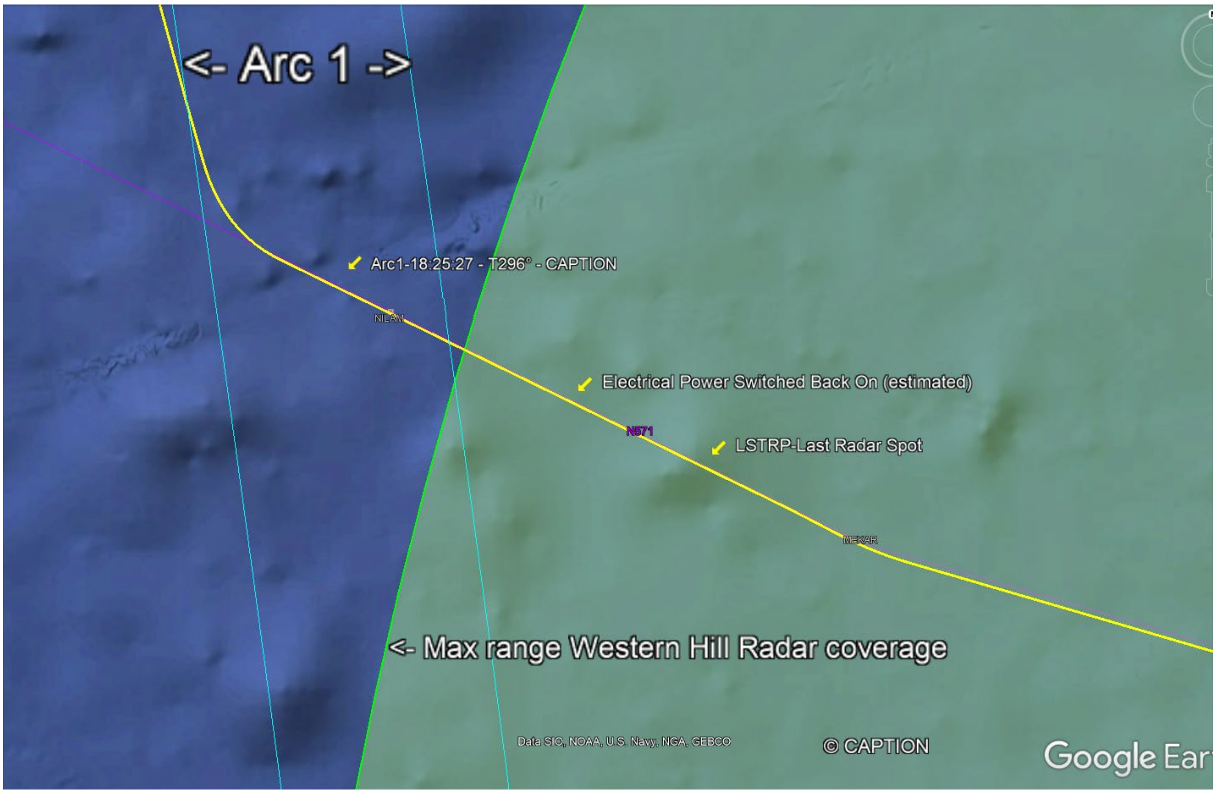

Figure 9: Exit from Western Hill radar coverage and Arc-1 crossing

10.10 Electrical power switched back on

The electrical power of the AES was switched back on just after exiting the Western Hill radar coverage meaning that at least the left electrical bus was re-powered. Bearing in mind the necessary time for booting, it is estimated that this occurred at ~18:22:30 UTC. Is it a coincidence or a well-thought action?

If the right bus was not isolated and was still powering the aircraft, there would have been no reason to reactivate the left bus as the aircraft would have been fully functional at this point in time. It could have continued that way under the same "semi degraded" situation. Still, maybe reactivating some comfort systems was a possible reason, although this is a weak explanation. Most probably the left bus re-powering was the consequence of a full electrical power re-activation and this must have been necessary, but why?

A convincing modus operandi is described by Captain Blelly in [30] which justifies the reason for the electrical power switch back on. In Annex 1 it is shown that the correlation of the technical aspects coming from Inmarsat data with operational actions and with the electrical status of the systems provides supporting elements to explain the sequence of events.

Referring to the assumption that the PIC had an initial plan in mind, the return of the power at such a point in time was a necessity for an acceptable continuation of the flight. This should also be placed in the context (cf. below) of the presence of surrounding traffic: an Emirates flight close behind and Indigo traffic coming ahead and the aim to stay undetected.

The sequence of actions at the power switch back on is described in Annex 1 and can be summarised as follows:

1) the IDG were switched back on. This powered up the SDU, the ACARS and the non-critical functions of the IFE.
2) Then a Reset Data Link command was executed via the Master Manager page before the SDU could become operational. This switched the ACARS media to the default central VHF in data mode. In addition, this reset the company and flight information to default values and thus making the Flight ID not available anymore.
3) Quickly afterwards, the ACARS was switched to "Auto Message Off" to block any message transmission as the Reset Data Link above had put it on.
4) The SDU reconnected to the Inmarsat network recognised only by the AES ID transmitted in all messages with no exception. The Log-on request could not include the missing flight ID.

10.11 Arc1 - first Inmarsat Ping

The consequence of switching the electrical power back on is that the SATCOM of the AES (SDU) rebooted and began to function, producing the first Inmarsat ping with a logon request coming from the aircraft also called Arc-1. This proper logon is an a-posteriori confirmation that the SDU did not log off properly earlier on.

This logon request was recorded at 18:25:27 UTC and only concerned the SDU while selected systems controlled from the cockpit remained off, like VHF Radios and the SSR transponder for example. As the SDU is located in a separate location (in the cabin ceiling close to the middle-rear), the People in Command could not control its powering. The CAPTION Arc1 crossing location is shown in Figure 9.

10.12 Turn right to a northern direction

The sequence of actions i.e. exiting radar coverage and making a significant change of heading recalls the manoeuvre executed after IGARI where the aircraft flew at the limit of radar coverage and turned back. The rationale for this turn here after NILAM might be the conjunction of several reasons: the surrounding traffic (Emirates flight EK343 closely following but more importantly Indigo flight 6E53 ahead of schedule and coming ahead) as well as Sabang radar avoidance in addition to a possible change of plan after the emergency arising from possible battery discharge consequences.

This manoeuvre proceeded using the same principles: when potentially seen by one surveillance system, get out of its reach and then execute a diversion to mislead real-time tracking systems which could not make the connection between these different unlinked radar plots going out and coming back in different directions.

The initial intention could have been to perform a simple descent while on route N571. But the proximity to the surrounding traffic may have put pressure on the PIC who reacted differently to the original plan.

Our opinion is that after leaving Western Hill coverage and in order to avoid the surrounding traffic to be able to pass under route N571, the aircraft turned north and descended to get out of range of the Sabang radar coverage potentially capable of tracking it. Thus, its next move was to exit this coverage completely. IDKUT is the most appropriate waypoint that could be used in the direction provided by the best BTO/BFOs. This was possible thanks to the LNAV function back in operations. Figure 10 sketches this manoeuvre.

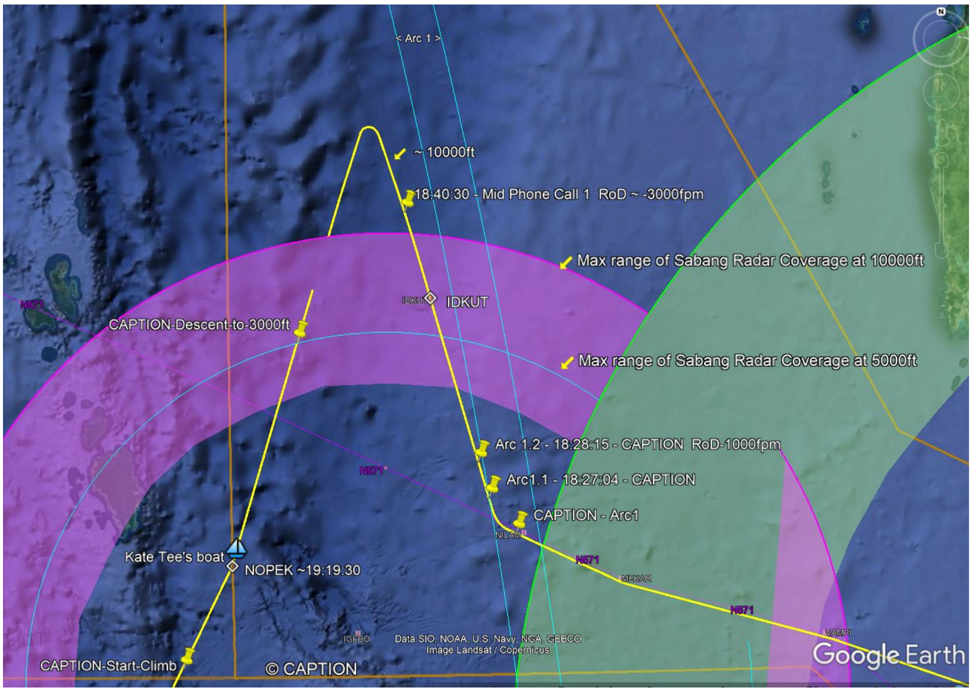

Figure 10: Leg after Arc1 including a northern turn to IDKUT
(Green area is Western Hill radar coverage, Purple area is Sabang radar coverage at 10000ft)

On that day, Sabang Radar was not operational. It is operated part-time for fuel-saving reasons. Whether the PIC were aware of this is unknown.

10.13 End of turn to the north – Arc1.1

SITA communication log files report that at 18:27:07 there was a set of BTO and BFO that could be considered. So far, they have not been considered but just mentioned by most of the analyses of which we are aware. They will be used here to infer CAPTION trajectory, as well as few others at later times.

At this time the BTO provides the information that the plane had to turn and the BFO matches only a northern turn. But, considering all track directions, no track leads to a BFO within the Inmarsat measured 175 ±7hz margin. The best BFO of 165Hz was found at 345°. But, considering waypoint IDKUT as the target and an approximate aircraft ground speed of around ~495kt, it was found that to match the Inmarsat measured BFO, the rate of climb (RoC) must be ~150 fpm. This could come from a small fluctuation after the turn as there are two possible, non-exclusive explanations for this small RoC:

1- referring to Richard Godfrey's analysis [15], during turns, the BFO increases up to 7.4Hz instead of the admitted 7Hz.

2- As the aircraft was finishing its turn to the right and thus was banking to the right, the roll back to the left to return to the horizontal made the antenna move upwards and towards the satellite with an estimated speed of ~120fpm.

Arc1.1 is illustrated in Figure 10. At this point the aircraft route is estimated at ~342.5° on route to IDKUT waypoint.

The reason for initiating the right turn to the north cannot be found in the technical data. One interpretation is that it was not planned initially but was provoked by an emergency situation and by the presence of Indigo traffic 6E53 incoming ahead which took off from Chennai 30 minutes ahead of schedule. Thus, instead of descending and exiting out of Sabang radar coverage on route N571 and then turning left, the PIC may have decided to perform this diversion another way in safer conditions and also, maybe to not be seen by this traffic.

10.14 Start descent – Arc1.2 to IDKUT waypoint?

SITA communication log file reports that at 18:28:15 there is a set of BFOs that could be considered.

At this point in time, two options are possible. The first one, already described in CAPTIO study [1], is to consider that the aircraft was proceeding with a contingency procedure and had turned left back to track 296° before starting a descent parallel to route N571. This has been also considered by the IG in [17] but in this case the flying by Kate Tee's boat is not timely and is missed by ~25 minutes i.e. 18:53:46 UTC compared to ~19:19:00 UTC. According to this timing, when the sighting took place, the aircraft would have been already gone by 120 Nm to the southwest. This does not fit the testimony and its analysis provided in unprecedented detail in Annex 2.

The second option to consider is evoked in paragraph 10.13 which is: no turn left but continuing on a **northern direct route to IDKUT** waypoint. At this time and location - on its way to IDKUT - the aircraft flying at approximately ~490kt, the rate of descent (RoD) has to be -1000 fpm to match the Inmarsat BFO. Thus, the aircraft must have initiated a descent corresponding to the FMS 240kt (or 250kt) Descent mode. The aircraft route is still estimated at ~342.5°.

This is illustrated by the ARC1.2 pin in Figure 10.

10.15 Increased descent rate

Considering the Sabang radar surveillance capability in this area, and in order to fly by Kate Tee's boat at about 19:19:30, the aircraft must have turned sharply southwards at some point. To match this timing, we are of the opinion that the PIC accelerated the descent of the aircraft in order to get more rapidly out of the Sabang Radar coverage in order to repeat their "now becoming usual" manoeuvre: get out of radar coverage, turn and come back as a different flight impossible to be linked with the profile flown a few minutes ago. They probably used the speed brakes to achieve a descent rate of about ~-3000fpm. This is a usual B777 practice for achieving a fast descent because it is a very good glider. An additional reason for this increase of rate of descent might also be an ash cloud avoidance manoeuvre as explained later in the note of paragraph 10.23 and visible in Figure 11.

We are of the opinion that after this descent they performed a left turn when being undetectable by the Sabang radar, i.e. when flying at an altitude of 10000ft or below as illustrated in Figure 10 repeating the same type of escape strategy for the third time as already done after IGARI and NILAM waypoints.

10.16 IDKUT waypoint

Considering that the LNAV and VNAV functions were still in operation (scenario 1) or were back to normal operation (scenario 2), IDKUT waypoint is the best candidate for accomplishing the descent as a selected reference waypoint for adjusting the descent down to 10000ft or below. It is located at

[8.005°N; 95.504°E]. In our simulations the overflying timing was ~18:35:25 UTC at the altitude of ~28000ft on a route at ~342.5° as depicted in Figure 10.

10.17 Start of Phone Call -1 Attempt

The communications log file reports that the start of an attempt by the Airline Operational Centre (AOC) on the ground to place a phone call to the aircraft was at 18:39:58. The attempt was about one minute long without going through. Along this track, at the instantaneous speed automatically selected by FMS, at this rate of descent, all BFOs are well matched during the full phone call attempt as reported in Table 1.

10.18 Phone Call-1 Attempt

In this study, phone call 1 attempt refers to the time tag selected to be the middle point in time of the reported attempt to connect to the aircraft which lasted about one minute. It is at ~18:40:33. Considering the Inmarsat BFO and the ground speed of ~347kt measured during our FsX-PMDG flight simulations with actual 4D interpolated meteo data, the aircraft must have been in descent at the rate of ~ -3000fpm on route at ~342.5° (cf Table 1).

In addition, this reading of the Inmarsat BFO explains a-posteriori the selected value of the increased RoD.

10.19 End of Phone Call -1 Attempt

This event is de facto similar to the two above. It provides the geographical location of the most northern point of the phone call attempt where the aircraft was still descending.

10.20 Exiting Sabang radar coverage at ~10000ft

At this altitude, exiting the Sabang radar coverage occurred around ~18:41:30 UTC during our flight simulations and still following the same track at 342.5°.

10.21 Bottom of Descent

At this stage either the altitude of ~10000ft is the bottom of descent or possibly lower than the 10000ft required to be out of the Sabang radar capability. According to Kate Tee's testimony (cf paragraph 10.25), the aircraft had descended further between her sighting Part 1 and Part 2, which indicates a continuation of the descent or that a possible further descent took place. This is addressed in paragraph 10.23 when discussing the potential ash cloud encounter.

Reaching altitude ~5000ft took place at ~18:44:45 in our FsX-PMDG flight simulations with a measured ground speed of ~277kt automatically controlled by the "ECON Descent 240kt" of the FMS.

10.22 Major-Turn3 Left

After being levelled at a low altitude (estimated between 10000ft to 5000ft), and being out of radar coverage, the aircraft could perform the Major-Turn3 to the left to pass safely under routes N571 and P574, repeating once more the same type of manoeuvre for the third time as at IGARI and at NILAM waypoints: exiting radar coverage first, followed by a significant change of heading.

Based on Kate Tee's testimony, our opinion is that the next target waypoint was NOPEK nearby her boat's location i.e. within 2Nm. Thus, the aircraft took a direct route to NOPEK waypoint following a track at ~198°. This fits well within the viewing sector of Kate Tee's sighting Part1 as analysed in Annex 2, which is between 185° and 199°.

10.23 Ash cloud encounter?

According to Section 6, a potential ash cloud coming from the Mount Sinabung volcano could have been transported in this area. NOAA simulations results estimate that the possible encounter altitude was between sea level and the altitude of ~20000ft. Our flight simulations indicate that the entry into the ash cloud could be at roughly ~19:05:00 UTC. The detailed analysis of the ash cloud journey is provided in Annex 3.

It is interesting to note that Kate Tee's sighting started like a rising star meaning that it was close to her sight horizon at 5000ft, which happens to be close to the entry of the aircraft in the potential ash cloud as shown in Figure 11.

Note: According to the NOAA simulations, the spread of the ash cloud might be such that around 18:30:00 UTC its boundary was geographically close to NILAM and intercepted by the leg to IDKUT. The fact that none of the two Emirates or Indigo flights complained confirms the absence of ash at cruise level. During the descent towards IDKUT the presence of ashes below ~20000ft may be an additional reason why the aircraft increased its rate of descent by using its speed brakes to get below the ash cloud. Thus, this paragraph could be in fact on a re-entry into the cloud (cf paragraph 10.15).

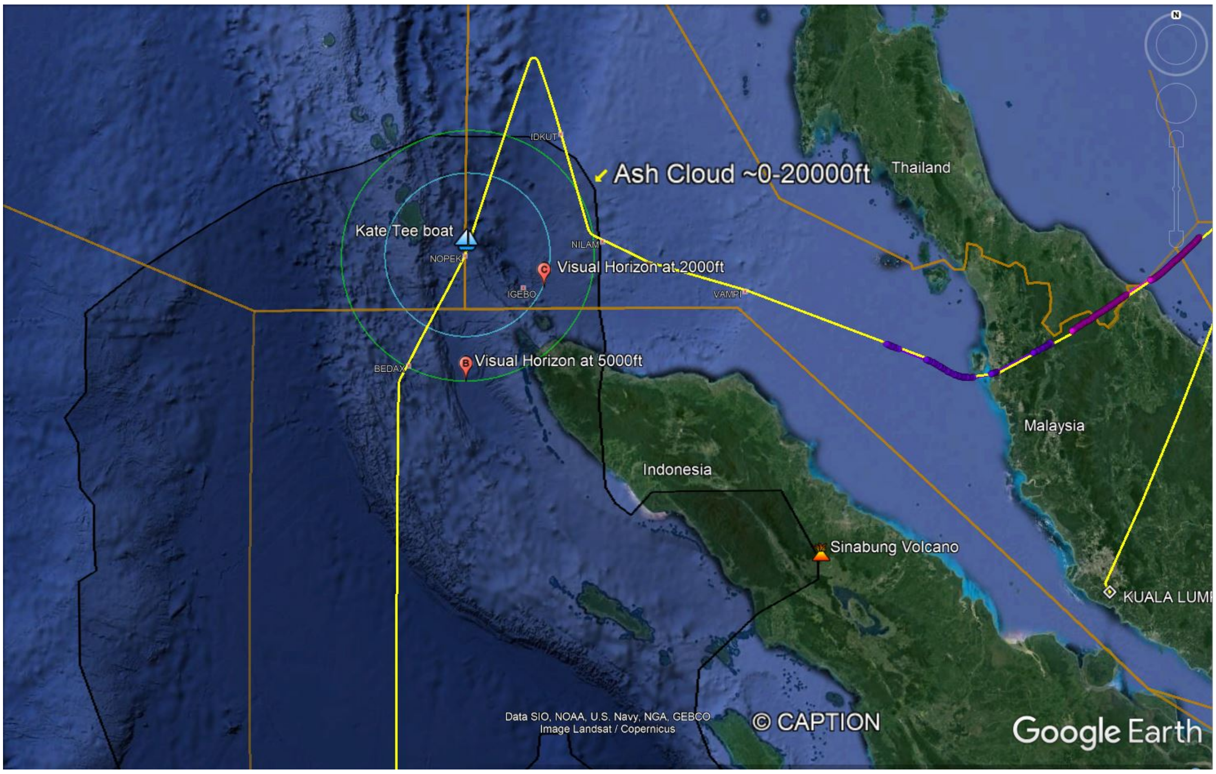

Figure 11: Encounter of the ash cloud. Ashes were most likely located between Sea level and 20000ft.

10.24 Crossing routes N571 and P574 and descending to 3000ft

At this location the aircraft started the manoeuvre for crossing the major routes N571 (which it had quit some time earlier) and P574. It was already at an adequate level to pass below these routes.

But, the standard flying procedure to avoid ash clouds [24] is to descend with the hope of reaching cleaner fresh air and avoid engine damage. Thus, Kate Tee's indication that the aircraft was descending is consistent with an ash cloud avoidance descent as explained above. It could also be explained by the intention to fly below the 5000ft altitude coverage of the Sabang radar.

Later, Kate Tee estimated that the aircraft passed by her boat at an altitude between ~2000ft and ~4000ft. Thus, one could consider the mid-altitude of ~3000ft as a working hypothesis for further calculations and simulations. In addition, according to the sighting, the aircraft appeared first as a rising star. Thus, one could make the assumption that the descent started not long after the entry into the ash cloud which is inside in a third tier of Kate Tee's visual horizon i.e. at about ~19:06:00.

10.25 Passing by Kate Tee's boat

This event has been comprehensively analysed in Annex 2 and summarised above in Section 5 "Sailor Kate Tee's eye sighting report". For us, the key reported event of her sighting is an aircraft passing-by her boat at about ~19:19:00 UTC. This timing is the result of the detailed analysis of her boat orientation provided in Annex 2. The second main results are the track directions of the 2-leg broken-line trajectory close to 198° for the first and second parts of her sighting and close to 208° for the exit out of her visual horizon. This is sketched in Figure 12.

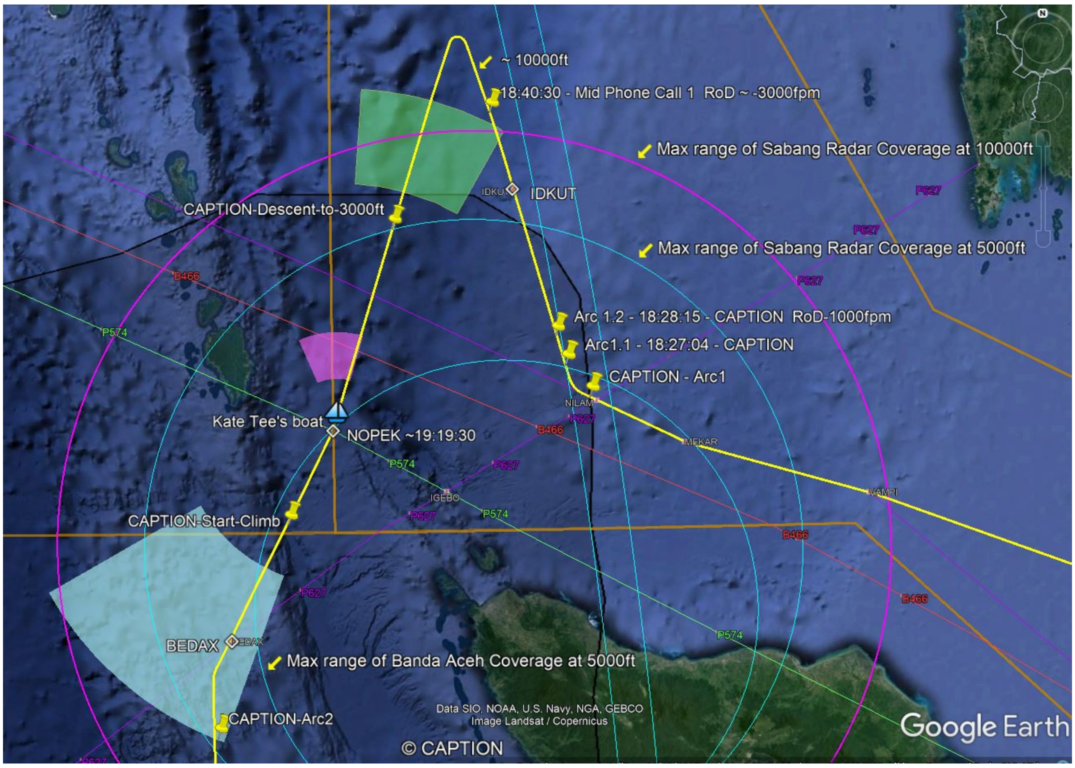

Figure 12: CAPTION leg from Turn3 to BEDAX via NOPEK passing through Kate Tee's sighting sectors

10.26 NOPEK waypoint - Exiting Malaysian FIR

Assuming that the PIC used waypoints for ensuring lateral navigation (LNAV) and accepting that Kate Tee's sighting is about the MH370, then NOPEK is the most realistic next waypoint. It was located within 2Nm of the boat and it is a logical path after the turn outside Sabang radar coverage, with the sailor sighting part1 and part2 angular sectors and with the indication of a turn when passing by the boat as shown in Figure 12. In addition, the leg NOPEK-BEDAX fits within the sighting part3 and part4 angular sectors when the aircraft went away from the boat.

At NOPEK waypoint, the aircraft is believed to have turned and taken a route at track ~208° to BEDAX waypoint. Doing so, the aircraft left FIR Malaysia and entered FIR Chennai into its extreme south-eastern corner, not covered by any Indian surveillance system, before entering into FIR Djakarta in a south-westerly direction. From the Indonesian Air Traffic Management (ATM) perspective, nothing could have been found suspicious in such a route. This was probably not seen as a threat by the Indonesian military surveillance, if any. It proceeded also as a kind of "normal" flight between Andaman Islands and Sumatra, passing also below Banda Aceh secondary radar coverage.

10.27 Start climb to 23000ft

Several reasons combine to explain the necessity of climbing at this stage. The first one is not operational and comes from the a-posteriori necessity for the aircraft to have reached Cocos Island at 22:22:22 UTC if one accepts the results outlined in section 7 "Seismic data recorded at the Cocos Islands". The speed of the aircraft when passing over NOPEK waypoint is not high enough to be able to achieve this time target. Another reason is to climb above the ash cloud ceiling which was about ~20000ft. A third reason is that the aircraft had stayed long enough below Sabang radar detection capability.

Our flight simulations show that an altitude of ~23000ft is the altitude at which the FMS VNAV flying mode called CRZ ECON (for economic cruise) automatically sets the IAS reference at ~298kt (or Mach 0.622) which provides the required ground speed in the range of ~382kt to timely cross Arc3 and Arc4 and later overfly Cocos at 22:22:22 UTC taking into account the actual 4D interpolated meteo.

Thus, our opinion is that the aircraft started an ECON Climb (for economic climb) with an automatically managed rate of climb (RoC) varying between ~3500fpm and ~4500fpm, as recorded during our simulations.

10.28 BEDAX waypoint

As explained in 10.26, BEDAX is the next waypoint best candidate after NOPEK waypoint, fitting with Kate Tee's sighting of the outgoing aircraft, as shown in Figure 12. It was overflown during the climb and on the same track of ~208°.

At BEDAX waypoint, the aircraft had entered the area of the FIR Djakarta a few minutes earlier.

10.29 ToC at 23000ft

This event is interesting because, in our opinion, the PIC waited to be levelled at 23000ft before turning to the next waypoint which is most likely ISBIX intending to target Cocos Island afterwards. Thus, BEDAX waypoint was probably overshot by few nautical miles.

Note: from this point, the constant altitude of 23000ft will be assumed until reaching Arc-6 at 00:11:00 UTC.

10.30 Major-Turn4 before a direct route to ISBIX waypoint

After having completed the levelling off, the aircraft turned southwards in the direction of BEDAX waypoint following a route at track 180°.

10.31 Arc2

At 19:41:03 UTC, and according to our simulations, Arc2 crossing point was found at [4.783°N;93.690°E] as illustrated in Figure 13. The track is 180° and the aircraft reported ground speed is ~390kt and it is levelled. In our simulator, this speed is obtained from the Mach number of M0.621 given by the FMS flying mode VNAV CRZ ECON and automatically selected for the altitude of 23000ft according the current aircraft status and the local 4D-interpolated quasi-real-time meteo.

BTO and BFO estimated values perfectly match Inmarsat measurements and can be found in Table 1.

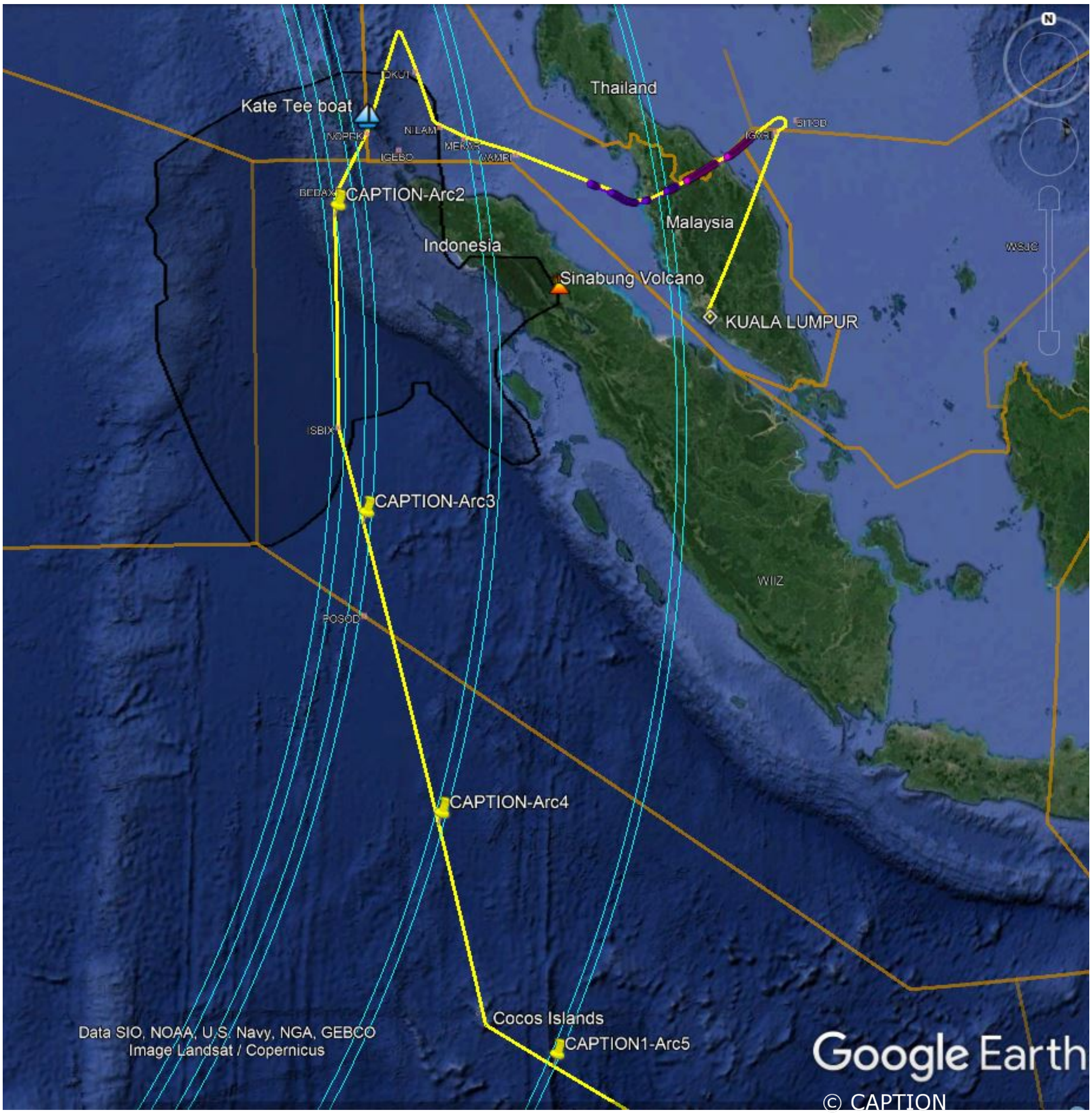

Figure 13: CAPTION crossing points of Arc2 to Arc5

10.32 ISBIX waypoint

Considering the next elements to overfly i.e. Arc3, Arc4 and Cocos Island, their crossing timing and the flight mode, ISBIX waypoint is a logical choice that fits well with the FMS selected Mach number in ECON CRZ mode and thus the path length. Arriving on a track at 180°, the aircraft left ISBIX waypoint on a new track at 166° in the direction of Cocos Islands.

Note: ISBIX waypoint is not far from the exit point out of the ash cloud as shown in Figure 6.

10.33 Arc-3

At 20:41:05, and according to our simulations, Arc3 crossing point was found at [1.611°S;94.163°E] as illustrated in Figure 13. The track continues at 166° and the aircraft ground speed is ~385kt. In our simulator, this speed corresponds to Mach number of M0.612 given by the FMS flying mode VNAV CRZ ECON and automatically selected for the altitude of 23000ft according to the current aircraft status and the actual local 4D interpolated meteo data.

10.34 Arc-4

At 21:41:27 UTC, and according to our simulations, Arc-4 crossing point was found at [7.832°S;95.716°E] as illustrated in Figure 13. The track is still at 166° and the aircraft ground speed is ~381kt as given by our simulator. This speed corresponds to a Mach number of M0.603 given by the FMS flying mode VNAV CRZ ECON Mach number of M0.603 and automatically selected for the altitude of 23000ft according the current aircraft status and the actual local 4D interpolated meteo data.

10.35 Cocos Islands at 22:22:22 UTC

This waypoint has been integrated to the CAPTION trajectory according to the new element detailed in Section 7. In all our flight simulations, overflying of Cocos Islands took place at ~22:22:50 UTC. Recalling that our simulator includes a B777-200LR model and not a B777-200ER, the 30 seconds time difference is found sufficiently small to validate the trajectory parameters.

This waypoint was a key decision-making location for the continuation of the flight and its next track. The wind was from around 120°/135° and its speed between 6 and 14kt.

There were several options for the flight continuation after overflying Cocos Islands.

In his analysis [13], Ed Anderson proposes route G200 with a direct leg to Christmas Island. But at this speed and altitude, the aircraft would be outside Arc-5 even though not too far from its inside boundary. Considering the corresponding track direction at 78.8°, the estimated BFO value at Arc-5 would be 222Hz to be compared to the Inmarsat 204Hz. The 18Hz difference is well above the admissible 7Hz BFO residual (BFOR). Thus, route G200 does not fit the purpose.

Option 1 is the path heading to Learmonth (probably as part of the PIC's baseline plan) following route T41 after a turn from track 166° to track 123.5°. In our simulator, the current speed corresponds to a Mach number of M0.597 given by the FMS flying mode VNAV CRZ ECON and automatically selected for the altitude of 23000ft according the current aircraft status and the actual local 4D interpolated meteo data. The reported aircraft ground speed is thus ~380kt. Subsequently, the estimated BFO value at Arc-5 is estimated at 206Hz i.e. 2Hz above the Inmarsat reference, as reported in Table 2.

Additionally, we ran several local simulations and performed a sensitivity analysis to determine what is the most probable outgoing direction taken by the aircraft by estimating the BTOs and BFOs value at the subsequent Arc-5.

This leads to option 2 in the south-east/south direction. Route M641 leading to Perth some ~1600Nm away is worth considering. At this speed and altitude, this is the most southerly possible route when considering the BTO. Considering the track direction at 141.3°, the corresponding estimated BFO value at Arc-5 would be 201Hz to be compared to the Inmarsat 204Hz as reported in Table 3. The difference of -3Hz is within the admissible ±7Hz BFOR.

10.36 Option 1: Arc-5 heading to Learmonth

The conclusion of the above analysis shows that most likely the aircraft took route T41 heading to Learmonth some ~1160Nm away from Cocos Islands, which would have been theoretically achievable if a potential initial plan at a higher constant altitude was followed from 18:25:37 UTC. At the current altitude of ~23000ft and the subsequent speed the Arc-5 crossing point is just inside the outer boundary. The new track is at 123.5° with the next target waypoint being VERIS distant from Arc-5 by ~452Nm.

Referring to the reported fuel discrepancy in [25], a question remains: at Cocos Islands, were the PIC confronted with misleading remaining fuel indications provided by the instruments? Was this information possibly de-calibrated because of the long electrical power shut down in flight after IGARI? Let's remember that if powered by the RAT only, the FMC does not provide fuel consumption estimate anymore. The behaviour of the estimation algorithm after an inflight sequence switch-Off/switch-On of the power is unknown, even more so in the case of a dramatic battery discharge. Thus, if scenario 2 occurred after IGARI, then there could have been a disruption in the fuel consumption estimation leading to misleading information presented to the PIC.

10.37 Option 1: Phone call-2 attempt from the ground

On route T41 heading to VERIS waypoint and at the mid time of the phone call attempt initiated from the ground which is ~23:14:30 UTC, the corresponding computed BFO is 219Hz for CAPTION.

Note: This information can be used as the bias identified by Inmarsat is used for the computation here and none of the phone calls BFO data was used to compensate for the possible frequency drift during the flight. Thus, the two measures are independent and valid as standalone samples.

In addition, a local analysis of the BFO sensitivity to the track direction shows that perfectly matching Inmarsat 217Hz reference is obtained at 132° which is close to the 123.5° track of route T41 followed at that stage by CAPTION option 1 referred as CAPTION-1.

This is a good indication that at this point in time the aircraft was still on that route.

10.38 Option 1: VERIS waypoint?

Assuming that the aircraft proceeded on route T41, what is the likelihood that it reached VERIS waypoint which is 2.5Nm outside of the Arc-6? Answering this question requires considering Arc-6 BFO sensitivity versus the track direction.

VERIS waypoint happens to be very close to the inner limit of Arc-6. But at the current estimated ground speed of ~362kt, the estimated time arrival is ~23:54:25 which is more than 16 minutes too early to be the crossing point at Arc-6.

The minimum BFOR at Arc-6 is obtained for a track direction of 23° and the ±7Hz margin leads to the angular sector of 23±45°. Assuming a continuous evolution of its direction (no zigzag) because of the remaining time to fly i.e. 16 minutes, this means that at a certain point in time the aircraft was on a northerly direction before being recorded as crossing Arc-6 at the right time.

Note: Please remember that an arc is a geographical location at a specific time.

Thus, the crossing point is somewhere else, after passing VERIS waypoint. A set of possible paths is thus possible as illustrated in Figure 14. This set of paths is based on the maximum possible range at the same constant altitude of 23000ft and same speed and finishing at 00:19:29. VERIS waypoint could have been a decision point and was probably the last possible waypoint on route T41. Two extreme cases are illustrated in Figure 14: turning to the north towards Christmas Island (Yellow) or being the approximate place where the right engine stopped or flamed out which could explain a southerly initiated circle (Green).

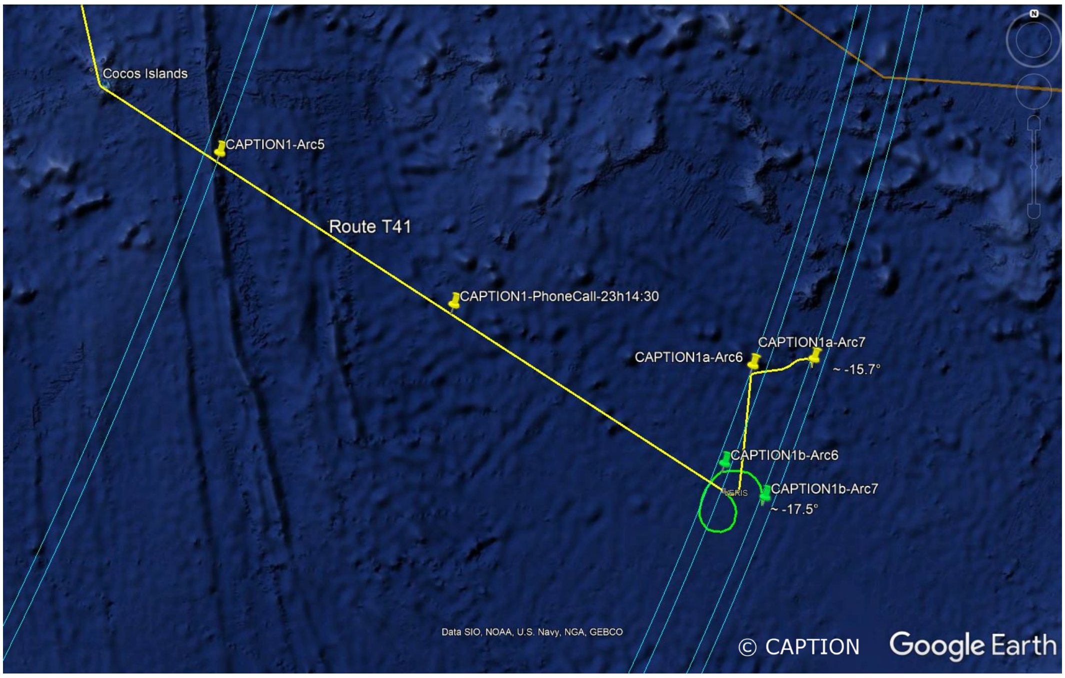

Figure 14: Option 1: Possible paths (Yellow and Green) from the vicinity of VERIS to Arc-6 at 00:10:58UTC

The northern assumption (in Yellow) is proposed as it corresponds to a possible check made at VERIS waypoint where the PIC could have realised that they were not going to make it to Learmonth (~600Nm), possibly because the prediction of remaining fuel evolved more rapidly or because something happened onboard. In addition, going back to Cocos Islands (~560Nm) was further than heading to Christmas Island (400Nm). Thus, the safest alternate route to land was Christmas Island i.e. select a track at 3° after VERIS waypoint.

The circle assumption (in Green) fits better with a fuel exhaustion, flame out or technical problem concerning the right engine. One should remember that if scenario 2 described in paragraph 10.3 is considered, the power supply by the RAT only means that the Thrust Asymmetry Control (TAC) button has been reset to Off. Whether it had been rearmed is unknown. In addition, the snail shape comes from the fact that at Arc-6 the trajectory must be northwards to match the Inmarsat BFO.

10.39 Option 1: Arc-6

Altogether, the zone of possible crossing points on Arc-6 is limited between ~15.8°S and ~ 17°S approximately as delineated in Figure 14. At the crossing point the assumed direction is 23±45° to satisfy the BFO constraints.

10.40 Option 1: Arc-7

Recalling that this BFO corresponds to a logon request initiated by the AES, something happened after the Arc-6 ping. It is commonly accepted that this happened after the engines flame out and the start of the APU.

Its timing was 00:19:29 on March 8th i.e. 8min31 after Arc-6. Considering the next event occurrence - very close to Arc-7 (cf below) - and the maximum rate of descent, the maximum altitude to consider is ~3000ft.

Assuming that the aircraft did not accelerate due to the flame out assumed to have taken place between Arc-6 and Arc-7, one can broadly delineate the area where the aircraft was at Arc-7 by the maximum distance flown at Arc-6 speed at most i.e. approximately 50Nm. The estimated latitude is between 15.7°S and 17.5°S as illustrated in Figure 15.

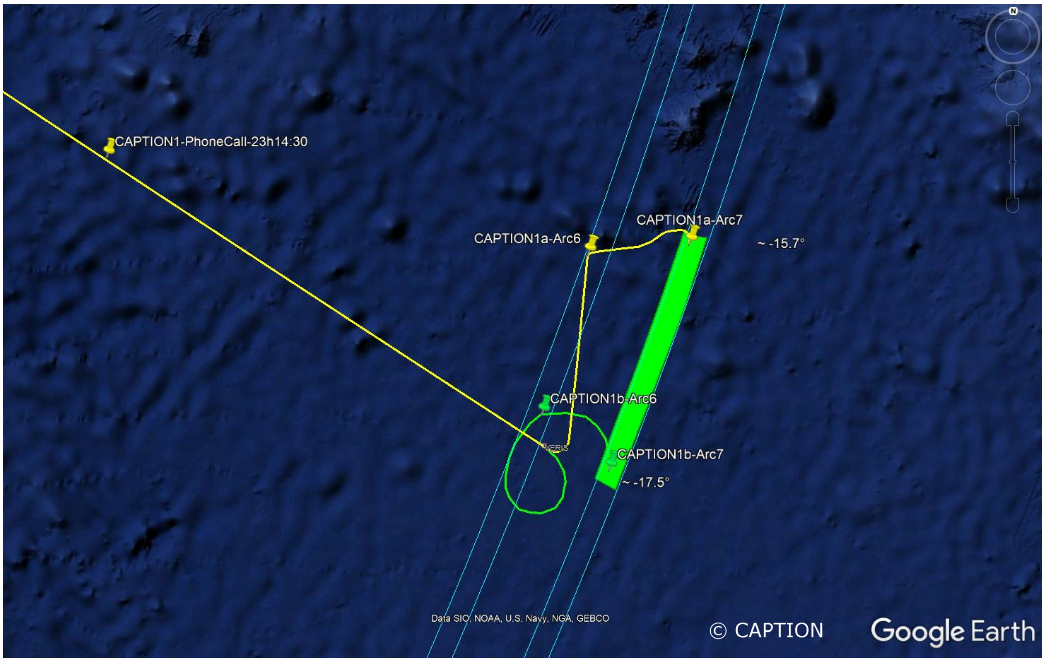

Figure 15: Option 1: Set of possible End of Flight points (Green area) close to Arc-7 at 00:19:29UTC

10.41 SATCOM Log-On Completed

Its timing is 00:19:37 UTC on March 8th i.e. 8 seconds after Arc-7.

Because of its abnormal BFO and the small time-lag of this logon completion and Arc-6, one could consider that the aircraft was either falling or rotating fast in a vertical plane around its wing when transmitting the signal.

Based on the work performed by Argiris Kamoulakos in [18] and [19] CAPTION makes the assumption that an attempt to ditch took place but the end of it provoked this rotation in a scenario where the right-wing touched down first and broke. In addition, the very low number of found pieces of debris leads to confirm the hypothesis of an attempted ditching.

Consequently, the End of Flight location is considered very close to Arc-7.

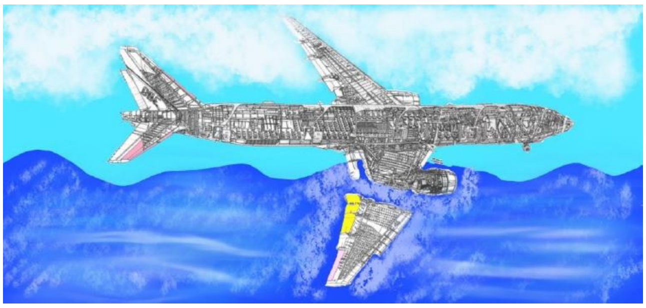

Figure 16: Artistic drawing of the wing breakage (Courtesy of Alexander Kamoulakos)

10.42 Option 2: Arc-5 heading to Perth

The second conclusion of the above analysis shows that it is possible that the aircraft took route M641 heading to Perth some ~1600Nm away from Cocos Islands which could not be theoretically reachable. Thus, at this speed the Arc-5 crossing point matches the Inmarsat BTO and the BFOs. The new track is at 141.5° with the next target waypoint being IKASA waypoint, distant from Arc-5 by ~490Nm. This path is illustrated in Figure 17.

The same issues could be raised here as in paragraph 10.36. They concern the rationale for the PIC to have chosen this route which is technically matching Inmarsat data but which is operationally irrational from an external perspective: the fuel was known to be insufficient, for example. The motivation of the PIC would have taken precedence here. If it was to end somewhere where they could not be found, choosing a documented route would not be the best choice compared to a random southern track.

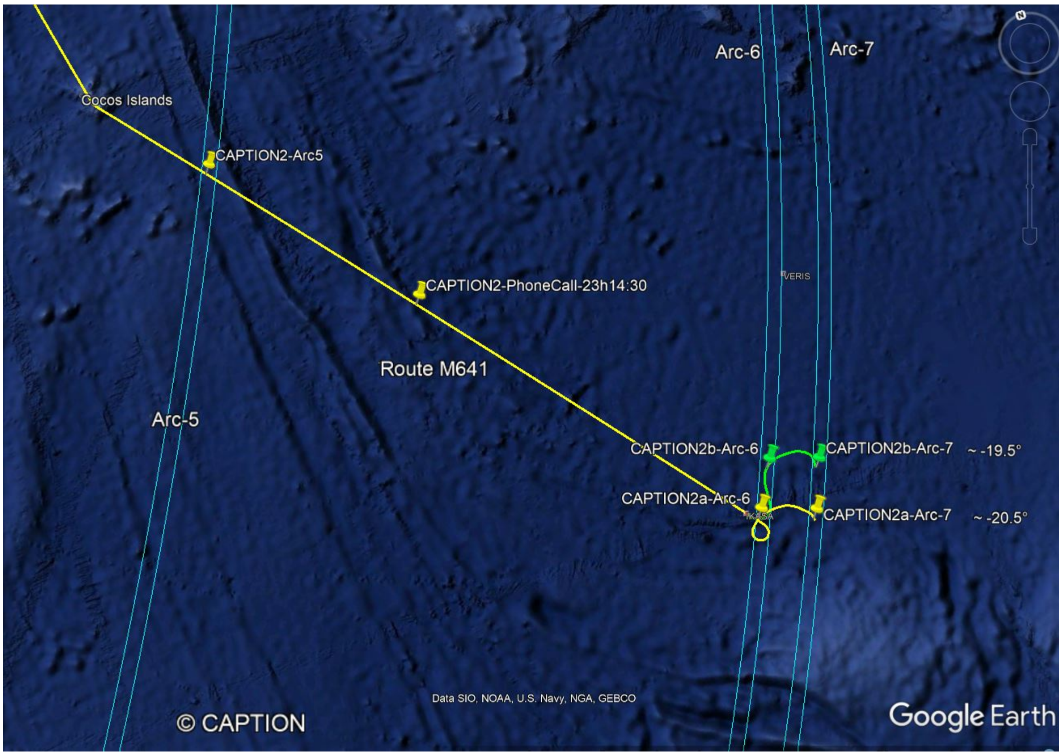

Figure 17: Option 2: Possible paths (Yellow and Green) from the vicinity of IKASA to Arc-6 at 00:10:58UTC

10.43 Option 2: Phone call-2 attempt from the ground

On route M641 heading to IKASA waypoint and at the mid-time of the phone call initiated from the ground i.e. 23:14:30 UTC, the computed BFO is 217Hz for CAPTION-2 perfectly matching Inmarsat 217Hz reference.

This is a good indication that at this point in time the aircraft was still on that route.

10.44 Option 2: Arc-6

If one accepts that the aircraft stayed on route M641, then it overflew ISAKA waypoint and probably lost the right engine a few miles later. If the TAC was OFF in the case of scenario 2 the aircraft could have started a right turn as illustrated in Figure 18 in Yellow.

Considering the BFO, a sensitivity analysis shows that the best BFO with no vertical speed and at the current speed of ~360kt is obtained for a route on track at 60°. The ±7Hz Inmarsat margin is respected by tracks between 255° to 100°. Thus, one should also consider the same range of possible paths as in paragraph 10.38.The aircraft could have gone north first or could have completed a 360° turn because of the asymmetric thrust before proceeding to Arc-7. This is illustrated in Figure 18.

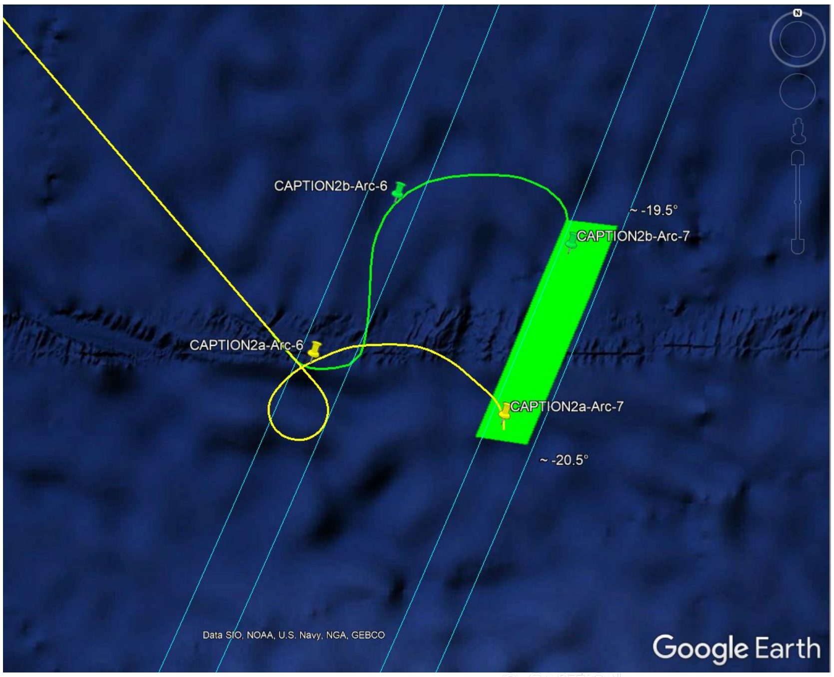

Figure 18: Option 2: Possible paths (Yellow and Green) and End of Flight points (Green area)

10.45 Option 2: Arc-7

For route M641, the analysis follows exactly the same reasoning as in paragraph 10.40 for route T41. The conclusion differs on the estimated latitude.

The estimated latitude is between 19.5°S and 20.5°S as illustrated in Figure 18.

10.46 SATCOM Log-On Completed

Please refer to paragraph 10.41 "SATCOM Log-On Completed" above, the rationale is identical. Only the geographical location of the ditching is different as provided in Table 3.

10.47 Initial plan: Learmonth or Perth?

At 17:06 UTC the aircraft reached its top of climb location (ToC) after take-off with 43.8 tons of fuel. This corresponds to a possible range of ~3250Nm approximately at a cruise altitude above 35000ft.

The measured distance between the ToC and Learmonth is 3150Nm and the distance ToC to Perth is measured equal to 3580Nm as reported in Table 1.

No one knows the PIC's actual intention, and Perth could have been the target. But, at this point in time of the journey, the comparison with the theoretical maximum range of the aircraft and the two distances shows that Perth could have been just reachable and that Learmonth would have been easily reachable if the aircraft had stayed at the altitude of ~38500ft.

Thus, CAPTION reconstructed trajectory privileges route T41 towards Learmonth.

11. How does CAPTION compare with Inmarsat data?

In Inmarsat paper [0], an example of a reconstructed path is presented in Table 9 and Figure 9. For the sake of comparison, Table 4 posts CAPTION trajectory computed values in the same way one to one with Inmarsat measured values. Additional information is provided in the notes beneath.

Extra elements have been added for completeness including the BTOs which are useful for the discussion provided in the important notes below Table 4, and also few intermediate points worth considering for “listening to the data”. Please note that in order to be comparable with the Inmarsat paper findings the same frequency bias δf of 150Hz has been used. In addition, the exact same four Inmarsat first points are provided to demonstrate the quality of our tools compared with Inmarsat’s.

Our computations are based on two software tools. The first is an excel workbook initially created by Prof. Yap F. Fah, NTU, Singapore (Version 4) that we have gradually enhanced as our knowledge progressed (now our own is Version 7). In particular, we have included SK999-Satellite Model which we have upgraded with a precision basically matching Inmarsat Ephemeris.

The second tool, the Constraint Assessment Tool (CAT) is a homemade software developed in parallel, encompassing similar functions as the software above (Version 7) with all required complementary operational data (fuel consumption, 4D interpolated actual meteo, arc generation, etc.) to allow us to estimate the flight characteristics in conditions closer to reality and to feed our FsX-PMDG simulator with 4D-interpolated quasi real-time meteo data.

Table 4: CAPTION Reconstructed Flight Path Results (ref. Inmarsat paper Table 9)

									Δ Fup*						Total Burst Freq. Offset (Hz)			Burst Time Offset (μs)		
	Time UTC	Lat°N	Lon°E	Altitude (100ft)	True Track (°ETN)	Speed (kt)	Speed (km/h)	Vertical Speed (fpm)	Aircraft (Hz)	Satellite (Hz)	Δ F down (Hz)	δ f comp (Hz)	δ Fsat + δ AFC (Hz)	δf bias (Hz)	Pred.	Meas.	Error	Pred.	Meas.	Error
Nominal-1-Inmarsat**	16:30:00	2.70	101.70	0	0	0	0	0	0	-6	-84	0	29	150	88	88	0	14893	14920	27
Nominal-2-Inmarsat**	16:42:31	2.80	101.70	20	333	235	435	1200	194	-6	-80	-180	27	150	130	125	-5	14931	14900	-31
Nominal-3-Inmarsat**	16:55:53	4.00	102.20	280	25	461	854	1500	-424	-4	-75	453	25	150	155	159	4	15212	15240	28
Nominal-4-Inmarsat**	17:07:19	5.30	102.80	350	25	468	867	0	-461		-71	488	24	150	130	132	2	15587	15660	73
Arc1	18:25:27	6.78	95.93	385	296	495	917	0	697	-1	-37	-677	10	150	142	142	0	12520	12520	0
Arc1.1 (a)	18:27:04	6.96	95.79	385	345	495	917	150	100	-1	-36	-55	10	150	168	175	7	12470	12520	50
Arc1.2 (b)	18:28:11	7.11	95.80	385	343	494	915	-1000	107	-1	-36	-88	10	150	142	147	5	12490	12480	-10
Phone Call1 (c)	18:40:33	8.46	95.37	152	343	347	643	-3000	0	-1	-30	-38	8	150	89	88	-1	12450	N/A	N/A
A2	19:41:03	4.78	93.69	230	180	393	728	0	56	-1	0	-93	-2	150	111	111	0	11540	11500	-40
A3	20:41:05	-1.61	94.16	230	166	385	713	0	-212	3	29	179	-2	150	147	141	-6	11730	11740	10
A4	21:41:27	-7.83	95.72	230	166	381	706	0	-321	10	56	292	-18	150	169	168	-1	12790	12780	-10
A5	22:41:22	-13.21	98.41	230	124	377	698	0	-700	20	78	687	-29	150	206	204	-2	14590	14540	-50
Call 23h14	23:14:30	-15.11	101.44	230	123	372	689	0	-739	24	88	728	-33	150	219	217	-2	16210	N/A	N/A
A6	00:11:00	-15.81	105.31	230	35	359	665	0	-224	28	100	233	-37	150	251	252	1	18020	18040	20
A7	00:19:29	-15.71	106.11	50	180	350	648	-3000	-286	28	102	223	-38	150	180	182	2	18400	18400	0
Logon (d) Acknowledge	00:19:37	90.00	180.00	0	180	150	278	-13700	-341	28	102	95	-38	150	-2	-2	0	N/A	N/A	N/A
Logon (e) Acknowledge	00:19:37	90.00	180.00	0	0	0	0	0							N/A	N/A	N/A	49940	49660	-280

Notes :

* ΔFup is provided as the sum of the aircraft contribution and the satellite contribution.

** These 4 lines of data correspond to the nominal leg of the flight as presented by Inmarsat in their Table9. They are provided here for the sake of comparison of CAPTION model results with Inmarsat findings. They do match very well, demonstrating the quality of the CAPTION computations.

(a) This intermediate point was used to validate the trajectory in more detail. For CAPTION, it is located at the end of the contingency turn northwards and when the aircraft rotates back to level thus adding a small vertical contribution to the vertical speed of the antenna circa 150 fpm.

(b) This intermediate point was used to validate the trajectory in more details. It is located somewhere after the beginning of the descent at -1000fpm northwards i.e. 360°.

(c) This point is at the mid-time of phone call attempt 1 which lasted around 1 minute. This occurred during the descent to get quickly out of Sabang Radar coverage and before the turn towards NOPEK waypoint (close to overflying Kate Tee's sailing boat).

Points (d) and (e) below will require further explanation, discussion and additional investigation as a deeper analysis of the system including "electrical power + ADIRU + SAARU + SATCOM" is required to understand the state-machine logic at "reset" and "switch ON" times. We made some hypotheses to be validated. These lines concern the last service message received and acknowledging the new logon.

(d) This line concerns the BFO only. If one trusts the data then at this geographical location and in the case of a ditching (small horizontal speed etc.), a vertical speed around -13700fpm is necessary to satisfy the measured BFO of -2Hz. This high vertical speed of -13600fpm is in contradiction with the expected order of magnitude of a ditching vertical speed typically of about a few hundred fpm (cf below point (e)).

(e) Thus, this new line illustrates our new hypothesis: line (d) cannot be trusted and in particular the measured BFO -2Hz shows that the onboard compensation algorithm has been misled by the transitional behaviour of the system "electrical power + ADIRU + SAARU + SATCOM". CAPTIO's understanding of the "reboot" of this system is that pre-defined aircraft attitude values are used. We assume that for this pre-set geographical location of the aircraft, these values are Lat=90° and Long=180°. Using these values shows that the predicted BTO value is very close to the measured BTO by Inmarsat. If this hypothesis is confirmed, then the measured BFO value of -2Hz cannot be trusted as it is the result of an erroneous frequency compensation by the SATCOM which used the default aircraft attitude values pre-defined at boot time and exchanged between the ADIRU (or SAARU) and the SATCOM. Please note that, to our view, for Arc1 the wake-up transitional state machine could be different from this one and in particular when considering the two potential Doppler compensation modes called open-loop and closed-loop (more details on these are provided in Holland's paper "MH370 BFO analysis and implications on Descent Rate at End-of-Flight).

Figure 19 and Figure 20 replicate Inmarsat Figure 9 with both CAPTION alternate routes. The orange plot posts Inmarsat data as provided by Inmarsat in [0]. The blue curve represents the computed estimation of the CAPTION BFOs. The matching is excellent as the standard deviation of the BFORs is ~2.3Hz for both options. When considering the available extra BFOs (like those we named Arc-1.1 and Arc-1.2 for example) which are not usually considered by the other studies the BFOR σ becomes ~3.5Hz.

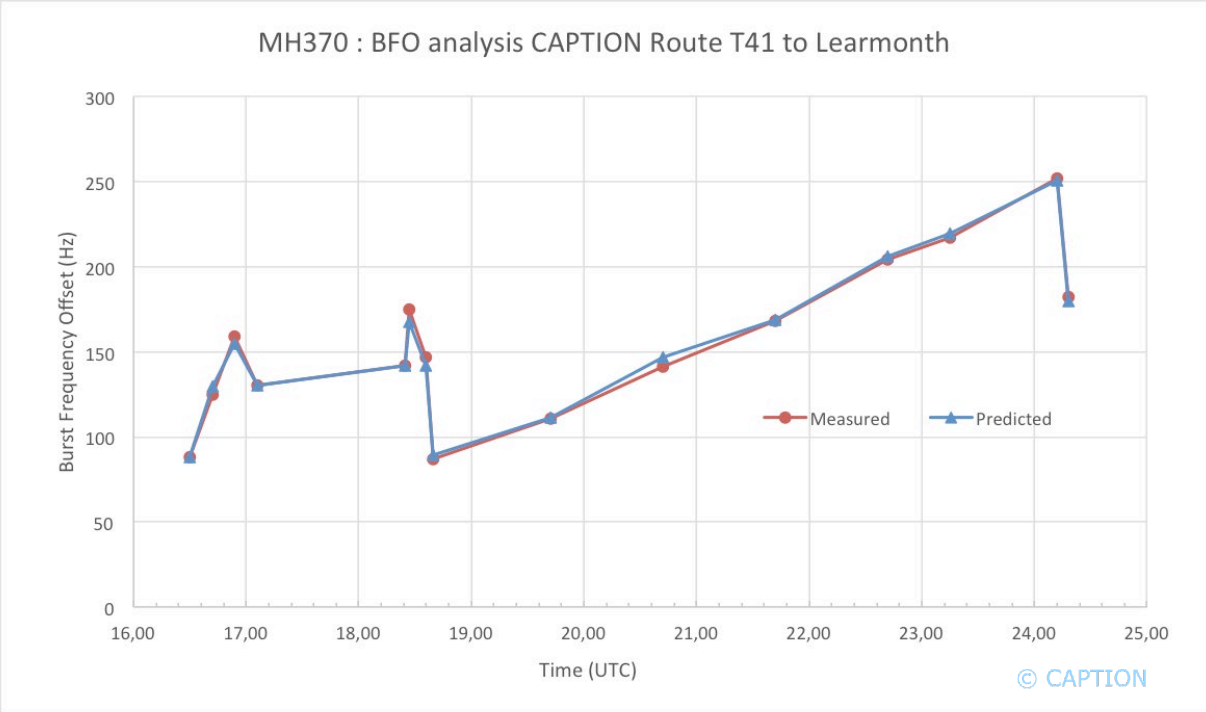

Figure 19: Comparison Inmarsat BFO versus CAPTION trajectory via route T41 (BFOR σ ~3.5Hz)

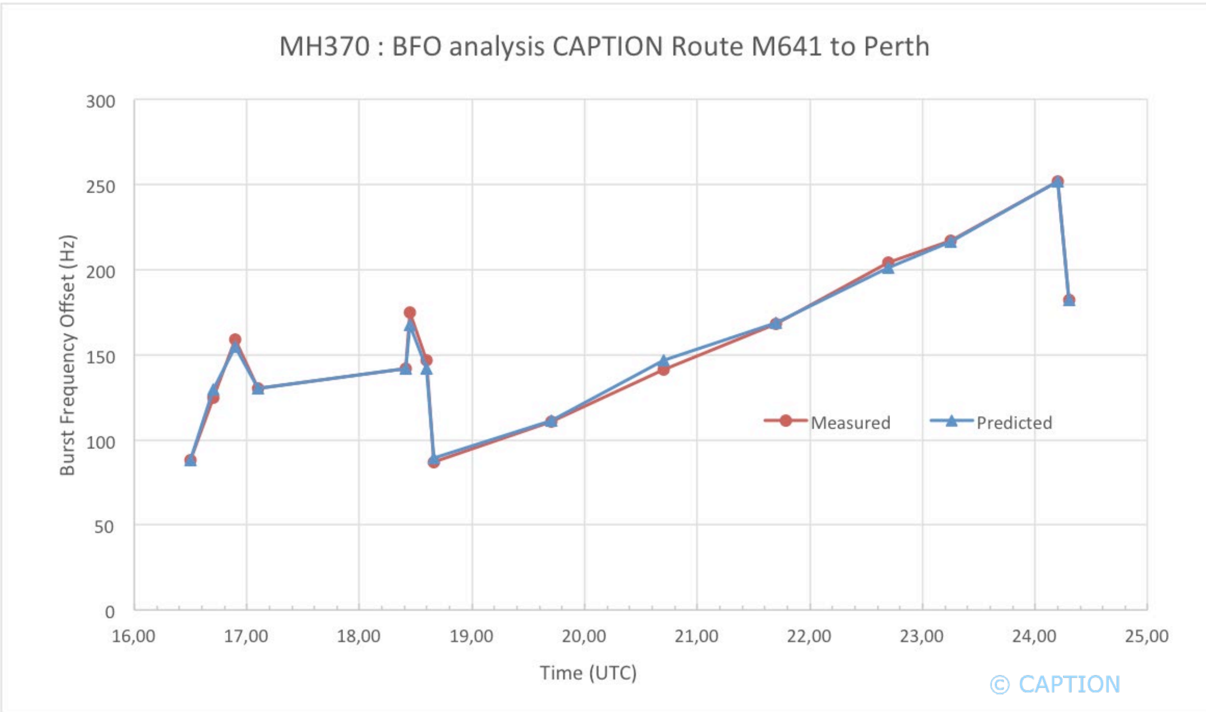

Figure 20: Comparison Inmarsat BFO versus CAPTION trajectory via route M641 (BFOR σ ~3.5Hz)

12. What about fuel consumption?

Until now, it is generally accepted that the fuel was fully consumed at the end of the flight i.e. at 00:19:29 TUC on 8th of March as assumed by the official report [2].

In the reconstructed CAPTION trajectory above, the flight time and the range flown by the aircraft are in full accordance with the flight modes automatically selected by the FMS which served as the basis for the fuel consumption computations.

Table 5 presents the results of our CAT tool computation of the fuel at key locations. The computations are performed every second of the flight taking into account the 4D interpolated actual meteo data which altogether provide a more realistic evolution of the remaining fuel weight. The fuel model is a version designed for the Rolls-Royce engines derived from the 9M-MRO Fuel Model provided by Dr B. Ulich and further enhanced by P. Gasser.

Table 5: Remaining fuel at CAPTION key locations (Route T41)

Location / Waypoint	Longitude °	Latitude °	Altitude ft	Fuel (x1000kg)
Top of Climb	102.81	5.30	35000	43.8
IGARI	103.59	6.94	35000	42.2
KENDI	100.14	5.14	38500	37.5
NILAM	95.98	6.76	38500	32.5
Arc1	95.91	6.92	38500	32.3
IDKUT	95.50	8.01	28000	31.7
Attempt Phone Call 1	95.37	8.46	15200	31.6
Bottom of Descent	95.26	8.80	10000	31.5
Turn3	95.19	8.92	10000	31.5
NOPEK	94.42	6.60	3000	29.7
Start of Climb 2	94.04	5.87	3000	28.6
BEDAX	93.79	5.36	20000	27.0
Top of Climb 2	93.73	5.27	23000	26.8
Arc 2	93.69	5.02	23000	26.5
ISBIX	93.68	0.37	23000	22.0
Arc3	94.18	-1.67	23000	20.0
Arc 4	95.71	-7.77	23000	14.1
YPCC – Cocos Islands	96.84	-12.20	23000	9.9
Arc 5	98.33	-13.16	23000	8.3
Attempt Phone Call 2	101.44	-15.12	23000	5.0
VERIS	105.00	-17.27	23000	0.6
Arc 6	104.85	-17.27	23000	0.4
Arc 7	105.47	-17.54	500	0.3

The estimation of the remaining fuel at Arc-6 is ~400kg and ~300kg at Arc-7 which is lower than the model precision estimated between 3 to 4% of the total fuel weight. Thus, **this value means that the tanks were basically empty at Arc-6 and even more likely at Arc-7**.

The hypothesis that the incomplete logon sequence that started at Arc-7 was provoked by a sequential flame out of the engines is in accordance with the above computation.

Thus, concluding that the fuel exhaustion was the main reason for the engines' stop is the best assumption at this point in time.

13. The End of Flight

The end of flight (EoF) is a subject of investigation by itself as it can be analysed independently from the previous part of the reconstructed trajectory. It will be studied in detail in a subsequent publication [26] where the different cases identified by Boeing will be scrutinised in light of the preliminary analysis presented in [27] by A. Kamoulakos.

It is usually considered that this phase of flight starts just before the signalling message sent to the ground station by the Satellite Data Unit (SDU) in response to the hourly signalling interrogation sent by the ground to the aircraft as sketched in the grey box in Figure 21 extracted from [28].

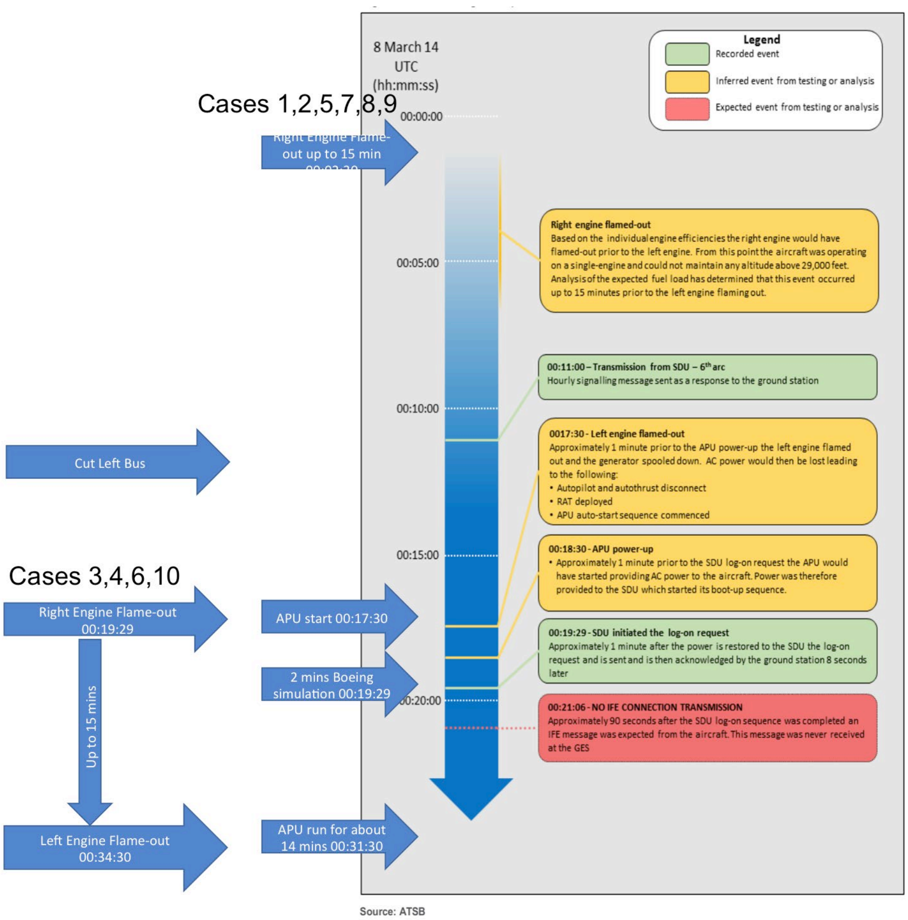

Figure 21: End of Flight sequence and Boeing simulations cases.

In 2015, based on this sequence and to support the definition of the search areas, Boeing performed simulations of several scenarios. The results have not been made public. In addition, in 2016, the ATSB requested Boeing to run additional simulations for ten cases they had identified as plausible. They are indicated by the blue arrows in Figure 21. The results were published in an official update report in November 2016 [29]. Figure 22 illustrates their findings in a detailed version provided by V. Iannello.

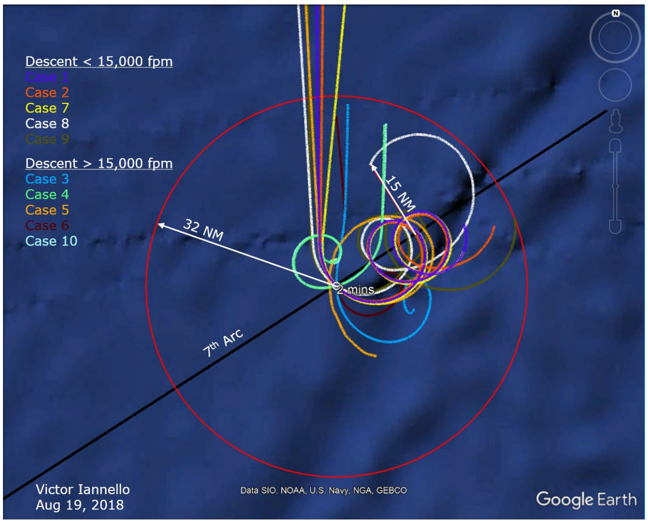

Figure 22: Graphical results of potential End of Flight trajectories from ASTB/Boeing simulations

As discussed in paragraph 10.41 referring to the analysis made on the flaperon damages, and in view of the very small number of retrieved debris and their broken shape, our opinion is that an attempted ditching is the most probable scenario for the end of the flight. A missed ditching is also suggested by professional accident investigator Larry Vance and by Captain Blelly in [30]

14. Conclusions

This analysis has shown that under the assumptions and using the new pieces of evidence listed in section 1 and described in the following sections, a new plausible fully piloted trajectory can be reconstructed making best use of the evidence.

According to these elements, CAPTION draws the conclusion that the PIC had an initial plan which could not be properly executed due to unforeseen events or constraints leading to a different path being flown.

CAPTION reconstructed trajectory encompasses two possible scenarios for the electrical power switch-off i.e. full or partial. The preferred scenario is a full power switch-off. In addition, two possible route options after passing over Cocos Islands could be compatible with Inmarsat data. The path via Route T41 heading to Learmonth is considered the most probable.

CAPTION reconstructed trajectory fully aligns with sailor Kate Tee's sighting of an aircraft closely passing-by, a likely ash cloud encounter - as probably seen also by Ms Tee - and the Seismic detection at Cocos Islands as analysed by Mr Anderson. All these elements match the timeline.

The method for reconstructing the trajectory is based on flight simulation runs with a B777-LR model with 4D-interpolated data supplied to it in quasi real-time. This method is more precise than other computational methods as it uses a trusted aircraft model including FMS automation algorithms developed in conjunction with Boeing. The difference with the actual B777-ER aircraft would slightly modify some results such as the exact altitude flown and the subsequent speed which, would need a fine tuning. But this is not identified as an issue as the impact would be very low.

The End of Flight area is assumed close to Arc-7 where an attempt to ditch probably took place. Consequently, the identified research zone would be around the segment of Arc-7 between 15.7°S and 17.5°S. This segment is considered the most likely when considering the a-priori feasibility of reaching Learmonth when deciding which way to go at Cocos Islands.

This area has not been searched during both wreckage research campaigns.

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16. Glossary:

Port	The left-hand side of the boat
Starboard	The right-hand side of the boat
Stern	The back of the boat
Tack	Heading of a sailing boat with reference to the wind direction
Winward	Towards the wind; upwind
Luffing up	The boat turns into the wind
Leeward	Away from the wind; downwind
Bearing away	The boat turns away from the wind
Astern	Behind the boat
Ahead	In front of the boat
Bow	The front of the boat
Aft	Inside the boat towards the stern

17. Annex 1: MH370 – IGARI-MEKAR: the leg flown with the sole power of the RAT

A new perspective has been followed to analyse the Inmarsat data correlating them with the electrical power status of the system and the operational action of the PICs.

There is a high probability that the aircraft could have flown powered by the RAM Air Turbine (RAT) only and subsequently flown manually until the power switch was back on at circa 18:23:00 UTC.

Annexe 1 can be downloaded form the new website at

https://www.mh370-caption.net/wp-content/uploads/MH370-CAPTION-Annex1-RAT-Deployed-Scenario.pdf

18. Annex 2: Kate Tee's sighting

"MH370 – What can be learnt from Kate Tee's sighting?"

Annex 2 can be downloaded from the new website at
https://www.mh370-caption.net/wp-content/uploads/CAPTION-KT-Sighting.pdf

19. Annex 3: Volcano ashes

MH370 – What can we say about Sinabung Volcano ashes?

Annex 3 can be downloaded from the new website at
https://www.mh370-caption.net/wp-content/uploads/CAPTION-Sinabung-Volcano.pdf

20. Changes log

Version	Section	Change
1.2	8	Modified: The statement on Route G200 is limited to the specific altitude of 23000ft and the current ground speed computed from the airspeed given by the FMS.
1.3	3	Annex 1 completely revisited as an external document detailing the correlation between Inmarsat data with the electrical power status of the systems. It provides also a detailed technical scenario 2 for the leg after U-Turn until Arc-1.
	3	The VOR radio navigation aid privileged as the navigation means during the manual piloting
	10.10	Included summary of Annex 1 elements during the electrical power switch back on.