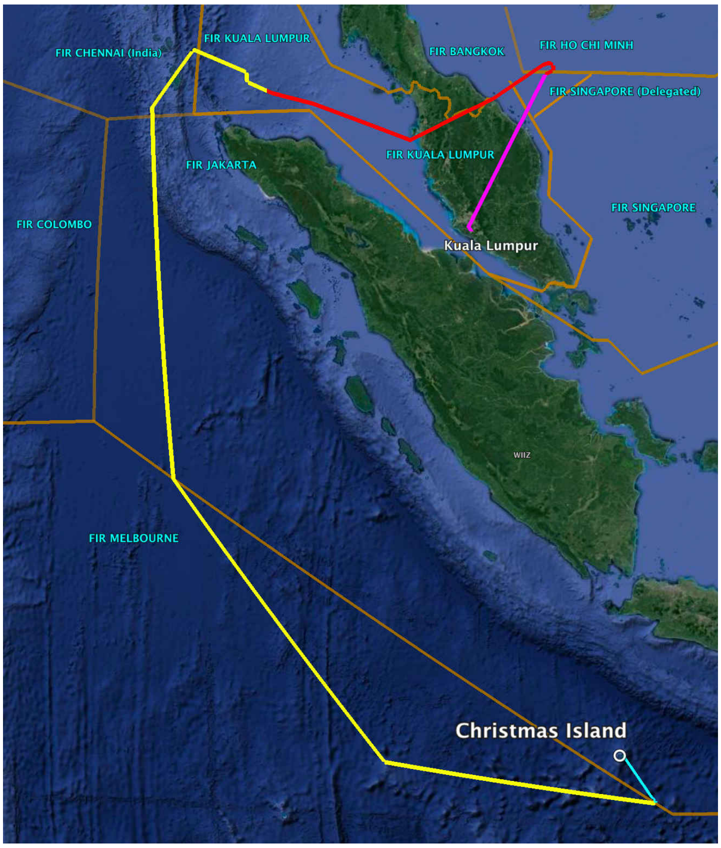
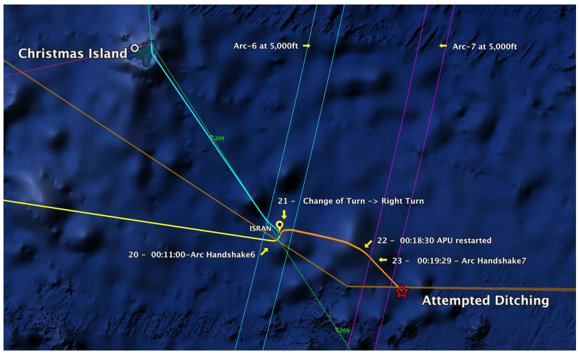
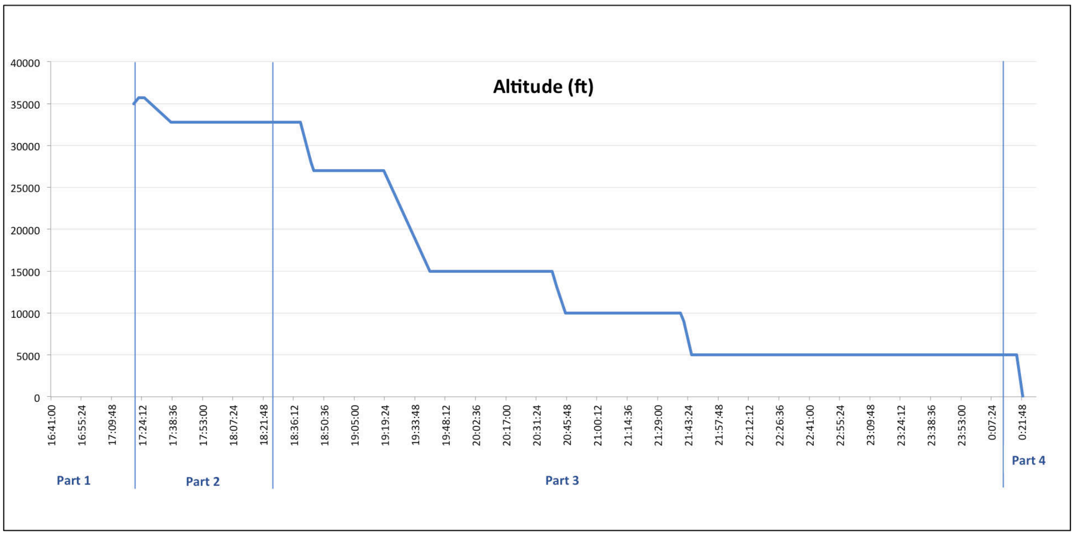
A plausible trajectory for MH370

Jean-Luc Marchand, Michel Delarche & Jean-Marc Garot

The planned trajectory	The end of the trajectory
	
The planned trajectory and the seven FIRs : a 2,670NM journey	(12°2'32"S, 107°22'48"E) Sea floor depth at -5,000m



MH370:
An Operational study of a start to end Piloted Trajectory
A new search area

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*The views expressed here are solely the authors' and do not represent the views of any other group or individual.
This document has been reviewed by Christopher North.*

Foreword

For relatives and friends of the 239 people aboard flight MH370 and for the safety of air transport, if resumed, the search for the MH370 wreck ought to be based upon tangible elements.

What next?

Our first objective (which we consider is achieved by this paper) is to demonstrate that a fully human-piloted trajectory should be considered as a valid alternative to existing MH370 localisation approaches since it:

a) meets all the space and time constraints set by available data,

b) explains the behaviour of the People in Command of the aircraft in operational terms,

c) meets the technical constraints set by the aircraft itself (in particular regarding fuel consumption)

Our second objective is to invite the scientific community and the stakeholders to analyse, check and consolidate it with better and more accurate tools than ours. If the expert community can be convinced that the trajectory proposed in this paper and the corresponding search area are worth some consideration, this paper could then be formally presented to the concerned safety authorities with a higher degree of confidence.

For example, our fuel consumption model should be compared with professional simulators or more elaborated models. Another example would be to further analyse the drifting of the debris in using the full set of meteorological data for a longer period than what we have been able to do and at least until July 2015.

The scientific community is welcome to help cross-checking our assumptions and results, which will be made public on a new specific web site (to be created).

In addition to this and before launching a new search campaign, it would be appropriate to invite Boeing to replay our proposed Piloted Trajectory using a Level-D B777 aircraft simulator in order to confirm or rectify our hypotheses on aircraft operations. This would reduce the uncertainty about the MH370 ditching point location and consequently the size of the area to be explored. As the search is planned to resume very soon, this study aims to bring tangible elements to help prioritising the zone to explore first.

We would be happy to provide assistance to such initiatives in order to increase the chances to pinpoint the correct location of the wreck. Searching the area we have delineated could save time, money and effort thanks to its small size (approximately 40 x 80 NM^2).

1- Introduction

Until today, the numerous studies and analyses have considered that the flight MH370 was flown autonomously from a certain point in time just before making what is usually called "the Final Major Turn" around 18:41:00 UTC time. But is there another potential location worth being considered before deciding to resume the search in a zone adjacent to the southern area already searched unsuccessfully?

The approach taken in this document consists of

a) taking account of an Air Traffic Management (ATM) point of view,

b) demonstrating that a human-piloted trajectory was possible (and indeed likely) and

c) checking that such a trajectory would be allowed by B777 performance and its modes of operation.

This document presents an analysis based on results already published by the scientific community but considering that the flight was humanly controlled and piloted until the end as described in [1][1]. At the end of the document one can find a comprehensive list of references. The list of abbreviations is fairly short since this document is supposed to be read by specialists.

One may dispute this point of view, but should put aside any "a priori" opinion while reading this paper and join us to re-think the problem from square one as recommended by Richard Quest in [39].

According to our scenario, the journey can be broken down into five parts, starting with a normal commercial flight that underwent a take-over and a diversion, after a temporary switch-off of electric power in the Electronic Equipment Bay (EEB) by unknown "people-in-command". This diversion and all the subsequent re-routing are analysed later. The plan of the "people-in-command" was to remain undetected, circumvent the Jakarta FIR and then safely land on Christmas Island. But because of a fuel shortage the aircraft just missed its destination and tried to make an emergency ditching (cf. Figure 1).

Two working hypotheses have been made for defining our scenario:

1. We assume that the "People in Command" conducted the re-routing of the aircraft by reprogramming the FMS towards a new destination through the pilot's interface available in the cockpit;
2. An action was carried out in the Electronic Equipment Bay (EEB) but whilst there are not enough technical elements to exclude a global power failure of a type never observed before, or a deliberate (but very risky) action taken in the cockpit. The hypothesis therefore of a break triggered from this compartment better explains the events observed and deserves further investigation, in particular to take measures to improve the safety and security of future flights. The technical arguments in favour of this second hypothesis are presented in Annex 1.

2- The Constraint Assessment Tools (CAT)

This work has been made possible thanks to a specifically developed, integrated set of tools for:

1. Creating, displaying and updating a four-dimensional (time, position, speed and heading) flight plan and capturing data as input to a simulation-based analysis
2. Determining 3D radar coverage at all altitudes,
3. Capturing and converting historical weather data,
4. Refining the trajectory and provide best estimated of Burst Frequency Offset (BFO), speed etc. values based on 3D (or 4D where the time is known) representations and Burst Time Offset (BTO)

[1] *The analysis was inspired by the French book [1] by J-M Garot and M. Delarche "Hijacking of the MH370: the reasons for searching for the wreck…somewhere else" (translated title) where the original idea is that the new "people in command" were hidden in the Electronic Equipment Bay (EEB) from some time before take-off and climbed into the cabin and cockpit eventually.*

information in combination with existing data e.g meteo

5. Calculating the drift of the MH370 flaperon,
6. Generating Inmarsat arc segments based on BTO and altitude values,
7. Estimating the remaining fuel at any point along the trajectory.

This set of tools has been built with Microsoft-Access Database (2010 version - compatible with the 2002-2003 version). Functions and procedures included in modules have been developed in Visual Basic.

A detailed description of the CAT is provided at Annex 2 and, in particular, the models used. The scientific community, concerned with the MH370 search, has made these models publicly available and we want to express our gratitude toward all the previous contributors.

3- Checking BTOs and BFOs

The set of BTO and BFO measurements provided by Inmarsat [7] is the essential foundation of this work. For every available validated record of the communication log [3], a systematic "reading" of its technical and operational signification has been carried out and used to derive the aircraft position at each time. The validation of the trajectory has been achieved by comparing the estimated BTOs and BFOs of the Piloted Trajectory with the original measurements at each so called "Inmarsat arc".

In addition, more than 50 flight simulations were performed with a PC based commercial flight simulator: the Microsoft Flight Simulator FsX with the B-777 add-on from the Precision Manuals Development Group (PMDG) and one short session was performed on a Level D Training Aircraft Simulator for assessing the Arc6-Arc7 leg with a professional B-777 pilot.

Table 1 shows that the estimated BTOs and BFOs along the Piloted Trajectory are fully within the acceptable margins as defined by Inmarsat [7] thus validating the Piloted Trajectory option. They have been verified in two independent ways: with the CAT and by using manually the model provided by Yap Fook Fah [14].

Table 1 presents the results obtained by using all the available BFO and BTO, even when the BFO is provided with no corresponding BTO.

	Time	Lat.	Long.	Flight Level	Ground Speed	Track	Rate of climb	Inmarsat BTO	Our Estimated BTO	Inmarsat BFO	Our Estimated BFO
	(UTC)	deg	deg	x100ft	knot	deg	ft/min	µ	µs	Hz	Hz
Arc1	18:25:27	6.7761	95.9363	328	498	296	0	12520	**12533**	142	**141**
Mid turn Offset	18:27:07	7.0034	95.7974	328	498	360	150	12520	**12488**	176	**170**
End turn Offset	18:28:06	7.1558	95.7581	328	498	296	0	12480	**12482**	143	**142**
Descent on Offset at 296°	18:40:23	7.8162	94.3560	316	400	296	-2500	n/a	**11945**	86	**86**
Arc2	19:41:03	3.1824	93.5550	150	301	173	-400	11500	**11457**	111	**111**
Arc3	20:41:05	-1.8455	94.0101	140	300	174	-500	11740	**11691**	141	**143**
Arc4	21:41:27	-6.0141	96.0227	90	280	143,5	-500	12780	**12753**	168	**169**
Arc5	22:41:27	-10.2533	99.2463	50	300	143,5	0	14540	**14539**	204	**202**
Phone Call Attempt 23:14/23:15	23:14:39	-11.0330	102.0109	50	300	100	0	n/a	**15855**	216-222	**223**
Arc6	00:11:00	-11.6735	106.5605	50	300	360	0	18040	**18054**	252	**246**
Arc7	00:19:29	-11.8293	107.1668	50	300	135	-2700	18400	**18363**	182	**184**

Table 1:
Comparison Inmarsat measured BTO/BFOs versus the Estimated ones for the Piloted Trajectory

Note: At the "mid-turn Offset" and at "Arc6", the aircraft was turning to the left, leading to low BFOs. These turns seem to yield a larger error in BFO measurements. *This is an open question to the scientific community.*

4- The "Event by Event" rationale to support the "start to end" Piloted Trajectory

Event after event, this section documents the multi criteria analysis, which led to select the trajectory. The trajectory has been separated in five parts corresponding to major phases of the flight:

- Part 1: piloted by the official crew;
- Part 2: the trajectory is known from the radar data; based on the OMR-2 [2], and ATSB-3 [6], and the attached civil and military radar plots and detailed timings, it is possible to identify the most probable horizontal path followed by the aircraft using the waypoints in the AIRAC database that was active on March 7th, 2014. Therefore, from all the documents available and an operational and technical analysis – both from an aircraft and air traffic management standpoint – the conclusion is that the aircraft was piloted by "People in Command" after Part 1 and during the rest of the whole trajectory. They were proficient enough to take advantage of the Flight Information Region (FIR) boundary configuration.

  The People in Command manually keyed the flight plan in the FMS via the MCDU. The time of activation of this flight plan is unknown, as it could have occurred before what the scientific community calls the Final Major Turn or in steps during the whole journey.
- Part 3: the trajectory is known from the Inmarsat data;

  The horizontal path complemented by a vertical profile was logically derived and operationally validated thanks to a number of flight simulations addressing operational constraints (route network, aircraft capability, local limits of radar coverage, fuel consumption...). The selected trajectory, among the fifty-odd trajectories simulated, is the one which best fits all the constraints included in the Constraint Assessment Tools (CAT), especially the BTO and BFO computations.
- Part 4 and 5: they start at the turn to have the aircraft align on the Christmas Island approach axis. The aircraft could not reach its destination and went for a ditching. Part 4 is the actual trajectory and part 5 is the planned trajectory for a safe landing on Christmas Island.

  The location proposed for the ditching point is validated by a debris drift analysis.

To simplify the presentation and thus the reading, all the events of the "from start to end" Piloted Trajectory have been grouped in 24 key events with a number, a name as meaningful or as striking as possible and a time in UTC. Their location and their reference number are reported on the different figures.

The goal of the tables, associated with these keys events, is to justify the computed 4D position, x, y, z, time and speed of the aircraft all along the Piloted Trajectory. These tables are a set of information based on data coming from references, from which one can derive assumptions with some degree of interpretation. When the assumptions made elicit a high level of confidence, they are called "facts" otherwise "interpretations". When needed, below the table, interpretations are supported by a rationale based upon the most logical operational behaviour under the local conditions for a continuous flight within the acceptable flying envelop of the aircraft

There are, as well, cases when events occurring near the key event are reported with their time and analysis.

The numbering is only for the sake of reference.

At the bottom of each table, for each key event, one can find elements of ***Conclusions***:

- 4D trajectory: time, **I**: position, **II**: heading and **III**: ground speed,
- in addition, when a position is at the intersection of the trajectory with one of the arcs, **IV**: our estimated BTO and BFO compared to the Inmarsat measured ones.

These 24 keys events are presented along the 5 parts of the trajectory shown in different colours in Figure 1.

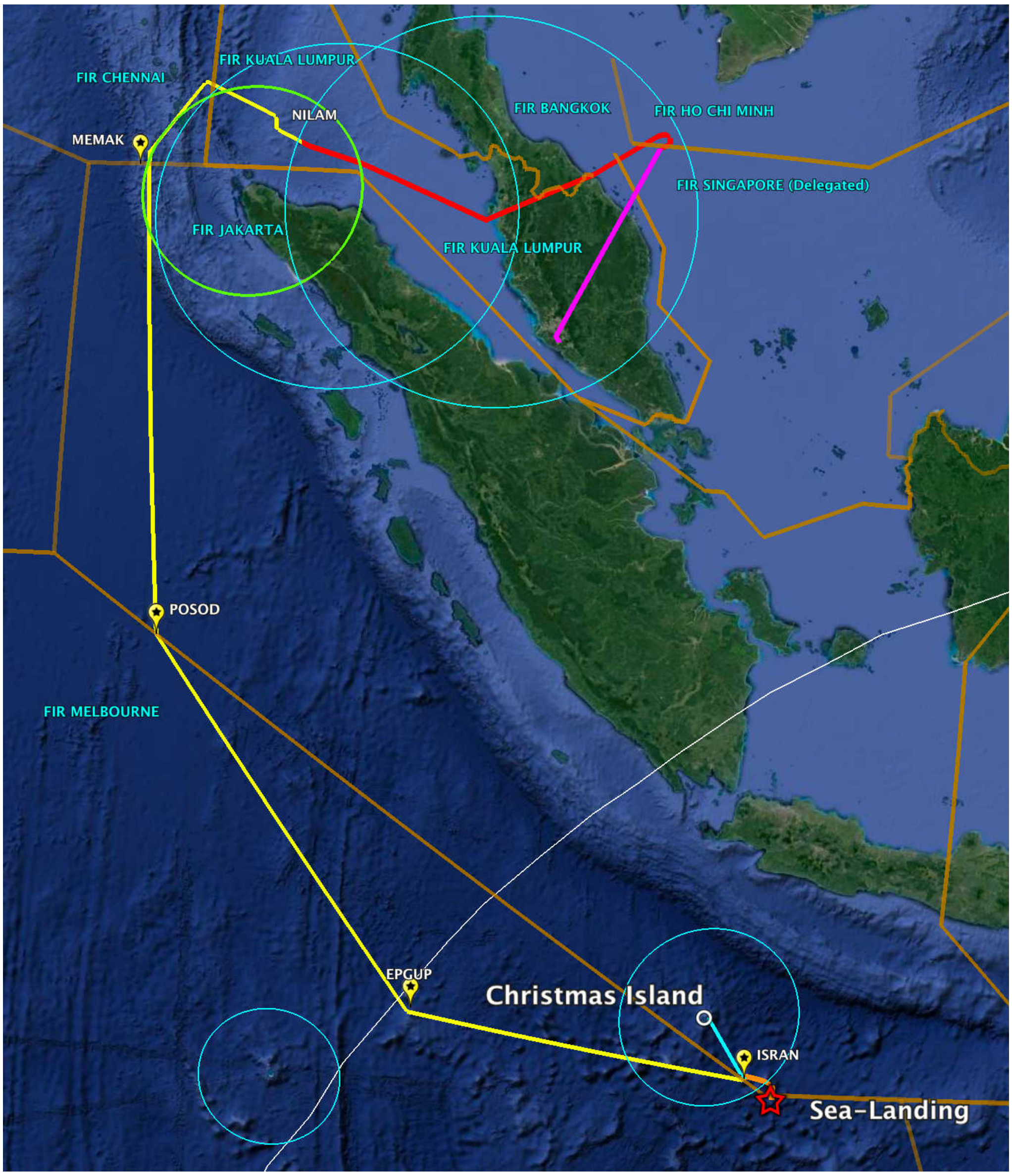

Figure 1:
The five parts of the Piloted Trajectory
and the FIR limits and the radar ranges

Figure 1 illustrates the planned and actual paths of the flight with the radar ranges at the corresponding altitude of the aircraft when it was in their vicinity. In particular, the light blue segment was planned for a safe landing at Christmas Island while the orange path leads to the location of the probable emergency ditching.

4.1 The normal part of the flight: from WMKK (Kuala Lumpur) to IGARI

The aircraft performed a normal take-off and proceeded according to its filed flight plan at the beginning of its night flight, levelled at FL350.

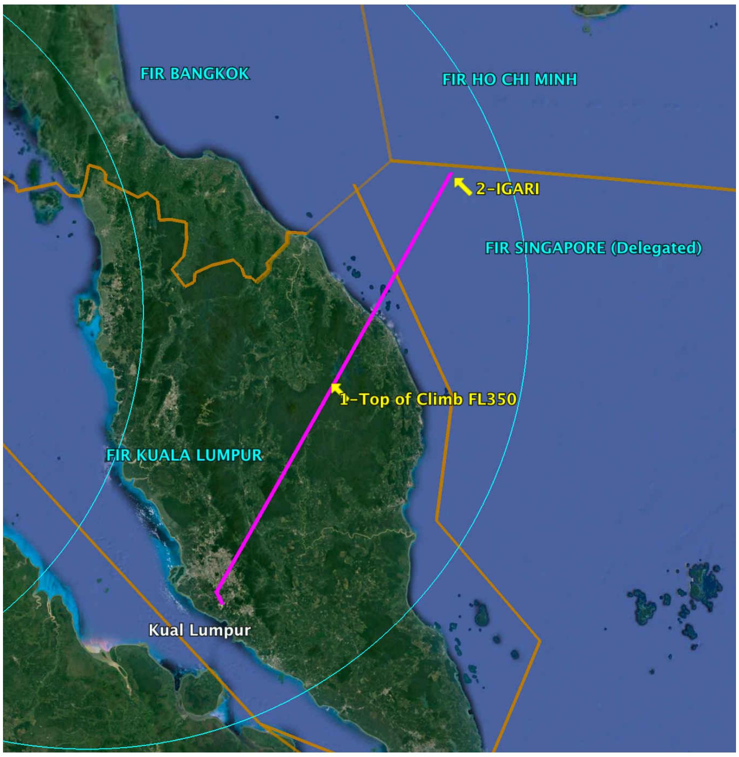

Figure 2:
The location of the key Events: Take-off, 1 and 2.

Figure 2 illustrates Part 1 of the trajectory i.e. flown according to the filed flight plan until waypoint IGARI.

1- Just After the Top of Climb

Location 1	***Leveled-off after ToC at Last ACARS message broadcast time.***	***Time: 17:06:43 UTC***[2]
1.1 event	ACARS message 5 from the aircraft at the Top of Climb providing aircraft mass ***Time 17:01:43*** The mass value of the aircraft 481,880 lbs is reported with a precision of 20lbs. ***Data:*** Last ACARS Report [2] Official Malaysian Report updated (OMR-2) p46 ***Fact:*** The mass, then computed in kg, was thus 218,577 kg.	
1.2 event	Last ACARS message 6 from the aircraft in cruise providing aircraft mass ***Time 17:06:43*** The mass value of the aircraft 480,600 lbs is reported with a precision of 20lbs. ***Data:*** Last ACARS Report [2] Official Malaysian Report updated (OMR-2) p46 ***fact*** Computed in kg, the mass was thus 217,997kg.	
1.3	The Deferred Defaults Table 1.6D reported on 7 Nov. 2013 that the Right Engine consumed 1,5T/h of fuel in excess at that time. ***Data:*** [2] Table 1.6D Deferred Defects n°3 of Official Malaysian Report updated (OMR-2) p28 ***Interpretation:*** *see below*	
1.4	Flight level was FL350 ***Data:*** Confirmed by the pilot himself as described in [2] Official Malaysian Report updated (OMR-2) at the top of climb. ***Fact:*** The aircraft was on its nominal En-Route phase towards IGARI according to its filed flight plan.	
1.5	Current speed was Mach ~0.821 at ~(5.229N, 102.813E) at FL350 corresponding to a ground speed of ~473kn. ***Data:*** Last ACARS report posts these values: Mach=0.821 and CAS 278kn The radar printout in [2] OMR-2 p11.	
Conclusions	***Time: 17:06:43 UTC***	
1.I	***Position: 5.229N, 102.813E, FL350***	
1.II	***En route with heading ~25°***	
1.III	***Ground Speed unchanged at ~473kn (Mach ~0.821)***	

Interpretation of item 1.3: How much was the right engine over-consuming?:

According to the Official Malaysian report [2], the right engine was consuming 1,5t/h more than the left engine. It is believed that this is a wrong transcript from the maintenance manifest, as no viable company would have kept in service such an engine (this would have cost them about 2M$ per year).

Between the two messages ACARS at Top Of Climb (17:01:43) and the last one at 17:06:43, the total fuel consumption is calculated by subtracting the gross weight of the aircraft at each time is 6,97 t/h with a gross weight at ~218t. Compared to the Operation Manual fuel consumption tables of the B-777 Flight Manual [32] and the Flight Crew Operations Manual of our simulator [34], a nominal consumption for this weight, at that flight level and that speed is about ~6,67t/h.

Taking into account the timestamps imprecision, this shows that the over-consumption could be at maximum ~300kg/h. Thus the value of 150kg/h is considered to be the most probable one. It is noticeable that B. Ulich has also used a closely related value in his computation of [11] introducing a corrective factor called “Ratio of R to L engine fuel flows in cruise” to take this imbalance into account along with the ageing factor of the engines.

Note: Rolls-Royce has been invited to confirm or correct our interpretation but neither a confirmation nor any correction was provided because the case is still under investigation from a legal standpoint.

[2] *Please note that all the times mentioned are UTC*

2- Passing IGARI

Location 2	***IGARI***	***Time: 17:20:31 UTC***
2.1	Kuala Lumpur ACC not in charge any more and Ho-Chi-Minh ACC not yet in charge ***Data:*** Pilot acknowledged transfer from Kuala-Lumpur ACC to Ho-Chi-Minh ACC Pilot did not contact Ho-Chi-Minh ACC [2] Official Malaysian Report updated (OMR-2) ***Fact:*** This is a normal operational procedure by ATC to transfer the flight to the next sector. It is up to the crew to call the next sector and let themselves known to the next ATC Controller. They did not comply.	
2.2	Flight level FL350 and ground speed was 473kn. ***Data:*** Confirmed by radar tracks provided "afterwards" by [2] Official Malaysian Report updated (OMR-2) p11 [13] Some Observations on the Radar Data for MH370, Victor Iannello p6	
2.3	The new heading just after IGARI was 58° towards BITOD on Route M765. ***Data:*** [2] Official Malaysian Report updated (OMR-2) p11 [13] Some Observations on the Radar Data for MH370, Victor Iannello p6 ***Fact:*** The aircraft was on its nominal route following its flight plan.	
Conclusions	***Time: 17:20:31 UTC***	
2.I	***Position: At IGARI at FL350***	
2.II	***En route with heading ~58° on M765***	
2.III	***Ground Speed unchanged at ~473kn (Mach ~0.821)***	

Airspace structure and organizational aspects:

The waypoint IGARI is in a particular area as far as the air traffic control is concerned. It is in Singapore FIR but in a specific area where the ATC has been delegated to Kuala Lumpur FIR (South China Sea Corridor as explained in [29] Malaysian air traffic services airspace.). When there is no sovereignty issue, and for efficiency purposes, this type of delegation is often put in place for adjacent FIRs.

Without this delegation, on this airway, route M765, not only the Singapore ACC centre would have to control the aircraft for only few minutes but to take care of the transfer from Kuala Lumpur ACC and to Ho Chi Minh ACC centre and the aircraft would have to change the VHF frequency inefficiently too many times.

4.2 The Piloted Trajectory known from the radar data

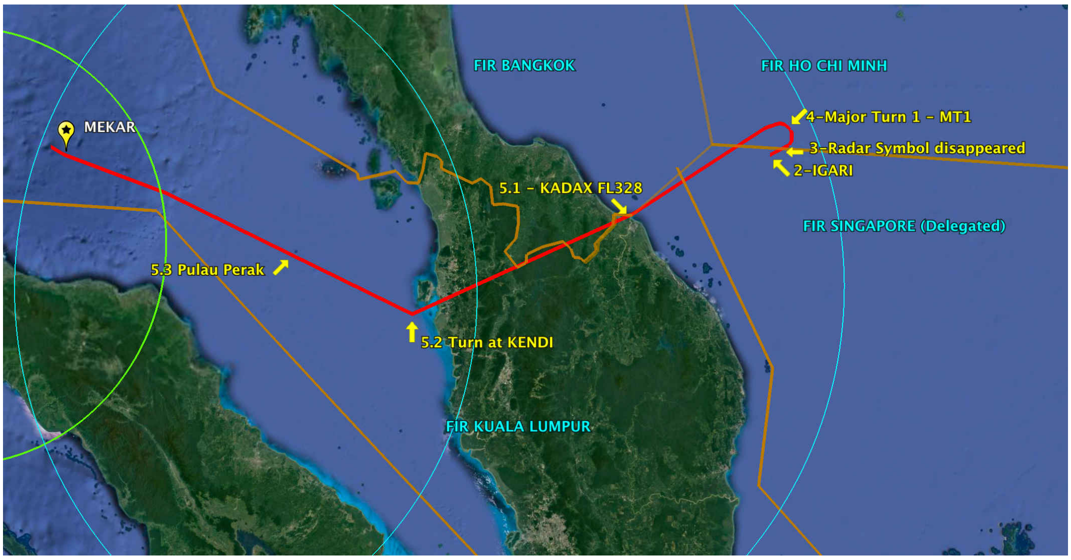

Figure 3:
The location of the key Events 3 to 5.

Figure 3 illustrates Part 2 from the SSR symbol disappearance to MEKAR.

3- SSR symbol disappearance

Location 3	***Mode S Transponder symbol and radar disappeared***	***Time: 17:20:36 UTC & 17:21:13 UTC***
3.1	Mode S Transponder disappeared and radar plot also disappeared. ***Data:*** [2] Official Malaysian Report updated (OMR-2) p6 and radar plots from Bangkok radar [13] Some observations on the Radar Data for MH370, Victor Iannello p6***:*** All the traces of the aircraft disappeared just before the boundary on the Singapore FIR with Ho Chi Minh FIR during the few moments when the aircraft was not in radio contact with any ACC. The Mode S transponder has been switched off. ***Interpretation:*** Take over of the aircraft by People in Command	
3.2	Flight level FL350 and ground speed was 473kn. ***data:*** No data as such. But the aircraft was supposed to be on course as the "Event" just happened. ***Interpretation:*** The Event is interpreted as a general electrical switch-off since a lot of systems were affected and in particular the Satellite Data Unit of the Aircraft Earth Station (AES).	
3.3	Ho-Chi-Minh ACC lost radar contact before BITOD ***data:*** P38 of verbal transcripts	
Conclusions	***At 17:21:13***	
3 I	***Position: 2NM before crossing the boundary of the Singapore and Ho Chi Minh FIRs at FL350***	
3.II	***En route with heading ~58° on M765***	
3.III	***Ground Speed unchanged at ~473kn (Mach ~0.821)***	

A well-prepared diversion from the flight plan:

a) **The position and time were carefully chosen:**

The indicated values provided by the report are 17:20:36 for the SSR symbol disappearance and 17:21:13 for the radar plot disappearance at 3.2NM after IGARI. This occurred 42s after IGARI which represents a distance of about 5.5NM from IGARI location i.e. 2NM before exiting the Singapore FIR.

All the traces of the aircraft disappeared basically at the boundary between Singapore FIR and Ho Chi Minh FIR during the short time lapse when the aircraft was not in radio contact with any ACC.

The people who did it must have been very well prepared and fully aware of aeronautical procedures, they became the new "People in Command". This was a key strategic location granting them a certain time before being recognised as missing by ATC operators. Indeed it took about 20 min (from about 19:21:13 to 19:41:23) to realise that flight MH370 had disappeared.

b) Electrical Switch off:

It is noticeable that the SATCOM log shows no more exchange from 17:07:49 onwards. Thus a disconnection of breakers of the left and right main transfer buses could have triggered the take-over by the Standby buses. Thus the Basic SATCOM (Rack E11) was powered-off. This is evoked in [1] but also in the ATSB official report [5] "*the circuit breakers in the electronic and equipment bay (EEB) being pulled and then later reset* ". More details on electrical issues are provided in Annex 1.

At least one person was in the EEB and most probably from the time the aircraft was at the gate.

Switching off both the main transfer buses implies to put the cabin in the dark. As it was night, getting out of the EEB and entering the cockpit would have been much easier in the dark (all the more so that the electromagnetic door lock would have been de-activated by the power shutdown). It was 2:00 am MYT.

4- Major Turn-1: U-Turn

Location 4	***Major Turn-1: U-turn***	***Time: 17:22:52 UTC***
4.1	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 Singapore FIR and Bangkok FIR and back towards the Malaysian Peninsula, in the direction of the waypoint KADAX (or ABTOK or GOLUD which are equivalent). ***data:*** [2] Official Malaysian Report updated (OMR-2) p3 and radar plots from Bangkok radar [6] ATSB-3 p10 [13] Some Observations on the Radar Data for MH370, Victor Iannello p6 ***Interpretation:*** On its way to BITOD, it was rerouted. Either the pilot or the People in Command engaged the heading ~235° on the MCP.	
4.2	U-turn i.e. sharp turn visible on the military radar plot ***Time 17:23:38 UTC*** ***data:*** No data as such. ***Interpretation:*** But from graphic estimation: the turn occurred between IGARI and BITOD at approximately at a third of the distance between these waypoints. Cf. [13] Iannello p4	
4.3	Climb to 35,700ft during the U-Turn ***data:*** Proven by tracking radar plots. [3] OMR-2 page 3: At 17:30:35 UTC to 17:35UTC the radar return was on heading 231 magnetic (M), ground speed of 496 knots (kn) and registered height of 35,700ft. ***Interpretation:*** The selected option was to turn at an intermediate flight level to minimise the collision risks with the traffic at even flight levels and to save time. The normal procedure would have been to offset on the right and descent before turning left and pass underneath the current route.	
4.4	Oscillations of altitude between 31,100 and 33,000ft. ***data:*** Proven by tracking radar plots. [3] OMR-2 page 3: At 1736 UTC to 17:36:40 UTC heading was 237M, ground speed fluctuations between 494 and 525kn. and height fluctuations between 31,100 and 33,000ft.	

4.5	Last known altitude 32,800ft. ***data:*** Proven by tracking radar plots. At 1739:59 UTC heading was 244M, local ground speed 529kn and height at 32,800 ft. ***Interpretation:*** Altitude 32,800ft is the last known altitude and will be kept until VAMPI as it is a safe level below standard levels used in cruise. It has been flown to avoid collision with other potential traffic, as no TCAS service was available because of the switch-off of the Mode S transponder.
4.6	The average ground speed was 508kn ***data:*** The meteo data fetched from [33] and interpolated in the CAT tools indicate a wind of about 14kn coming from 80°. ***Interpretation:*** Thus the ground speed has been calculated by the CAT.
Conclusions	***At 17:22:52***
4.I	***Position: ~(7.23N, 103,56E), Altitude was 35,700ft***
4.II	***After Major Turn-1, en route with heading ~242° on the boundary of Singapore FIR and Bangkok FIR and later on the boundary of Kuala Lumpur FIR and Bangkok FIR***
4.III	***After Major Turn-1, Ground Speed at ~508kn (local Mach ~0.823)***

Airspace structure and organisational aspects:

In case of communication loss, the normal procedure is to continue along the flight plan (cf PANS 4444, Chapters 8.8.3 and 15.3). Here the "loss" of operational equipment is a major one. So either the pilot entered himself the new heading with the change of flight level either the People in Command did it, this is unknown.

The different flight levels:

The choice of the flight levels (FL) made by the People in Command reveals valuable information.

If it was an electrical failure concerning only communications system, the standard procedure is to continue according to the filed flight plan as if no problem occurred. This explains why the ATC Controllers looked for the aircraft in the continuation of its initial trajectory.

If it was a more serious problem like a general electrical outage, then the standard procedure is to go to nearest airport to try an emergency landing but with specific procedures: to deviate to the right of the airway centreline by about 5NM (Offset), then turn left to follow a track parallel to the original route, then climb or descend to the new level and eventually turn back.

One should remember that the on-board anti-collision system TCAS was switched off and no longer operable. Thus one can speculate that the People in command (or the pilot) choose to save time in adopting an intermediate FL357 to minimise the risks of collision with traffic at that Flight Level in passing just above without following the more lengthy standard procedure.

Concerning the 180° back turn, the normal option is to descend under the Minimum Flight Level of Route M765 and turn and climb again. This would have forced the aircraft to descend below FL250 and used a lot of fuel for climbing again. In addition staying at almost the same level allowed the People in Command to save time in the race for not being discovered.

Finally FL328 was adopted for similar reasons. FL328 is an intermediate flight level on top of the traffic southwest-bound at level FL320 on M765 and later B219 (West Track RVSM) and slightly below the traffic northeast-bound at FL330 (East Track RVSM).

5- New Flight Plan and turn (south of Penang and passing near Pulau Perak)

In this paragraph, the key event is split in three sub-events linked together by a smooth flight at constant FL and speed. The aircraft behaved normally as any aircraft would do with a non-functioning Mode-S transponder. Thus there is only ***one set of conclusions N°5.***

Location 5.1	***New Flight Plan activated towards PUKAR***	***Time: 17:37:22 UTC***
5.1	The Radar plots show a path passing in the vicinity of KADAX waypoint which is on the boundary between Bangkok FIR and Kuala Lumpur FIR (or ABTOK or GOLUD which are within 3NM from KADAX). Then PUKAR. ***data:*** [2] Official Malaysian Report updated (OMR-2) p6 and radar plots from Bangkok radar [13] Some Observations on the Radar Data for MH370, Victor Iannello p6 [6] ATSB-3 p10: ABTOK, KADAX and GOLUD (which are within 3 NM of each other) and later PUKAR ***Interpretation:*** The aircraft stayed on the boundary of Bangkok FIR and Kuala Lumpur FIR. This was done on purpose such that the controller on each side of the boundary might have assumed the other was controlling the aircraft.	
Location 5.2	***KENDI: Slow right turn at the south of Penang***	***Time: 17:52:27 UTC***
5.2.1	First officer's mobile phone detected by Penang communications system at 17:52:27 ***data:*** [6] ASTB-3 page 10 ***Interpretation:*** The most likely waypoint in the trajectory fitting with a fly-by 6NM in the south of Penang-WMKK is KENDI	
5.2.2	At 17:52:35 UTC a radar echo was observed to be slightly south of Penang Island. The last Radar spot on the printed plots reports the aircraft at approx. 6NM south of Penang making a slow right turn. ***data:*** [2] Official Malaysian Report updated (OMR-2) p6 and radar plots from Bangkok radar [13] Some Observations on the Radar Data for MH370, Victor Iannello p7 [6] ATSB-3 p10: ABTOK, KADAX and GOLUD (which are within 3 NM of each other) and later PUKAR The aircraft was on the leg from PUKAR to KENDI as it passes at 6NM south of WMKK. At KENDI it turned right towards VAMPI. ***Interpretation:*** People in Command wanted the aircraft to be seen as flying a standard trajectory along waypoints especially in such a sensitive area monitored by Kuala Lumpur and Bangkok civil and military ACCs.	
Location 5.3	***Over Flying Pulau Perak towards VAMPI***	***Time: 18:02:33 UTC***
5.3.1	The military radar plot shown is close to and south of Pulau Perak Island by 2.7NM. Location ~(5.6836N, 98.9384E) ***data:*** [2] Official Malaysian Report updated (OMR-2) p7 and radar plots from radar [13] Some Observations on the Radar Data for MH370, Victor Iannello p7 [6] ATSB-3 p10: aircraft on its way to join route N571 The aircraft stayed on the Kuala Lumpur side of the boundary of between Kuala Lumpur FIR and Jakarta FIR.	
5.3.2	The averaged ground speed was 508kn ***data:*** The meteo data fetched from [33] and interpolated in the CAT indicate a wind of about 12kn coming from 90°. ***Interpretation:*** The average ground speed was calculated by the CAT.	
Conclusions	***At 18:02:33***	
5.I	***Position: Over Flying Pulau Perak FL328***	
5.II	***En route with heading ~290° towards VAMPI***	
5.III	***Average Ground Speed unchanged at ~508kn***	

Interpretation of 5.3.1:

This was done on purpose to show a normal behaviour apart from a communication problem.

4.3 The Piloted Trajectory known from the Inmarsat data

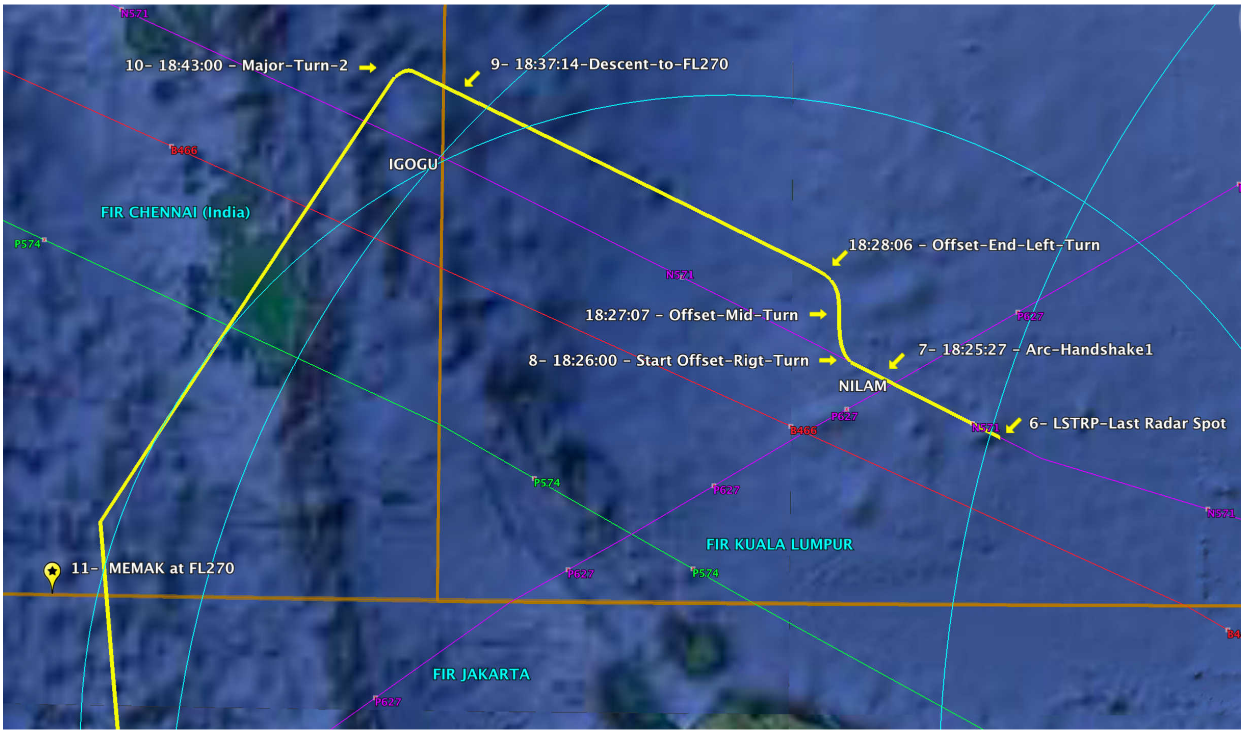

Figure 4:
The location of the key Events 6 to 11.

6- Disappearance after the Last Radar Spot Position (LRSP)

Location 6	***Exit from Penang radar coverage***	***Time: 18:22:12***
6.1	The aircraft disappeared from the military radar records. The Last Radar Spot Position (LRSP) is at approximately10NM beyond IFR waypoint MEKAR on route N571 northwest i.e. ~(6.5770N, 96.3423E). ***data:*** Normal exit out of radar range detection capacity. "The aircraft continued [on route N571] to the northwest until a final radar position for the aircraft was recorded approximately 10NM beyond IFR waypoint MEKAR at 18:22:12" (cf [1] p7 & [6] p19)	
6.2	Western Hill Penang radar coverage ***data:*** At the range of the last radar spot (~243NM), the radar can only detect aircraft flying at altitude ~31,000ft and above with 5,000ft precision (maximum detection range is ~255NM). Our computations on the radar capacity thanks to its specifications [27] confirmed the location of the expected exit. ***Interpretation:*** The aircraft was flying at FL310 +/- 25.	
6.3	***data:*** End of the radar coverage according to radar specifications (Max range=471km). The Last Radar Spot Point (LSTRP) is within this range by 7NM.	
6.4	The aircraft altitude is still 32,800ft. ***data:*** Analysis of the radar plot, the radar coverage and documentation [16.1] and Figure 5 below based on the work done by Stefan Geens and Keith Ledgerwood. ***Interpretation:*** Confirmed by our analysis. The aircraft exited the radar coverage at an altitude close to 32,800ft.	
6.5	The exit speed of the aircraft was ~498kn ***data:*** The average ground speed of the aircraft was ~508kn from Pulau Perak to MEKAR i.e. 154NM covered in 00:18:08. But the distance from Pulau Perak to LSTRP is ~164NM and covered in 00:19:39 Thus the average ground speed of the aircraft was ~495kn. But because of the wind variation from downwind ~12kn at Pulau Perak to -0,4kn at LSTRP, the exit speed is ~498kn. (cf B. Ulich [10], R. Godfrey [16] and the radar time stamps image from Pulau Perak to MEKAR) ***Interpretation:*** The ground speed has evolved in line with the decreasing wind.	
Conclusions	***Time: 18:22:12***	
6.I	***Position: The LRSP is at (6.5770N, 96.3423E) at the altitude of 32,800ft and exited the range of the radar at the same level.***	
6.II	***The aircraft followed Route N571 with the corresponding heading of 296°***	
6.III	***The aircraft ground speed was ~498kn at the exit of the radar coverage***	

Rationale on the exit of radar coverage at the altitude of 32,800ft:

According to the specifications of the radar [27], it is a Thales Ground Master 400. This radar is characterised with a range accuracy of 50 meters, an azimuth accuracy of 0.3 degrees and an altitude accuracy of 2,000ft. at 100NM distance.

Figure 5 below shows the limits of the Western Hill Penang radar capability at range 450km, 460km and 470km corresponding to 31,100, 32,900 and 34,800ft respectively. The picture is a composite of the work done by Stefan Geens [16] based on Keith Ledgerwood's contribution. On top of it, computed radar detection rings at the levels of interest have been added. The last known position of the aircraft shows that the exit flight level is indeed close to 32,800ft.

The commonly agreed coordinates of the LRSP are ~(6.5770N, 96.3423E) which, according to our computation of the radar range capacity, suggest an even lower exit level closer to 31,200ft.

Either way, knowing the exact flight level does not constrain strongly the following segments of the trajectory.

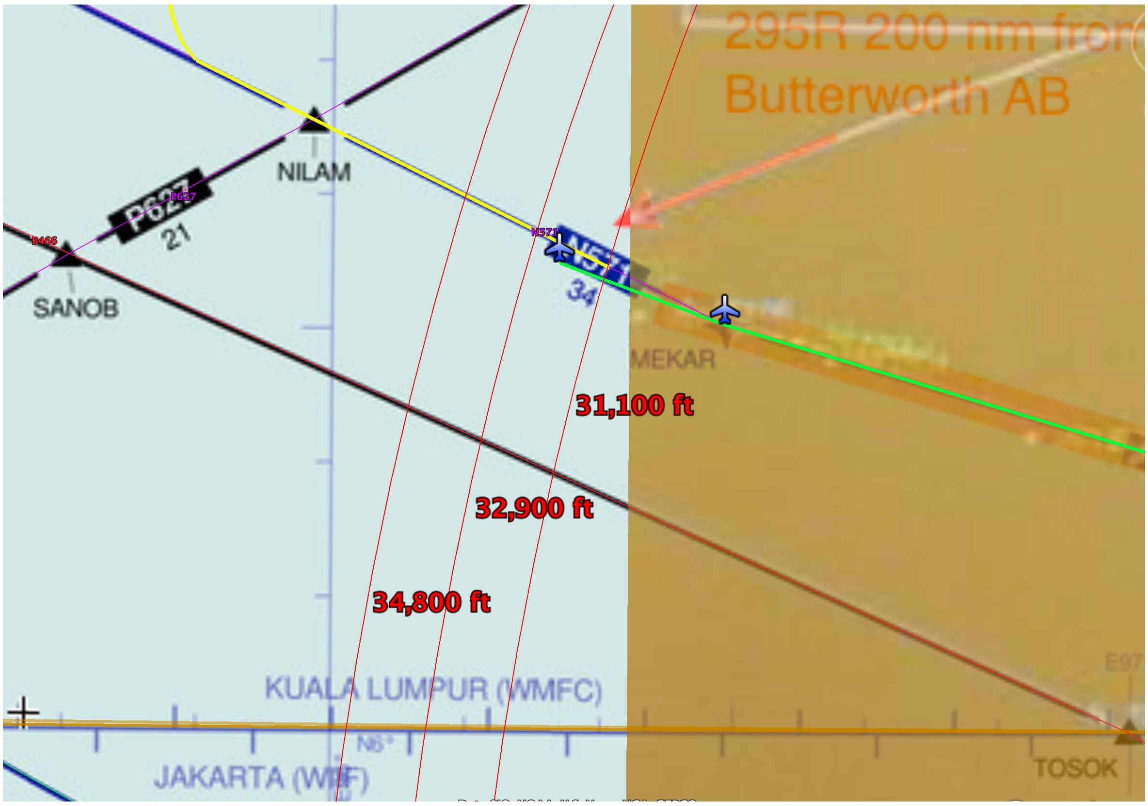

Figure 5:
Position of the aircraft at 18:22:12 versus the Penang radar range coverage limits at 31,100, 32,900 and 34,800ft

Rationale on the speed:

According to [6], the aircraft flew by approximately 6NM of the south of Penang and probably turned when passing by the waypoint KENDI. The distance between south of Penang to the LRSP is ~245NM. It took 29:45sec for the aircraft to travel along this path. Thus the average ground speed was ~495kn. On the last segment from Pulau Perak to MEKAR the radar time stamps provide a scale indicating an average ground speed ~508-510kn. On that segment, the wind component along the track of the aircraft was between ~12kn and -0.4kn. Thus the exit ground speed was probably close to ~498kn. This value is coherent with the estimations and conclusions of other analysts and is generally taken as a working hypothesis.

Incomplete information on radar tracking:

There are still some unexplained, missing information from the Phuket Radar, which should have been able to detect the aircraft trajectory as it was well within its detection range according to our computations. It is most likely that because the aircraft was not in the corresponding sector/zone of surveillance and was in an "exit" direction it has just been ignored probably. The same could be said about the Sabang Aceh military radar.

7- Handshake 1 – Arc-1 – Re-connection of the AES to the Network

This event is related to the sudden re-connection of the AES to the Inmarsat network.

It should be noted that at 18:03 a phone call from the ground could not be forwarded to the AES. So the disconnection occurred between 17:07 when the last ACARS message was sent and 18:03.

In our view, closing the circuit-breakers - that had been opened just after IGARI probably at 17:21- was done **intentionally**.

Location 7	***Handshake 1 - Crossing Arc1 at FL328*** ***Time: 18:25:27 UTC***
7.1	The Satellite Data Unit (SDU) powered up at ~18:22:30 ***data:*** According to event 7.2, event 7.1 must have occurred a few minutes before event 7.2. In [10] p1, Bobby Ulich describes that after a long power-off period, the SDU needs approximately between 120 to 180 seconds to warm up and boot. ***Interpretation:*** The Electrical Power has been switch back on. But selected systems controlled from the cockpit were still kept OFF (VHF Radios and SSR transponder mainly). As the SDU is located in a separate location (in the ceiling close to the middle-rear of the cabin), the People in Command have probably overlooked it or they simply were not aware of the way it is powered.
7.2	Log-on Request (ISU)/Log-on Flight Information (SSU) from the SDU ***Time 18:25:27 UTC*** ***data:*** Inmarsat has published an analysis ([7] Table 1 p3) and a log of the communications between the aircraft and the ground [3]. The posted reference values are for BTO=12,520µs and for BFO=142Hz. The official Malaysian report acknowledged the existence of such communications [2]. ***Interpretation:*** These are essential clues of the aircraft trajectory. Nevertheless, the location is a function of both the Flight Level and the BTO whose value are discussed in more details below.
7.3	Estimated BTO=12533 (reference 12,520µs +/- 50µs) Estimated BFO=141Hz (reference is 142Hz +/- 7Hz) with a Rate of Descent =0 ***data:*** The BTO is correct by construction, as the point has been selected specifically on Arc1 at the correct distance from the last radar spot. The BFO has been estimated thanks to Yap Fook Fah's model-V4. The reference values have been verified and validated by the Inmarsat analysis [7]. ***Interpretation:*** These estimated values are within the margins defined in [7]. See the discussion below.
7.4	Arc1 location is ~(6.7761N, 95.9363E) at 32,800ft ***data:*** Considering the time interval between the last radar spot (18:22:12) and Arc1 time stamp (18:25:27) and the estimated ground speed (~498kn), Arc1 location is further away from the LSTRP (Location 6) by ~27NM.
Conclusions	***Time: 18:25:27 UTC***
7. I	***Position: Arc1 location is (6.7761N, 95.9363E) at 32,800ft***
7.II	***On route N571 with heading 296°***
7.III	***Ground Speed unchanged at ~498kn (with a wind 4kn from 311°)***
7.IV	***Computed BTO=12,533µs and BFO=141Hz*** ***compared to Inmarsat computation BTO= 12,520µs and BFO 142Hz***

The Power-back On event

This Power-back On event is the result of a timely action at a location where the People in Command felt comfortable as they were out of range of Malaysian radar coverage. Switching electricity back on at this point allowed them:

1) to properly complete the next manoeuvre (cf. event N° 8 below) in a more comfortable way with all instruments operational and possibly the TCAS and

2) to take care of the passengers (light in the cabin, kitchens, entertainment, etc…).

In addition, at this stage, they were already preparing a manoeuvre similar to events 3 and 4, including the same tactical elements: false track, hide & turn. The first step here is to exit the radar coverage at a stable level following an identified route looking like any normal aircraft having just a transponder failure. They knew that ATM would look for them on a projected path along route N751 first, according to the standard procedure.

BTO and BFO at Arc-1 at 32,800ft:

Let's consider the consequences of these conclusions on the values of the BTO and BFO at the Arc-1 location.

According to [14] Autopilot Flight Path BFO Error, the computation shows that the location of the aircraft at 18:25:27 which corresponds to the BTO=12,520µs at 35,000ft on route N571 is (N6.7869, S95.9142). Using the computed ground speed of ~498kn, the corresponding BFO is thus 141Hz. This figure is within the acceptable range as set in [7] by Inmarsat.

But at the altitude of 32,800ft (named FL328 for simplicity) the new estimated location ~(6.7761N, 95.9363E) leads to new values of BTO and BFO. Using the same model in [14], the new predicted values are BTO=12,533µs and BFO=141Hz which are also within the acceptable specification of [7] and [10] and thus validate the conclusions.

8- Contingency Procedure - CP

This key event relates to a standard aeronautical procedure to fly a parallel path on the right side of the nominal route or plan. This manoeuvre is analysed in detail and is described as a Strategic Lateral Offset Procedure (SLOP) by B. Ulich in [9] and [10] based on a private conversation he had with V. Iannello. But actually it is a contingency procedure (CP).

The new perspective offered below is based on this CP and makes full use of the BFO values provided in the Communication log [3] between the time stamps 18:27:03.9 and 18:28:14.9. The BFOs are taken into account for the flight operations analysis adding credibility to the offset manoeuvre at level FL328. This allows for more details to the description of the CP by just reading and interpreting the technical data.

Location 8	***Contingency Procedure - CP***	***Time: 18:26:00 UTC***
Hypothesis	The flight level did not change and the offset manoeuvre was done at constant FL (which is coherent with the obtained results and with Fact 9 below).	
8.1	Start a right turn to begin with the offset manoeuvre. ***data:*** Because of event 8.2, which is the middle of the manoeuvre, this event must have taken place. ***Interpretation:*** At constant flight level and at 60° per minute, this event is estimated to have taken place at ~18:26:00.	
8.2	18:27:04 – 18:27:08 The In-Flight Entertainment system set up a ground connection for the SMS/email application ***data:*** Inmarsat has published an analysis ([7] Table 1 p3) and a log of the communications between the aircraft and the ground [3], more details are provided in [16] where the data have been conveniently organised in a spreadsheet by R. Godfrey and analysed in [3.2 & 3.3] by B. Ulich. Reference measured values are ranging as BTO=12,520-12,560µs and as BFO=176-172Hz. ***Interpretation:*** At constant flight level and at ground speed ~498kn, the increase of BFO values provides evidences on that the best heading was ~355-360° but still the corresponding predicted BFOs are found too low compared to the measured ones. These communications took place at the very end of the right turn and at the beginning of the left turn of the manoeuvre when the aircraft was rotating from right bank to left bank. More details are given below in this section below for a more precise estimation of the BFOs.	

8.3	18:28:06-18:28:15 The In-Flight Entertainment system set up a ground connection for a Built-In Test Equipment (BITE) application ***data:*** Inmarsat has published an analysis ([7] Table 1 p3) and a log of the communications between the aircraft and the ground [3] and more details are provided in [16] where the data have been conveniently organised in a spreadsheet by R. Godfrey and analysed in [3.2 & 3.3] by B. Ulich Reference values are BTO=12,500-12,480µs and BFO=144-143Hz. ***Interpretation:*** At constant flight level, the decreased BFO values (the estimated value is back to about 142Hz) provide evidence that the best heading is ~296° i.e. the aircraft was flying an offset path parallel to N571 (The measured BFO is 143Hz).
Conclusions	***Time: 18:26:00 UTC Offset started at ~18:26:00 and finished at 18:28:06***
8.I	***Position: (6.8272N, 95,8379E) at FL328***
8.II	***Ground Speed unchanged at ~498kn (wind unchanged)***
8.III	***Offset from route N571 with heading 296° by approximately ~10 to 15NM***

Using and interpreting more available BFOs:

From what we have read so far in the literature, the previously published analyses have excluded the BTO and BFO measurements between 18:25:34 and 18:28:1 as provided in the Communication Log [3] and the Inmarsat paper [7] Table 1 and in particular in the elaboration of the final Inmarsat reference Table 6 in [7]. Communication Log [3] provides additional consistent data from another channel (Channel N°4) all the way through (except the one at 18:25:34 Log-on/Log-off Acknowledge) along with the other channels measured BTO values and should not be ignored.

The present analysis relies on the full set of BTO and BFO measurements except the abnormal values measured at 18:25:34,461 (273Hz) for which B. Ulich's explanation in [10] could be the warm-up of Channel 4. BFO values were also used even when they are provided with no corresponding BTO.

Rationale for the Contingency Procedure (CP):

In Bobby Ulich's analysis [10], it is suggested that an offset of 15NM took place on the right. This manoeuvre corresponds to a standard manoeuvre performed when an aircraft intends to descend from an airway and turn left to pass underneath it: offset to the right and descend is the usual way to proceed. As we assume that the intention of the People in Command was to turn left eventually (cf Major Turn-2 at event N°10 below), an offset is the first step, before descending and finally turning to the left to pass under route N571 for which the En-route Chart Kuala Lumpur FIR [28] indicates the Minimum Flight Level to be FL280. Thus the aircraft should get prepared to descend to FL270 at minimum.

Unlike [10] where the presented timing indicates that the offset manoeuvre took place between ~18:23:24 and ~18:26:42 leading to an artificial correction of the BFO at Arc-1 as this time window includes the ping at 18:25:27, it is preferred to "read" the data and suppose that the offset manoeuvre started shortly after the Handshake1 of Arc1.

Considering the offset Manoeuvre first and thanks to the measured BFO values around 176Hz at about 18:27:06, and comparing them with the estimated values via a sensitivity analysis (Best BFO=167Hz) one can conclude that the aircraft was probably heading to 360° (northwards) with a ground speed=498kn. But one can see that the estimated BFO is outside the acceptable margins defined in [7].

Taking a closer look, this is when the aircraft had finished turning to the right and had started its turn to the left thus rotating from +25° to -25° banking. Considering that this is a rotation usually carried out at 10°/s and that the antenna on the roof is at ~4m above the axis of rotation between the wings, this creates vertical speed of the antenna of about +150fpm increasing the BFO by about 3Hz and raising it up to 170Hz which is in the acceptable margins.

Thus, we assumed that the right turn started around 18:26:00 with a turning rate of 60° per minute, and then the left turn started at about 18:27:06 at the same turning rate to finish just before 18:28:06 where the estimated BFOs are back to similar values of an aircraft heading to 296° at 498kn (BFO ~144Hz). Please note that the flight level has basically no influence on the BFO value due to the satellite-aircraft configuration at this time. Our simulations confirmed such a turn rate, the time required by our flight simulator to complete this manoeuvre was about 1:10min.

At 18:28:15, the estimated BFOs ~142Hz computed for the aircraft on the offset track matches the measurement of 143Hz given in [7]. This validates the fact that the aircraft was back on track 296° on the offset path.

9- Descent to FL270

This is the first and second step of the "descent, hide and turn" way to proceed, which is a slight variation of the protocol already used for the Major Turn MT-1 after IGARI (Events N° 3 and N°4).

Location 9	***Before IGOGU on offset of route N571 north***	***Time: start before 18:39:55 and finished after 18:40:56***
9.1	Start fast descent just after having exited the Banda Aceh and Lhokseumawe radars range coverage at FL328. The descent lasted about ~2:20min from FL328 to FL270. ***data:*** For Event 9.2 to happen, the start of the descent must have occurred before 18:39:55 ***Interpretation:*** The aircraft stayed on the same offset track until exiting the limit of radar coverage and it descended to ensure its disappearance from the radar screens to mislead potential monitoring ATC controllers. This was done was in a similar way as in Major Turn MT-1: leaving behind a false intent before hiding and then turning.	
9.2	The measured values of the BFOs are between 86 and 90Hz. ***Time 18:39:55-18:40:56*** ***data:*** Inmarsat has published an analysis ([7] Table 1 p3) and a log of the communications between the aircraft and the ground [3] and more details are provided in [16] where the data have been conveniently organised in a spreadsheet by R. Godfrey and analysed in [3.2 & 3.3] by B. Ulich Yap Fook Fah's model to estimate the BFOs. ***Interpretation:*** Considering the heading to 296°, the proximity of the exit of the Kuala Lumpur FIR, the limit of the range coverage of the Pukhet radar and Lohkseumawe radar, the aircraft entered Chennai FIR via a fast descent to reach FL270 and prepared its Major Turn 2 to the left to pass underneath FL280 which is the Minimum Flight Level of Route N571.	
9.3	Estimated BFO=88Hz (ref {86~ 90} +/- 7Hz) with a heading to 296° with Rate of Descent RoD -2500fpm No BTO measurement. ***data:*** The reference-measured values have been verified and validated by the Inmarsat analysis [7]. The BFO has been estimated thanks to the location flown during our simulations and Yap Fook Fah's model-V4 and our CAT. ***Interpretation:*** The aircraft was descending fast to FL270 in a parallel route offset of N751 at approximately 10 to 15NM.	
Conclusions	***Time: after 18:41:00 UTC***	
9.I	***Position: In the vicinity of IGOGU Started somewhere outside radar coverage and finished just before Major Turn-2 at ~(7.8511N 94.2821E). New level is FL270***	
9;II	***heading 296°***	
9.III	***The FMS automatically ACTivated the ECONomic Descent 240kn mode which engaged the reference KIAS at ~240kn thus gs= ~350kn at the bottom of the descent, the wind was almost headwind 12kn from 260°.***	

How to escape radar coverage and detection:

Our interpretation is that the CP described at Location-8 had a different goal than the ones described by the research community so far. The CP was indeed the first step of a standard procedure to descent without interfering with the current potential traffic on route N751 and later B466 and then P574. To prepare the next diversion turn on the left (i.e. crossing the traffic), the People in Command had to choose between climbing and descending to pass above or below the Minimum Flight Level of Route N751 which is FL280. Climbing would have increased the risk of being detected again by the Penang radar and to attract attention from the Banda Aceh and Lhokseumawe Aceh radars. Thus descending after exiting the coverage of both radars was the most logical choice to stay under cover, following the same strategy observed from the beginning of what we consider to be a take-over.

In section 13 of paper [10] analysing the offset after Arc1, a descent at RoD -2300fpm is evoked as being possible and lasting until ~18:41:00. It is stated "*this would imply to have descended to FL200 without clear explanation on this conclusion. There is no objection that a fast descent took place followed by a left Major Turn*".

To our point of view, this descent is operationally fully realistic with a RoD=-2500fpm which is operationally more commonly selected rather than -2300fpm. Thus the timing should be analysed more precisely: the time, during which the measured BFOs are at around ~89Hz on average, is basically one minute i.e. from 18:39:55 to 18:40:56. Thus the descent duration could have lasted 1 min or longer. In particular, it could have lasted the 2:20 minutes necessary for the aircraft to descent from FL328 and reach FL270 at a Rate of Descend (RoD) of ~-2500fpm. Computing backwards, and knowing that the descent must have finished by 18:41:00 at the earliest, this means that the aircraft travelled during ~10 min after the end of the offset manoeuvre at 18:28:14 i.e. ~85NM. This fits with the distance between the end of offset manoeuvre and the boundary of the Banda Aceh radar coverage. This justifies the derived Foot of Descent (FoD) distant to IGOGU by ~21NM in the northwest direction.

In addition, it is noticeable that the aircraft left Kuala Lumpur FIR at FL328, with a ground speed of 498kn and heading at 296° and that, a few moment later, entered Chennai FIR at FL270, with a ground speed at ~350kn heading 210°. It could have been detected as two different flights increasing the difficulty to identify the aircraft through a co-ordination between the two ACC centres.

Note: The new FL270 is justified in the next section event N°10 with the goal of passing under routes N571 and P574 eventually with route B466 in between. On route B466 the maximum authorised altitude is FL270, the aircraft could not descend lower at this point.

Aircraft Operations aspects:

The descent was triggered ~10min after the end of the offset manoeuvre.

The People in Command entered the target FL270 and the vertical speed (RoD) -2500fpm in the MCP and validated them. Consequently, this switched off the VNAV function of the Auto/Pilot (A/P) and the FMS interpreted this as the beginning of descent of the flight. It automatically activated the economy descent 240kn mode (ACT ECON DES 240kn) which subsequently engaged the reference KIAS at ~240kn thus controlling automatically the aircraft air speed during its descent.

In fact, a RoD of -2500fpm is the most appropriate rate to keep the aircraft within the flight envelop of the B777 taking care of the relation FL/air-speed for a continuous descent and avoiding potential over speeding which occurred systematically for a faster RoD in all of our simulations. Consequently the ground speed harmoniously decreased from ~498kn to ~350kn at the bottom of the descent.

Alternative option to the CP: a slow descent before Major Turn-2:

Another possibility is that the Major Turn MT-2 took place earlier and finished before ~18:39:45. It would mean that the descent to prepare for it would have taken place between 18:28:14 and 18:38:15. It means a slow descent at RoD=-650fpm from FL328 down to FL270, which is realistic. Then the MT-2 would have taken place during 01:30 min. Then, when the communications exchanges took place between 18:39:50 and 18:41:00 with the aircraft flying at FL260 heading ~225°, the estimated BFOs match the measured BFOs.

But this alternative is not retained in our scenario as the aircraft would have remained within the Banda Aceh radar coverage – and even would have not left it at all – a situation where the ATC would have expected the aircraft SSR transponder to reply to radar interrogation. Secondly the RoD=-700fpm is not a typical value for pilots in this situation. A round figure like -500 or -1000fpm would have been naturally preferred.

10- 2nd Major Turn (MT-2)

The MT-2 took place north of IGOGU but close to it, which is a waypoint, located exactly on the boundary between Chennai FIR and Kuala Lumpur FIR. The aircraft gave the implicit message to ACC Kuala-Lumpur and Jakarta FIR that it exited FIR Kuala-Lumpur. Jakarta FIR is the most concerned neighbour with detection capacity that the aircraft wanted to mislead. On the other end, it showed to Chennai FIR that it was entering just for a passing-by when considering its actual direction in Chennai FIR i.e. ~210° which is short cutting the corner of the FIR. All of the above lead to the hypothesis of a clever use of the intersection of 3 FIRs adding confusion in the potential identification of the flight.

When it entered the Chennai FIR, the flight had changed dramatically its configuration: a different direction, a different flight level and a different speed i.e. like a complete different flight. For Jakarta FIR it appeared as a flight coming from Chennai FIR and also clearly showing it was passing by and not entering towards Sumatra.

Location 10	***Major Turn 2 – MT-2 passing underneath N571*** ***Time: ~18:43:xx UTC***
10.1	Start of Major Turn-2 (MT-2) at about ~(7.8511N 94.2821E): ***data:*** There is no data of the turn except that the northern path towards Kazakhstan was not retained as explained in [6]. The remaining part of the full analysis below demonstrates that this turn occurred. ***Interpretation:*** There has been an activation of the new flight plan with a Direct to MEMAK, which is the most logical choice for the next waypoint to stay out of range of the Banda Aceh radar.
10.2	Flight levels on Route N571 and P 574 are FL280 and above. To pass underneath these routes, aircraft should fly at FL270 because of 1000ft vertical separation RVSM. ***data:*** En-route Chart Kuala Lumpur FIR [28] indicates N571 Minimum Flight Level to be FL280. ***Interpretation:*** The aircraft continued to behave normally according to ICAO flying procedures in order not to attract attention.
10.3	The aircraft crossed route B466 some 30NM after passing under N571. Maximum Authorised Altitude of route B466 is FL270. To cross it the aircraft must have climbed a little bit to pass above then descended once more because of route P754. ***data:*** En-route Chart Kuala Lumpur FIR [28] indicates B466's Maximum Authorised Altitude of route B466 is FL270. ***Interpretation:*** The aircraft continued to behave normally according to ICAO flying procedures in order not to attract attention. It made a possible small "bump" at FL275 for crossing B466 and came back to FL270 afterwards. Alternatively it could have stayed levelled at FL270 if its TCAS was ON.
10.4	Eyewitness Katherine Tee saw an aircraft flying southward with black smoke at the tail of the engines. Her location coordinates are approximately (6.67N, 94.57E). The aircraft was flying well below two other aircraft. ***Testimony:*** Her testimony brings interesting information about the surrounding traffic: « she saw the outline of the plane; it looked longer than planes usually do. […] There were two other planes passing well above it – moving the other way – at that time. They had normal navigation lights. ». ***Interpretation:*** Mrs Tee saw the MH370. This correlates with the estimated path of the aircraft at about 50NM from her location. It can be deduced that the MH370 was flying at a lower altitude. Her testimony shows that the People in Command did the correct thing to avoid any collision in descending under the route, as there was surrounding traffic indeed.
10.5	The aircraft FMS selected the most adapted speed for the flight level and the characteristics of the aircraft.

	Data: There is no data as such. But in order to fly as far as possible the People in Command must have used the FMS to its best. ***Interpretation:*** The KIAS speed of the aircraft was about ~240kn which means a ground speed ~350kn at FL270. This has been verified on our simulator.
Conclusions	***Time: ~18:43:xx UTC***
10.I	***Position: the Start of MT-2 is ~(7.8511N 94.2821E) at FL270***
10.II	***The aircraft was flying direct to MEMAK, heading ~210°***
10.III	***The FMS had no reason to change from the currently ACTive ECONomic Descent 240kn mode maintaining the reference KIAS at ~240kn thus gs= ~350kn.*** ***At this flight level the wind was lateral-down wind of 9kn from 169°***

Rationale for MEMAK:

So far, the People in Command followed a clear strategy to make best use of their knowledge of the ATM zones of responsibility i.e. the FIRs. After having exited Kuala Lumpur FIR and letting believe the aircraft was heading 296° at FL328 with ground speed=498kn, they entered Chennai FIR heading 213° at FL270, thus with a slower speed because of the lower flight level.

Until this point they avoided entering in Jakarta FIR, but pursuing this further would have implied a large detour to stay outside of it. It should be noted here that the civil Indonesian ATC had no interest in following this flight outside its region of responsibility.

So eventually, the People in Command had to plan an aircraft trajectory to enter the Jakarta FIR but without attracting too much attention from Indonesian controllers. How to do this? If the SSR Transponder was switched on because of the TCAS, the aircraft had to stay out of range of the SSR capabilities in the vicinity i.e. Banda Aceh and Lohkseumawe. If the SSR Transponder was switched off, the aircraft had also to stay out of range of the SSR capabilities. The aircraft being out of range, it was normal for the Banda Aceh ACC controller to –possibly – see this aircraft passing by with no SSR identification. Consequently, the aircraft avoided this radar coverage in taking a direction that passes just outside or at the very limit of the radar coverage and this leads naturally to MEMAK.

Figures 6 demonstrates the strategy of the manoeuvre that took place at MT-2 point which was sufficiently wide enough after IGOGU at 18:43:00 in turning left to ensure that the aircraft was out of range of the coverage of the civilian Banda Aceh radar and Lohkseumawe. The straight-line path from MT-2 point to MEMAK is basically a tangent to -but outside of- the maximum range of the radar. Thus ACC Jakarta had no means to be aware that it was the same aircraft entering its FIR.

Aircraft operations aspects:

After having passed to the north of IGOGU, the waypoint MEMAK was probably entered in the MCDU in place of IGOGU and validated. The aircraft turned left at level FL270 and the reference KIAS was kept by the FMS at 240kn as it considered the aircraft was still in descent and thus maintained active the ACT ECON DES mode (ACTive ECONomy DEScent).

From now on, our assumption is that this mode was kept active as the aircraft was descending in steps as shown later.

This led to a ground speed of ~350kn and a new heading around ~210°. The later depends on where exactly the MT-2 turn took place, which cannot be known precisely as it depended on a human intervention.

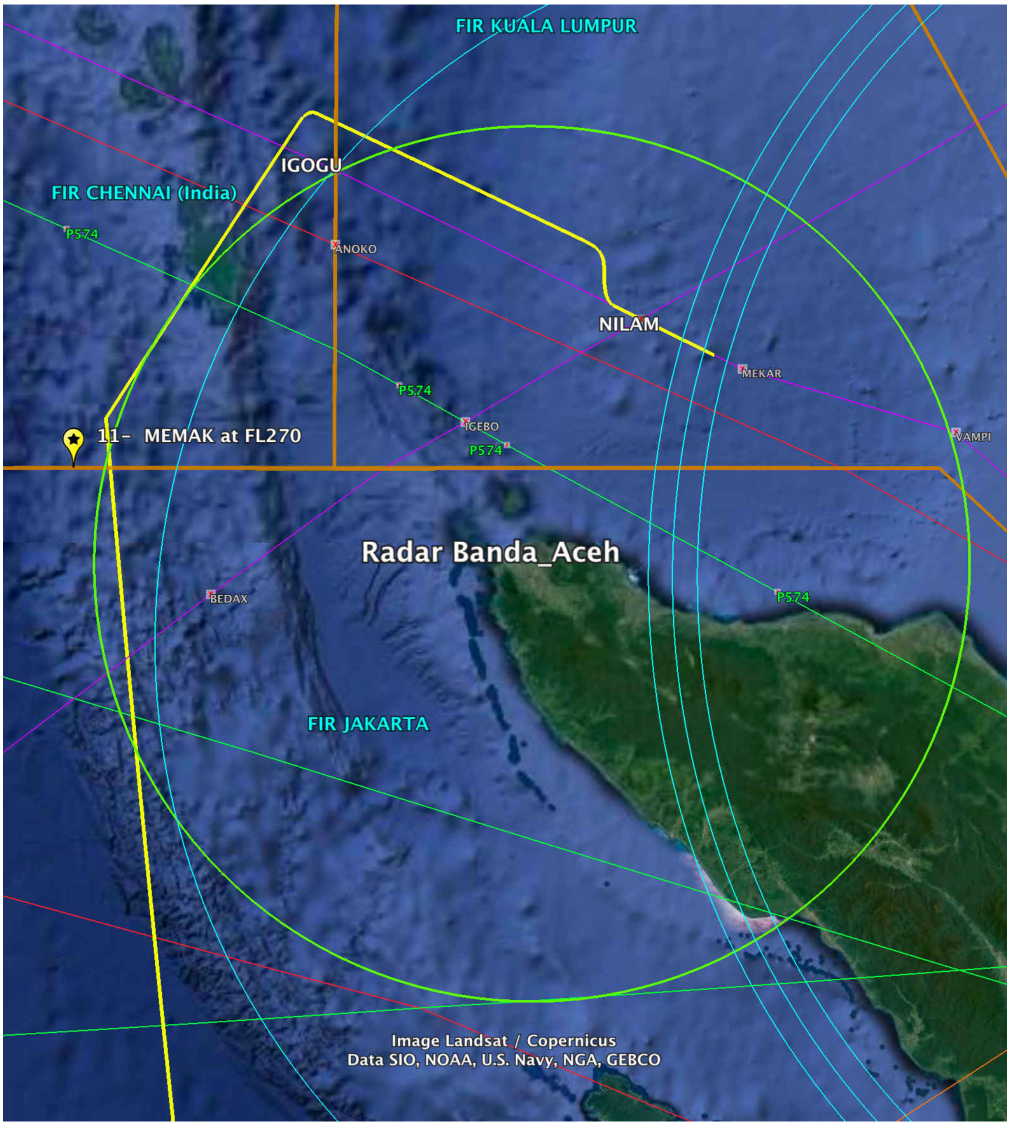

Figure 6:
The path MT-2 to MEMAK stays out of range of Banda Aceh SSR radar.
The green circle is the maximum range at FL270.
The yellow track is the aircraft path since the offset manoeuvre.

Note: The path of the aircraft was within the coverage of the military Sabang Radar. It is intriguing that there is no trace of it. On the other end, there must have been many spots on the screen at that time and the MH370 was just one amongst many others. In addition, the MT-2 manoeuvre of the aircraft may have not been captured as it occurred within a short lapse of time (less than 1:30 min).

11- MEMAK Waypoint

MEMAK waypoint was the entry point into Jakarta FIR, which the People in Command wanted to avoid. Thus they geared the path of the aircraft to the quickest waypoint to exit Jakarta FIR on their way to FIR Melbourne. Thus the aircraft turned to the left into a southward direction.

It is important to note here that the turn took place somewhere about 20NM before MEMAK. The crossing of Arc2 correlates this fact (cf. rationale for event N°12). This early turn is not unusual.

Location 11	***MEMAK***	***Time: ~19:03:xx UTC***
11.1	End of the DIRECT route MT-2-MEMAK and beginning of a DIRECT to POSOD. Light turn to the left (from heading 213° to new heading ~174°) taken place ~20NM before MEMAK. ***Interpretation:*** POSOD is the most logical next waypoint when considering the characteristic of the technical data of the ping at Arc-2 (and later at Arc-3) and the ground speed of the aircraft about 350kn but it is not a data per se. Our computations and simulations validated this assumption. POSOD is the closest waypoint towards Australia to exit Jakarta FIR as it is on the boundary with FIR Melbourne.	
11.2	MEMAK is distant from Major Turn-2 location by ~132NM. ***data:*** Computed by the CAT (great circle method) and cross-checked via Google Earth. ***Interpretation:*** Considering that a priori no change occurred since MT-2, the speed remained at ~350kn. The estimated time stamp at MEMAK is therefore 22:30 min after MT-2 i.e. ~19:03:xx. The low precision of this time stamp is of little importance, the value provided is only indicative.	
Conclusions	***Time: ~19:03:xx UTC***	
11.I	Position : (6.0N, 93.08E) Flight level was unchanged at FL270	
11.II	DIRECT route to POSOD with new heading at ~174°	
11.III	The FMS still in the mode ACTive ECONomic Descent with KIAS ~240kn thus a ground speed gs ~350kn. The wind was ~7kn coming from75°	

How to take care of the FIR boundaries:

The path followed by the aircraft is almost parallel to the boundary of Jakarta FIR and Colombo FIR. Thus the aircraft would not have been perceived by the Sabang military as an intruder having to be closely monitored.

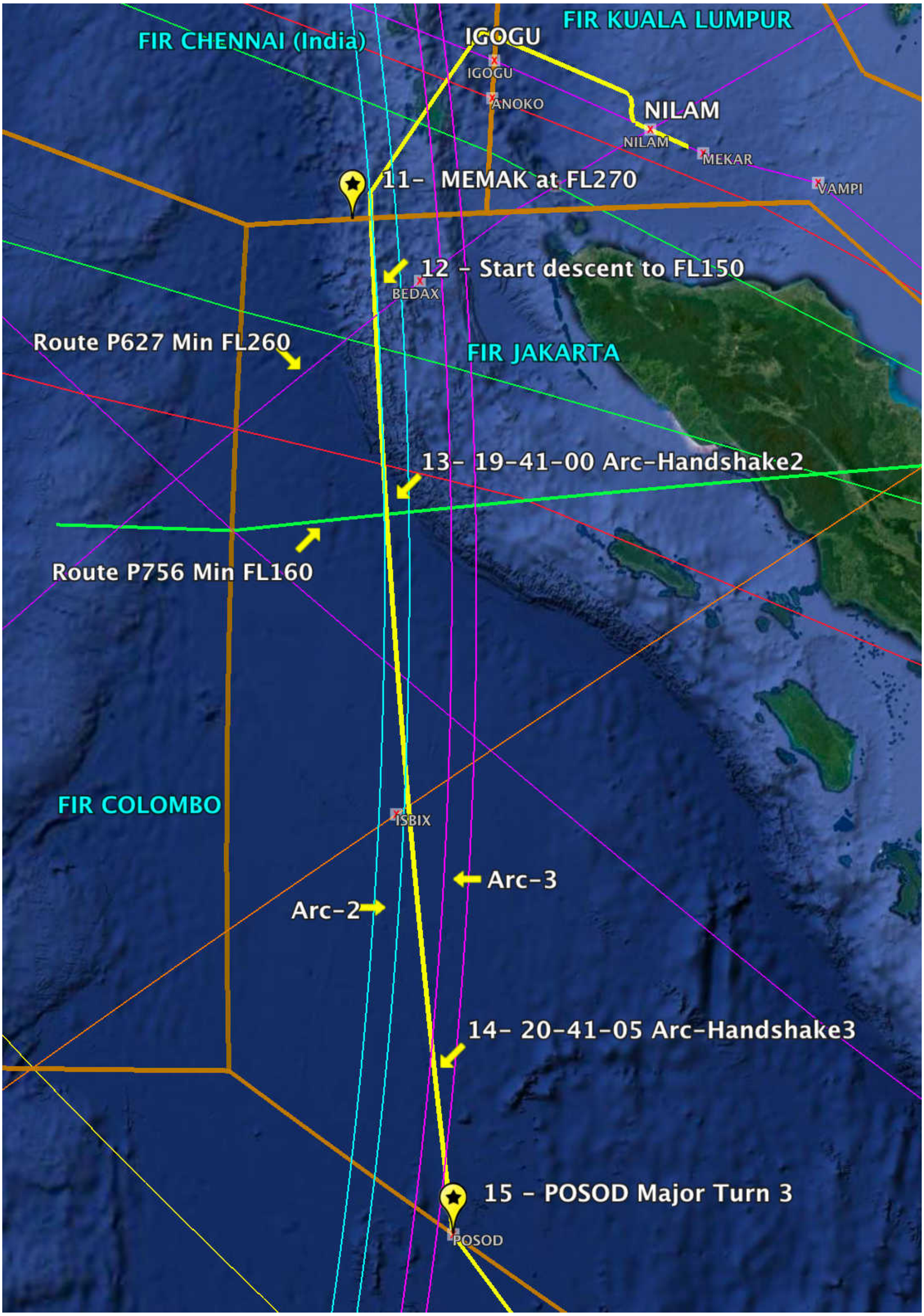

Figure 7:
Location of the key events 12 to 15.

12- Start descent to pass underneath route P627 and later route P756

The aircraft could have been under scrutiny of the military controllers because it was still in the primary radar coverage of Sabang Aceh.

Thus the People in Command had to show them (provided that anybody was actually watching…) that the aircraft trajectory complied with standard procedures. This trajectory was going to cross orthogonally two routes on its way: first route P627 whose Minimum Flight Level was FL260 (it has been changed into FL240 in Nov 2017) and later route P756 whose Minimum Flight Level was FL160.

Consequently, the aircraft flew a continuous descent to pass underneath both routes starting in the north of route P627.

The standard procedure is to descend at FL150 (RVSM airspace) and to pass underneath P756 eventually.

Location 12	***Start descent from FL270 to FL150***	***Time: ~19:17:00 UTC***
12.1	Start descent towards FL150 in order to pass underneath route P627 first and later route P756 whose Minimum Flight Level is FL160. Top of Descent (ToD) at location ~(5.375035N, 93.329712E) at the north of route P627. ***data:*** En-route Chart Kuala Lumpur FIR [28] indicates that west-east route P756 close to 5°N has a Minimum Flight Level at FL160. It also indicates a Minimum Flight Level at FL260 for P627. In addition, by just reading the communication log [3], the BFO value at the Arc-2 (occurring just in the north of P756) shows that the aircraft had a vertical speed RoD ~ -400fpm. ***Interpretation:*** The aircraft needed to descent on time to pass underneath Minimum Flight Level of P627 and P756 for respecting the safety rules but also to show to the possible military controller at Sabang Aceh that it did behave as a normal aircraft.	
Conclusions	***Time: ~19:17:00 UTC***	
12.I	***Position:(5.2592N, 93.3406E) with a rate of descent (RoD) ~ -500fpm***	
12.II	***Steady heading at ~174°***	
12.III	***The FMS still in the mode ACTive ECONomic Descent with KIAS ~240kn thus a ground speed decreasing from ~350kn to ~300kn at the bottom of the descent. The wind was cross wind of ~10kn coming from 98°.***	

Rationale for the Top of Descent-2 (ToD-2):

Because the aircraft had to cross route P627 whose Minimum Flight Level is FL260 it must have started its descent before crossing this route.

A rate of descent RoD of -500fpm is a value communally used for an economical, comfortable descent. Choosing a faster rate could have been intriguing for the military of Sabang Aceh. Descending from FL270 to FL150 requires 24:00 min. As read in [3] (cf. Facts at Location 12 below), the BFO shows that at Arc-2 the aircraft was still descending. Thus the ToD must have been around ~19:17:xx. This points to a location around ~(5.2592N, 93.3406E) at about 130NM before crossing route P756

Aircraft flight management:

The People in Command were still controlling the descent of the aircraft via direct entries on Vertical Profile (FL and Vertical speed) made on the MCP. Thus the FMS kept the reference KIAS at 240kn as it considered the aircraft was still in the ACT ECON DES mode (ACTive(ated) ECONomy DEScent). This leads to decreasing ground speed accordingly to the decreasing Flight Level.

13- Handshake 2 - Arc-2: Log-on/Log-off Acknowledge

Location 13	***Arc-2 - Handshake 2: Log-on/Log-off Acknowledge*** ***Time: ~19:41:03 UTC***
13.1	Communication between Satellite and the aircraft AES-SDU: 0x14 - Log Control - Log-on Interrogation on Channel 10. 0x15 - Log-on/Log-off Acknowledge on Channel 4 after ***data:*** Inmarsat analysis ([7] Table 1 p3) and the log of the communications between the aircraft and the ground [3] and more details are provided in [16] spreadsheet by R. Godfrey and analysed in [3.2 & 3.3] by B. Ulich & Yap Fook Fah's model-V4 to estimate the BFOs. Standard Inmarsat technical and operational procedure for checking SDU status by the ground.
13.2	***Interpretation:*** Estimated BTO=11457 (reference 11,500µs +/- 50µs) Estimated BFO=111Hz (reference is 111Hz +/- 7Hz) with a Rate of Descent ~400fpm The BTO is matching very well the measured BTO as it had to be almost at the crossing with Route P756 and finishing its descent. The BFO has been estimated thanks the CAT and Yap Fook Fah's model-V4. The reference values have been verified and validated by the Inmarsat analysis [7]. These estimated values are within the margins defined in [7]. See the discussion below.
13.3	Route P756 west-east close to 5°N with a Minimum Flight Level at FL160 ***data:*** En-Route Chart from Indonesian DGCA [28] ***Interpretation:*** The aircraft had to descent in order to safely pass underneath according to aeronautical rules to avoid passing traffic on route P756. Until now, the aircraft flew safely according to aeronautical rules. There is no reason to deviate from this behaviour.
13.4	Sabang Aceh military range circle coverage finishes at ~(2.25,93.55) which is in the vicinity (~25NM south) of the crossing with Arc-2 ***data:*** Sabang Aceh has a maximum range of 445km. ***Interpretation:*** From Pulau Perak, the aircraft was permanently within the range of this military radar. Thus the People in Command behave as much as possible as normal civilian traffic during their visibility inside the radar range.
13.5	***Interpretation*** The location is estimated at ~ (3.1824N, 93.5550E). This is a realistic location. Considering that the aircraft was flying tangentially to the arc, the location within Arc-2 satisfying the BTO could be along a segment of 150NM long. The exact location of the Arc2 crossing point is not of much importance due to the geometry aircraft-satellite.
13.6	The wind was 8kn at 86° ***data:*** Data from Nullschool website [33]. ***Interpretation:*** As the aircraft heading was 174° the wind component along its path was 1.5kn.
13.7	The FMS still in the mode ACTive ECONomic DEScent 240kn. The reference speed at the bottom of the descent was KIAS=240kn which gave a gs~301kn at FL150 including the wind. ***data:*** No proof as such. Our simulations demonstrated that this value is operationally realistic as the simulator automatically adopted them. ***Interpretation:*** Normal behaviour of the FMS automation adapting the speed to the FL. As the People in Command were following the prepared flight plan with still some descent to come, they had no reason to modify their way of "driving" the aircraft. So no change is expected here.
Conclusions	***Time: ~19:41:03 UTC***
13.I	***Position: (3.1824N, 93.5550E) determined by our simulations. The rate of descent (RoD) was ~ -400fpm (levelling at the bottom of the descent at ~-500fpm before passing under route P756)***
13.II	***Steady heading at ~174° towards POSOD***
13.III	***The FMS still in the mode ACTive ECONomic Descent with KIAS ~240kn thus a ground speed gs~301kn at FL150. The wind was cross wind of ~8kn coming from 86°.***
13.IV	***BTO=11,457µs and BFO=111Hz*** ***compared to Inmarsat reference BTO 11,500µs and BFO 111Hz***

Rationale for Arc-2:

The geometry of the configuration satellite movement vs. aircraft movement at Arc-2 is sensitive as the aircraft is flying tangentially to the Arc. Thus a small shift of the real aircraft path due to crosswind, flight (un)precision or human intervention for example could induce a small lateral displacement changing the location of the tangential crossing much more than would be the case for an orthogonal crossing.

Reading the Inmarsat-measured BFO at Arc-2, the value is BFO=111Hz. Considering that the aircraft was just above (but close) to FL150 and its ground speed was about ~300kn (also demonstrated by our flight simulations), the estimated value for a Rate of Descent RoD=0fpm would give a BFO=124Hz. If it was a RoD=-300fpm, the estimated value would have been BFO=113Hz and for RoD=-500fpm it would be 109Hz. Thus the aircraft was probably towards the end of the descent that was performed at RoD=-500fpm.

The vertical speed providing the best BFO value is about RoD -400fpm. This means that the aircraft was levelling at the bottom of the descent. Thus this helps to identify Arc-2 location more precisely just at the north of Route P756.

The probability that the aircraft was descending at the time of the crossing of the arc was high. The duration of the descent was about 24min and represents a third of the time since the MT-2. In addition the presence of route P756 forcing the flight level to be lowered towards the end of the leg increases the probability of a descent at Arc-2.

Operational aspects:

The People in Command were still controlling the descent of the aircraft via direct entries on Vertical Profile (FL and Vertical speed) made on the MCP. Thus the FMS kept the KIAS at 240kn as it considered the aircraft still in the ACT ECON DES mode (ACTive(ated) ECONomy DEScent). This leads to decreasing ground speed accordingly to the decreasing Flight Level.

14- Handshake 6 - Arc-3 and descent before leaving Jakarta FIR/enter FIR Melbourne

As the exit from the Jakarta FIR to enter the Melbourne FIR was approaching, the People in Command followed the same procedure as applied for the earlier MTs: leaving a false intent behind, descend to hide and turn. They also prepared their descent to pass under the potential detection of the Australian radar system whose actual performances are not known precisely, in particular the JOR-2 system.

The handshake-3 (Arc-3) took place while the aircraft was still in Jakarta FIR.

Location 14	***Arc-3 - Handshake 3: Log-on/Log-off Acknowledge***	***Time: ~20:41:05 UTC***
14.1	Communication between Satellite and the aircraft AES-SDU: 0x14 - Log Control - Log-on Interrogation on Channel 10. 0x15 - Log-on/Log-off Acknowledge on Channel 4 after ***data:*** Inmarsat analysis ([7] Table 1 p3) and the log of the communications between the aircraft and the ground [3] and more details are provided in [16] spreadsheet by R. Godfrey and analysed in [3.2 & 3.3] by B. Ulich Yap Fook Fah's model to estimate the BFOs. Standard Inmarsat technical and operational procedure for checking SDU status by the ground.	
14.2	***Interpretation:*** BTO= 11,691µs (reference 11,740µs +/- 50µs) BFO=143Hz (reference 141+/- 7Hz) with a RoD= -500fpm The estimated BTO is matching the measured BTO. The location is suiting best the distance and speed of the aircraft to reach Arc-4 later. The BFO has been estimated thanks to the CAT and Yap Fook Fah's model-V4. The reference values have been verified and validated by the Inmarsat analysis [7]. These estimated values are within the margins defined in [7].	
14.3	***Interpretation*** From 14.2 above, it is deduced that the aircraft was descending in view to hide before entering Melbourne FIR. Considering the heading of the aircraft ~174° towards POSOD and the ground speed of ~300kn levelled at FL150, the estimated BFO would be ~158Hz. Reading the measured BFO of 141Hz, this indicates a vertical speed of at least approximately RoD=-500fpm to reach 143Hz as computed with Yap Fook Fah's model. In addition, our computations and flight simulations confirmed these measurements. Slow descent to prepare the entry into Melbourne FIR at low altitude.	
14.4	***Interpretation:*** The location is estimated at ~ (-1.8455S, 94.0101E). Computed by our CAT complemented by location measurements from our simulations. The aircraft was flying less tangentially to the Arc-3 than it was at Arc-2, but still the location is approximate as it is dependent on the aircraft flying precision, human control and crosswind. This is a realistic location. Our simulator flew within the acceptable limits of Arc-3 at that level.	
14.5	***data:*** Data from Nullschool website [33]. ***Interpretation:*** As the aircraft heading was 174° the wind component along its path was 6kn. The wind was 6.75kn at 34°	
14.6	***data:*** The ground speed at Arc-3 was ~300kn. Our flight simulations demonstrated that this value is operationally realistic as the simulator automatically adopted it. ***Interpretation:*** The FMS was still in the mode ACTive ECONomic DEScent 240kn. As the KIAS=240kn during the descent, the ground speed decreased from ~306kn down to ~283kn at FL100 with the wind. ***The speed at Arc-3 is thus between these two values*** Normal behaviour of the FMS automation adapting the speed to the altitude so the ground speed decreased from ~306kn down to ~283kn. As the People in Command are following a prepared flight plan with still some descent to come, they had no reason to modify their way of "driving" the aircraft. So no change expected here.	

Conclusions	***Time: ~20:41:05 UTC***
14.I	***Position: Arc3 location is estimated at (-1.8455S, 94.0101E) ~ at FL140***
14.II	***Steady heading at ~174° towards POSOD***
14.III	***The FMS still in the mode ACTive ECONomic Descent with KIAS ~240kn thus a ground speed gs~300kn with rate of descent (RoD) of ~ -500fpm***
14.IV	***BTO=11,691µs and BFO=143Hz*** ***compared to Inmarsat measured BTO 11,740µs and BFO 141Hz***

Rationale for Arc-3:

The geometry of the configuration satellite movement vs. aircraft movement at Arc-3 is less sensitive than for Arc-2 but still its position could be along a segment of 65NM long as the aircraft is flying almost tangentially to the Arc.

Thus a small shift of the real aircraft path due to crosswind flight (un)precision or human intervention for example could induce a small lateral displacement impacting much more on the location of the tangential crossing than it would be on an orthogonal crossing.

Reading the Inmarsat measured BFO at Arc-3, the value is BFO=141Hz. Considering that the aircraft was below (but close) to FL150 and its ground speed was about ~300kn (also demonstrated by our flight simulations), the estimated value for a Rate of Descent RoD=0fpm would give a BFO=155Hz. If it was a RoD=-1000fpm, the estimated value would have been BFO=132Hz.

The vertical speed providing the best BFO=141Hz value is RoD -600fpm. This is an unusual value in this phase of flight where there is no real constraint. Thus the aircraft was most probably descending at RoD=-500fpm. In any case was it -600fpm or -500fpm, this does not have much impact.

Operational aspects:

The People in Command were still controlling the descent of the aircraft via direct entries on Vertical Profile (FL and Vertical speed) made on the MCP. Thus the FMS maintained the KIAS at 240kn as it considered the aircraft was still in the ACT ECON DES mode (ACTive(ated) ECONomy DEScent). This led to decreasing ground speed accordingly to the decreasing Flight Level.

Note on the speed: Considering the distance between Arc-3 location with POSOD, it is likely that Arc-3 was crossed at the early stage of the descent. In addition the ground speed providing the best BFO is the highest possible speed at that location with this heading which is ~300kn which confirms this hypothesis. Remember that the descent at lower altitudes implies a reduced speed.

Note: The precise location of the Top of Descent is not important.

15- POSOD Waypoint and Major Turn-3

POSOD is the exit point from Jakarta FIR and the entry point into Melbourne FIR.

Location 15	***POSOD***	***Time: ~20:59:xx UTC***
15.1	End of the direct route from MEMAK to POSOD . Turn left DIRECT to EPGUP (Hdg 174° to 143.5°) Leaving Jakarta FIR and entry into Melbourne FIR ***Interpretation:*** This is a deduction and computation from the aircraft speed and flight level. Our simulations validated this hypothesis: in distance and in time under the currently selected flying mode of the aircraft. The People in Command, once more applied their strategy, leave a FIR with certain flight characteristics and enter a new FIR as a different flight. The aircraft had skirted round Sumatra and started to fly a route to avoid the Australian radars.	
15.2	The wind was 4.4kn at 27° ***data:*** Data from Nullschool website [33]. ***Interpretation:*** As the aircraft heading was 174° the wind component along its path was 4kn.	
Conclusions	***Time: ~20:59:xx UTC***	
15.I	***Position: POSOD (-3.4916S, 94.165E) levelled at FL100***	
15.II	***Turn to new heading at ~143.5° towards EPGUP***	
15.III	***The FMS still in the mode ACTive ECONomic Descent with KIAS ~240kn thus a ground speed gs~281kn at FL100***	

How to avoid radar detection:

The aircraft has been out of any radar detection range for about 25NM after crossing Arc-2. As it approached FIR Melbourne, care should have been taken by People in Command to stay invisible. This is the reason why a descent to FL100 took place before POSOD which is the entry into the FIR (cf. key event 14).

At this stage, it is worth noticing that the waypoint EPGUP is almost right in the middle between the Keeling Islands and the Christmas Island. Thus, this is the ideal path to fly below radar coverage with confidence to stay out of detection range from their respective radar.

Waypoints which make sense

The aircraft passed Arc-3 with a ground speed of ~300kn which has decreased down to 281kn at POSOD and then about 274kn later. Thus the ping at Arc-4, one hour after, should occur at a distance of ~285NM from Arc-3. Envisaging a direct path from Arc-3, the crossing of Arc-4 would mean that the aircraft would have turned exactly at Arc-3 since the shortest distance path is not in line with the precedent segment MEMAK-POSOD (20° difference). This is unlikely, as Arc-3 is purely artificial and is a virtual point unknown by the aircraft. Arc-3 was of no signification for the People in Command and there was no reason to turn inside Jakarta FIR at that point in the middle of nowhere. On the other end, if the straight line in continuation of the segment Arc-3-POSOD was followed, the potential intersection point with Arc-4 does not lead to any other identifiable waypoint with no potential meaningful route in addition to the fact that the crossing (at about 530NM from Arc-3) could not have occurred at the right time for this speed. To match the time stamps would lead to over speeding.

Thus the aircraft turned somewhere and most likely at a planned waypoint, as there was no reason to change from the way it had proceeded so far. Turning at POSOD looks like the only suitable option.

Thus the Arc-4 crossing point at a distance of ~285NM from Arc-3 would be near ~(6.0141S, 96.0227E) which is a point located exactly on the segment POSOD-EPGUP.

At POSOD, the flying mode of the aircraft was still ACTive ECOnomy DEScent at KIAS=240kn. There was no reason for the FMS to switch to another mode as the People in Command were still in a descent performed via successive small descents.

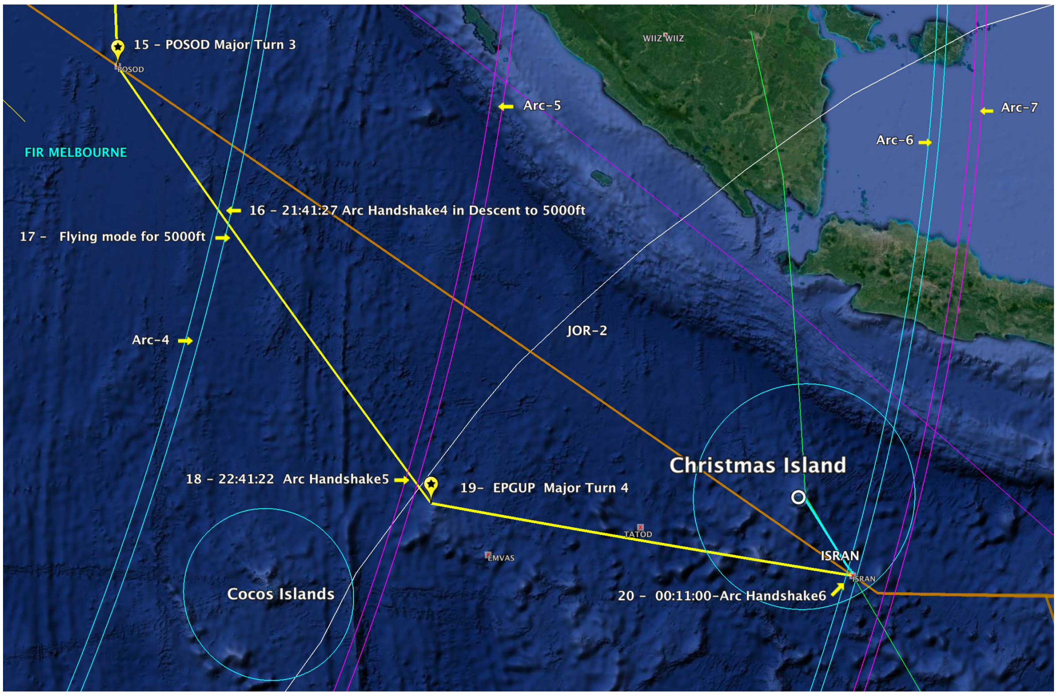

Figure 8: Location of the key Events 16 to 20.

16- Handshake 4 - Arc-4 and descent in approaching the Australian radars

Location 16	***Arc-4 - Handshake 4: Log-on/Log-off Acknowledge***	***Time: ~21:41:27 UTC***
16.1	Communication between Satellite and the aircraft AES-SDU: 0x14 - Log Control - Log-on Interrogation on Channel 10. 0x15 - Log-on/Log-off Acknowledge on Channel 4 after ***data:*** Inmarsat analysis ([7] Table 1 p3) and the log of the communications between the aircraft and the ground [3] and more details are provided in [16] spreadsheet by R. Godfrey and analysed in [3.2 & 3.3] by B. Ulich Yap Fook Fah's model-V4 to estimate the BFOs. Standard Inmarsat technical and operational procedure for checking SDU status by the ground.	
16.2	***Interpretation:*** Estimated BTO=12,753µs (reference 12,780µs +/- 50µs) Estimated BFO=169Hz (reference 168Hz +/- 7Hz) at RoD -500fpm The BFO has been estimated thanks to the CAT and Yap Fook Fah's model-V4. The reference values have been verified and validated by the Inmarsat analysis [7]. The aircraft was descending according to the BFO. The satellite-aircraft geometry is that the trajectory of the aircraft is now at ~50° which reduces the uncertainty on the crossing of Arc-4.	
16.3	The location is estimated at ~ (-6.0141S, 96.0227E) ***data:*** No proof but computed by the CAT and crosschecked via cartographic measurement and location measurements from our simulations. ***Interpretation:*** This is a realistic location. It also comes from the measurement on the map and our simulator flew it properly in space and time. The satellite-aircraft geometry is that the trajectory of the aircraft is now at ~50° to Arc-4 which reduces the uncertainty on its crossing.	

16.4	From 16.2 above, it is deduced that the aircraft was descending in view to get under the radar detection range. The 5,000ft descent took about 10min. ***Interpretation:*** The aircraft was descending (but we don't know if it was at the beginning or at the end of the descent, the BTO suggest it was at 9,000ft thus at the beginning) Slow descent to get below radar detection coverage.
16.5	The wind was 1kn at 64° ***data:*** Data from Nullschool website [33]. ***Interpretation:*** As the aircraft heading was 143.5 ° the wind component along its path was 0.9kn.
16.6	The FMS was still in the mode ACTive ECONomic DEScent 240kn. As the reference was KIAS=240kn during the descent, the ground speed decreased from ~281kn down to ~266kn at 5,000ft with the wind. The speed at Arc-4 around 9,000ft is thus between these two values so around ~278kn. ***data:*** No proof as such. ***Interpretation:*** Our flight simulations demonstrated that this value is operationally realistic as the simulator automatically adopted it. Normal behaviour of the FMS automation maintaining the KIAS speed to the altitude so the ground speed decreased from ~281kn down to ~266kn. As the People in Command are following the prepared flight plan with this last descent to come, they had no reason to modify their way of "driving" the aircraft. So no change expected before reaching the altitude of 5,000ft.
Conclusions	***Time: ~21:41:27 UTC***
16.I	***Position (-6.0141S, 96.0227E) with a rate of descent (RoD) of ~ -500fpm***
16.II	***Steady heading at ~143.5° towards EPGUP***
16.III	***The FMS still in the mode ACTive ECONomic Descent with KIAS ~240kn thus a ground speed was decreasing from gs~281kn to gs=266kn at 5,000ft.***
16.IV	***BTO=12,753µs and BFO=169Hz*** ***compared to Inmarsat reference BTO 12,780µs and BFO 168Hz***

Rationale for Arc-4:

Reading the Inmarsat measured BFO at Arc-4, the value is BFO=168Hz. Considering that the aircraft was below (but close to) 10,000 ft and its ground speed was about ~278kn (also demonstrated by our flight simulations) with a heading to ~143°, the estimated value for a Rate of Descent RoD=0 fpm would give a BFO=180 Hz. If it was a RoD=-1000 fpm, the estimated value would have been BFO=158Hz.

The vertical speed providing the best BFO=168 Hz value is RoD -530 fpm as computed with Yap Fook Fah's model. This is an unusual value in this phase of flight where there is no real constraint. Thus the aircraft was most probably descending at RoD=-500 fpm. In any case if it was -530 fpm rather then -500 fpm, it wouldn't have much of an impact on the trajectory. In addition, our computations and flight simulations confirmed these measurements.

How to avoid possible radar detection:

As no information is available on the capacity the Australian JORN (and in particular JOR-2 in this region) network detection system, the aircraft had to mitigate the risk of being detected. Thus at the time of Arc-4 it was probably preparing to descend lower to stay below radar coverage.

In addition, it was continuing to follow a pre-established timely flight plan to stay as much as possible undetected by Australian radars, and the Cocos Islands and Christmas Island radars in particular.

Aircraft flight management:

At the crossing of Arc-4, the flying mode of the aircraft was still ACTive ECOnomy DEScent with reference KIAS=240kn. There is no reason for the FMS to switch to another mode as the People in

Command started the descent to 5000ft and the aircraft was descending as indicated by the BFO measurement.

17- Cruise at altitude 5,000ft

Location 17	***After the end of descent to 5,000ft***	***Time: before ~21:52:00 UTC***
17.1	***Interpretation:*** The flying mode of the aircraft changed to LRC CRUIZE. The speed of the aircraft increased between Arc-4 to Arc-5. This fact is mandatory for the aircraft to have crossed Arc-5 on time. Our simulations confirmed that one hour of flight from Arc-4 lead to a crossing point at Arc-5 within the acceptable margins in distance. The distance Arc-4/Arc-5 is ~310NM +/- 5NM which were flown in 1 hour. Thus the average ground speed of the aircraft was ~310kn+/- 5kn. Thus, the VNAV function of the Auto-pilot was engaged leaving the descent mode to the cruise mode.	
17.2	The wind was 4kn at 115° ***data:*** Data from Nullschool website [33]. ***Interpretation:*** As the aircraft heading was 143.5 ° the wind component along its path was -3.6kn.	
Conclusions	***Time: before ~21:52:00 UTC***	
17.I	***Position: just after Arc-4***	
17. II	***Steady heading at ~143.5° towards EPGUP***	
17.III	***The Auto-pilot has been engaged leading to a new flying mode with a new reference KIAS=~285kn corresponding to a ground speed of ~301kn with the wind.***	

Aircraft flight management at 5,000ft

As the descent in steps was finished, the People in Command entered the value 5,000ft in the FMS VNAV page of the MCDU. This triggered the computation of a new KIAS reference value of about ~285kn which became active when the VNAV button of the A/P was pressed leading to the LRC CRZ flying mode.

18- Handshake 5 - Arc-5: Log-on/Log-off Acknowledge

Location 18	***Arc-5 - Handshake 5 - at altitude 5,000ft***	***Time: ~22:41:22 UTC***
18.1	Communication between Satellite and the aircraft AES-SDU: 0x14 - Log Control - Log-on Interrogation on Channel 10. 0x15 - Log-on/Log-off Acknowledge on Channel 4 after ***data:*** Inmarsat analysis ([7] Table 1 p3) and the log of the communications between the aircraft and the ground [3] and more details are provided in [16] spreadsheet by R. Godfrey and analysed in [3.2 & 3.3] by B. Ulich CAT and Yap Fook Fah's model-V4 to estimate the BFOs. Standard Inmarsat technical and operational procedure for checking SDU status by the ground.	
18.2	At a constant KIAS speed of ~285kn corresponding to an average ground speed of ~305kn, the travel distance from Arc-4 to Arc-5 would be ~310NM. ***data:*** Not applicable. This is a pure computation. ***Interpretation:*** Considering the current heading 143.5°, the measured and the CAT computed distance from Arc-4 to Arc-5 on this heading is between 295 to 330NM which is matching perfectly the hypothesis of a constant KIAS speed ~285kn in a straight line. Thus EPGUP is still the most likely next waypoint at this stage.	
18.3	BTO=14,539µs (reference 12,540µs +/- 50µs) BFO=202Hz (reference 204 +/- 7Hz) ***data:*** The BFO has been estimated thanks to the CAT and Yap Fook Fah's model-V4. The reference values have been verified and validated by the Inmarsat analysis [7]. ***Interpretation:*** The satellite-aircraft geometry is that the trajectory of the aircraft is still at ~50° which reduces the uncertainty on the crossing of Arc-5.	
18.4	The location is estimated at ~ (-10.2533S, 99.2463E) ***data:*** No proof but geometric computation and cartographic measurement from our simulations. ***Interpretation:*** This is a realistic location. Our simulator flew it properly in space and time within the acceptable limits of Arc-5 at an altitude of 5,000ft.	
18.5	The wind was 8,4kn at 126 ***data:*** Data from Nullschool website [33] ***Interpretation:*** As the aircraft heading was 143.5 ° the wind component along its path was -8kn.	
18.6	The FMS was still in the mode LRC at slowly varying reference KIAS=~285kn corresponding to a ground speed of ~300kn at 5,000ft. ***data:*** No proof as such. ***Interpretation:*** Our flight simulations demonstrated that this value is operationally realistic as the simulator automatically adopted it. Normal behaviour of the FMS automation adapting the speed to the weight of the aircraft and consequently decreasing the ground speed. No reason for the People in Command to intervene at this stage.	
Conclusions	***Time: ~22:41:22 UTC***	
18.I	***Position ~(-10,2533S, 99,2463E) computed by the CAT and measured from our simulations. The flight was levelled at 5,000ft***	
18.II	***Steady heading at ~143.5° towards EPGUP***	
18.III	***The FMS still in the mode LRC CRZ with reference KIAS slowly decreasing from KIAS=285kn with the aircraft weight thus the ground speed was also slowly decreasing from gs~305kn to gs=297kn at 5,000ft.***	
18.IV	***BTO=14,539µs and BFO=202Hz*** ***compared to Inmarsat measured BTO 14,540µs and BFO 204Hz***	

Operational aspects:

The aircraft was on its way to EPGUP flying DIRECT EPGUP at an altitude of 5,000ft. No reason to change the aircraft settings at this point in time.

19- Turn at EPGUP Waypoint - Major Turn-4

Location 19	***EPGUP – Major Turn-4***	***Time: ~22:47:xx UTC***
19.1	The distance Arc-5-EPGUP is ~31NM requiring ~6:15min at a ground speed of ~297kn with the wind ***Proof:*** Measured values. ***Interpretation:*** En route to EPGUP.	
19.2	The distance EPGUP-Arc-6 is ~417NM+/- 5NM requiring ~1:23:45 hour at a ground speed of 297kn. ***Proof:*** Measured values. ***Interpretation:*** This is fully matching the timing. See rationale below.	
19.3	The wind was 9.5kn at 127° ***data:*** Data from Nullschool website [33]. ***Interpretation:*** As the aircraft heading was 143.5 ° the wind component along its path was -9kn and then -8,5kn after the turn.	
Conclusions	***Time: ~22:47:xx UTC***	
19.I	***Position: (-10.6506S, 95.5516E) at altitude 5,000ft***	
19.II	***The aircraft turned to DIRECT ISRAN to new heading ~100°***	
19.III	***The FMS still in the mode LRC CRZ with KIAS=~280kn with a gs=297kn.***	

The people in command facing the unforeseen:

The distance Arc5-Arc6 along the followed path is ~450NM and took ~1:29:33 hour. This means an average ground speed of ~300kn which is matching the flying mode controlling the aircraft

At this key event, one could envisage that the aircraft continued on the same heading 143.5° with the same mode of flight LRC CRZ at a ground speed of about ~300-296kn (since the aircraft got lighter). As the next known event is the crossing of Arc-6 at ~00:11:00 it would mean that the aircraft flew in straight line in continuation to the segment Arc-5-EPGUP during ~1:24:00 hour which represents a distance close to 418NM. But on this current heading 143,5° the distance from EPGUP to Arc-6 is about ~500NM. Consequently, the aircraft would have accelerated.

Then comes the question why to accelerate without a reachable target especially when being aware that the fuel is short and that the Australian Continent is more than 1,000NM away out of reach in regards of the fuel (the closest airport being Learmonth at ~1,085NM)?

Accelerating on the same heading makes no sense for an expedition that wanted to land safely.

Thus at this location, the landing on Christmas Island is the only target left for a safe landing on an adequate runway. This confirms that the original flight plan actually targeted Christmas Island as their primary target.

Thus it can be concluded that the aircraft changed heading and turned with a DIRECT to ISRAN, which is at 418NM from EPGUP.

During our simulations, the flight simulator FMS announced that Christmas Airport (YPXM) was reachable from EPGUP location as fuel was concerned. In particular when passing close by TATOD, the FMS posted that YPXM was reachable at 5,000ft with about 3.5t of fuel remaining.

As the FMS permanently recomputed fuel values at destination, at a later point in time during this leg EPGUP to ISRAN the value "0 fuel at destination" came up indicating that the destination was not no longer reachable.

4.4 The end because of fuel shortage

20- Handshake 6 – Arc-6 – ISRAN Waypoint: Log-on/Log-off Acknowledge

Location 20	***Arc-6- Handshake 6 – ISRAN***	***Time: ~00:11:00 the next day***
20.1	***data:*** Communication between Satellite and the aircraft AES-SDU: 0x14 - Log Control - Log-on Interrogation on Channel 10. 0x15 - Log-on/Log-off Acknowledge on Channel 4 after Inmarsat analysis ([7] Table 1 p3) and the log of the communications between the aircraft and the ground [3] and more details are provided in [16] spreadsheet by R. Godfrey and analysed in [3.2 & 3.3] by B. Ulich Standard Inmarsat technical and operational procedure for checking SDU status by the ground.	
20.2	At this point of the trajectory, the waypoint ISRAN is located exactly within the Arc-6 limits ***data:*** The actual coordinates of ISRAN combined with our computation of the family of Arc-6 at 5,000ft show that they are within the acceptable Inmarsat margins (cf Fig 9). ***Interpretation:*** Thus, the next event of interest is actually the crossing of Arc-6, which happened within a few NM away from ISRAN inside the aircraft active route and within the Arc-6 limits at 5,000ft.	
20.3	***Interpretation:*** BTO=18,054µs (reference BTO=18,040µs +/- 50µs) BFO=246Hz (reference 252 +/- 7Hz) with a heading at 360° with RoC 0 fpm The BTO is correct by construction, as the point has been selected specifically on Arc-6 at the correct distance from EPGUP. The BFO has been estimated thanks to the CAT and Yap Fook Fah's model-V4. The reference values have been verified and validated by the Inmarsat analysis [7] The aircraft was turning left at ISRAN to align itself with the approach to Christmas YPXM on Route G209. See rationale below.	
20.4	The location is estimated at ~ (-11.6735S, 106.5605E) ***data:*** No proof but CAT computation and cartographic measurement and location measurements from our simulations paths. ***Interpretation:*** This is a realistic location in the middle of the turn. It comes from computation and also the measurement on the map from our simulator flights as it properly flew in space and time within the acceptable limits of Arc-6 at an altitude of 5,000ft.	
20.5	The wind was 8.7kn at 179° ***Data:*** Data from Nullschool website [33]. ***Interpretation:*** As the aircraft heading was 100° the wind component along its path was -1.7kn, and thus basically null when heading 360°.	
Conclusions	***Time: ~00:11:00 the next day***	
20.I	***Position:(-11.6735S, 106.5605E) The flight at altitude 5000ft (cf. rationale below)***	
20.II	***The heading was ~360° as the aircraft was turning left towards Christmas Island to follow Route G209.***	
20.III	***The reference was KIAS=285kn with a ground speed at about gs=~300kn***	
20.IV	***BTO=18,054µs and BFO=246Hz*** ***compared to Inmarsat measured BTO=18,040µs and BFO=252Hz***	

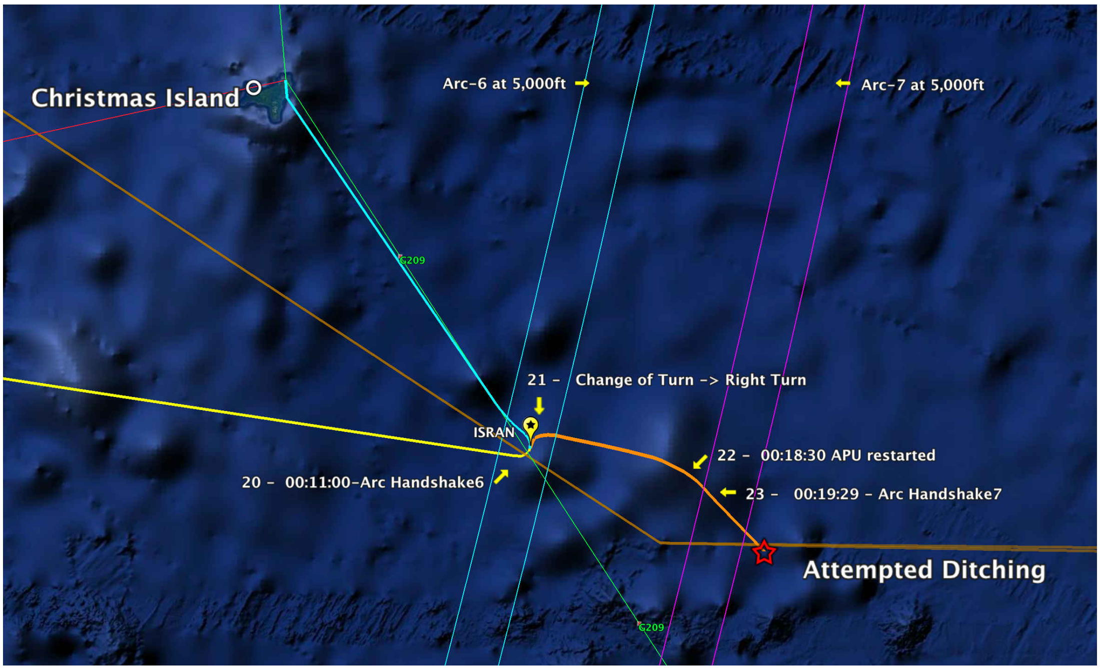

Figure 9: the location of the key Events 21 to 24.

Operational aspects:

At the time of Arc-6, the aircraft was at ISRAN turning to align itself with the approach to Christmas YPXM.

Why was it turning at this particular time? Because at ground speed=~300kn and levelled at 5000ft, if the aircraft was flying in a straight line from EPGUP with a heading at 100°, the BFO would be 235Hz outside the BFO margins.

Besides, a short sensitivity analysis shows that for the BFOs to stay within the margins -but just in- at 246Hz at this location, the best heading is ~360° with the same speed and level. With a climbing RoC=~500Hz, then the BFO=252 would be matched for two headings 40° and 320°. This would indicate that the aircraft would be turning left and climbing

If we retain this hypothesis, then the sensitivity analysis would be:

A- Heading

Two different headings match the best BFO=252Hz. These headings are ~40° and ~320°. In both cases this means a left turn. Which is fully coherent to take Route G209 for an eventual landing at Christmas.

1- The heading 320° would mean that the aircraft had almost finished turning and was in the light corrective right turn. This is a usual manoeuvre as it needed to compensate for the overshoot due to the sharp angle from 100° where it came from to 327° towards Christmas that it could not perform instantaneously. As a fact of life, an aircraft actually turns wider that the sharp angle of the geometrical design of the routes.
2- The heading 40° would mean that the aircraft was in the first quarter on the left turn towards Christmas.

Considering the short time (8:30min) and the minimum distance travelled between Arc-6 to Arc-7 i.e. 38NM and the subsequent required average speed at about ~270kn, the heading 40° better fits with the follow-up situation of an aircraft running with one engine only towards Arc-7

B- Vertical speed - RoC

In addition, the sensitivity analysis shows that to reach the best BFO=252Hz, the aircraft would have been climbing at a RoC between +400 and +500fpm. Operationally speaking this could be explained by:

1- The aircraft needed to climb from 5,000ft for better intercepting the landings aids when approaching YPXM. ***But this is found unnecessary to climb at ISRAN, which is 90NM before the runway.***

2- The People in Command took the decision to go to a higher altitude for some reason. For example for preparing a potential longer glide if needed when the fuel would ran out.

With the information available, it is impossible to say what was the actual situation (or possibly a combination of both). But the sure thing is that the aircraft was either levelled or slightly climbing.

To which level did the aircraft climb?

To answer this question we did some simulations with the same aircraft configuration as arriving at ISRAN. To climb from 5,000ft to 15,000ft the fuel flow must have increased from 5t/h to 8.4t/h. Thus the extra consumption is 3.4t/h i.e. ~57kg/min. As the aircraft could not cover the 90NM from ISRAN to YPXM but covered 38NM from arc-6 to Arc-7, the missing fuel is thus for about 53NM which could be translated in time i.e. 52NM/300kn ~11min of flight. This is equivalent to 900kg of fuel at 5,000ft altitude.

Using this fuel to climb would mean 15min of climb. Thus at the estimated RoC +500 it is a maximum of 7,500ft. Thus the aircraft could have climbed at maximum 12,500ft.

But what would be the reason to climb so early if the necessary fuel to reach destination was actually on-board? And what would be the rationale to climb blindly and follow a procedure when the fuel is going to be missing? It can be concluded that if there was a climb, it was a last minute climb to gain altitude when the tanks were close to be empty in order to allow a longer glide eventually.

The aircraft could have been above 5,000ft but below 12,500ft.

Our assumption is that the People in Command were not prepared for such a situation requiring an evaluation of the options within the aircraft flying envelop.

Therefore we assume that they did not climb but stayed at 5,000ft. However, it should be kept in mind that there is a large uncertainty on the flight level. Consequently, this will impact the dimensions of the final search area.

4.5 Change of plan

21- Right turn

At this point there is no evidence provided by any data or measurement. Our logical assumption is that for reaching Arc-7, which is at a minimum distance of 38NM and without increasing its speed in 8:30min, the aircraft must have turned to the right just after the Handshake-6 at Arc-6.

We conclude here that this was provoked by the loss of the right engine which stopped because of fuel exhaustion in the right tank. It stopped first probably because it was consuming more fuel per hour than the left engine.

Location 21	***Right Turn – Right Engine Stopped.***	***Time: after 00:11:00 UTC***
21.1	The aircraft suddenly diverted and turned right in the middle of its on-going left turn towards Christmas Airport. ***data:*** No proof. This is a hypothesis in coherence with the coming handshake 7 ***Interpretation:*** The large banking and the emptiness of the right tank made that there was no more fuel for the right engine. Right engine stopped.	
Conclusions	***Time: after 00:11:00 UTC***	
21.I	***Position : very close to Arc-6 (-11.6735S, 106.5605E) The aircraft was levelled (above 5,000ft and below 12,500ft)***	
21.II	***The reference was KIAS=285kn with a ground speed at about gs=~300kn***	
21.II	***The aircraft was turning to the right. The new heading was ~105° (cf explanation below)***	

Operational aspects:

1- Thrust Asymmetry Compensation (TAC)

To be coherent in time and speed, the right turn must have occurred during the left turn towards Christmas. During the stop of the right engine, the loss of thrust on the right side and the on-going left engine thrust temporarily made the aircraft rotate and turn to the right.

In the normal situation, when the first engine failed the Thrust Asymmetry Compensation (TAC) function should have been automatically activated and set to trim the aircraft to fly along the flight plan with the auto-throttle managing the left thrust in order to maintain air speed and altitude, as far as possible [18]. A real time simulation was performed on a Level-D simulator. It shows that if the TAC is armed and if the engine parameters are acceptable for the TAC, the aircraft continues as if no engine was flamed-out.

Depending on the specifics of the situation, the pilot will intervene in different ways on the automation. For the MH370, the consequences of the Electrical Power switch Off at ~17:30 are not known in particular for the TAC. After this event, was TAC armed on "Automatic" or was it Off ?

In any case, the time of reaction of the system led to a turn to the right as 50% of the thrust disappeared in a few seconds and as the parameters fed to the FMC needed to be validated or for the People in Command to react.

Usually, in such a situation, professional pilots would take over and pilot the aircraft directly using the rudder pedals. How much the People in Command knew how to fly this way is unknown.

As the time to reach Arc-7 was short (~8:30min) and considering the shortest distance to Arc-7 of ~38NM, it means that the minimum average ground speed of the aircraft was 38/8,5min = ~270kn. And the shortest maximum distance to Arc-7 is 47NM giving an aircraft speed of ~330kn. From Arc-6 to the centre of Arc-7, the distance is 42NM leading to a ground speed of ~300kn. This is fully coherent with Arc-6 aircraft situation (~300kn) and the assumption 21.II and correlates well with a heading at ~360° at Arc-6 (and also 40° if climbing).

If at Arc-6 the heading was ~320°, the aircraft would have travelled an additional 8NM to fully turn backwards towards Arc-7 increasing the minimum flight distance to ~50NM to reach Arc-7. Consequently, the average ground speed would have been ~352kn. The same computation is even worse when considering that the aircraft would have continued its left turn and would have completed a 360° turn before heading to Arc-7. The travel distance would be thus of about ~55NM requiring an average speed of ~388kn.

This is in contradiction with the fact that with one engine left and the low fuel quantity, there was no reason to accelerate.

The People in Command were facing a situation with a single engine running and fuel shortage announced and coming soon. Extrapolating their reaction and actions on the aircraft is very difficult. A lot of things could have happened at that point.

As they could have been pilots, a Type-Rated Instructor has been interviewed to determine what would be the procedures to follow by a professional pilot under these circumstances. The following actions would have been done in first priority: engaged the TAC if possible and let the aircraft follow its course on the flight plan.

2- New Heading

If we considered that the aircraft speed stayed at ~300kn, then about 42NM were flown to reach Arc-7. Then the possible sector within which it flew is (75°-135°) which represent 105° with ±30° around the orthogonal segment joining Arc-6 to Arc-7.

22- Auxiliary Power Unit (APU) started – Left Engine Stopped

Location 22	***APU up and running***	***Time: ~00:18:29***
22.1	APU has re-started. ***data*** Not a proof. But this must have happened for the Handshake-7 to happen. (c.f. [9] p6 : 60 sec for a hot EAS booting). Cf also [9] ATSB-3 p99 ***Interpretation:*** The main power supply from the left engine failed (probably because the left engine eventually stopped because of shortage of fuel). Thus the APU started automatically.	
Conclusions		
22.I	***The aircraft has started its glide***	
22.II	***The aircraft was at the beginning of the descent***	

Interpretation of 22.1:

This is inferred from the nature of the last transmission from the EAS to the Satellite and the fact that some time is needed for the EAS-SDU to boot properly after a short interruption of power (hot reboot).

It should be noted that from [31] p11: "In flight, when both transfer buses are unpowered, the APU starts automatically, regardless of APU selector position".

Please refer to Annex-1 for further explanations on the Electrical Power issues.

23- Handshake 7 – ARC7: Log-on/Log-off Acknowledge

This event is not yet completely understood and explained even by Boeing who is still assessing it (as stated in [10] ATSB-3 report Appendix B p16). This probably happened just after the plane began an unpowered ditching and descent.

Location 23	***Handshake 7*** ***Time: ~00:19:29 - 00:19:37 next day***
23.1	Communication between Satellite and the aircraft AES-SDU: 0x10 - Log-on Request (ISU)/Log-on Flight Information (SSU) on Channel 10 0x15 - Log-on/Log-off Acknowledge on Channel 10. ***data*** Inmarsat analysis ([7] Table 1 p3) and the log of the communications between the aircraft and the ground [3] and more details are provided in [16] spreadsheet by R. Godfrey and analysed in [3.2 & 3.3] by B. Ulich ***Interpretation:*** As the Electrical Power from the APU had been switch ON a minute earlier, the EAS requested a new X-25 circuit establishment.
23.2	***Interpretation:*** BTO= 18,363µs (reference BTO=18,400µs +/- 50µs) BFO=184Hz (reference BFO=182 +/- 7Hz) with a heading to 135° with RoD -2700fp The BTO is correct by construction, as the point has been selected specifically on Arc-7 at a distance of 42NM from the point of Arc-6 thanks to the known speed. The BFO has been estimated thanks to the location flown during our simulations and Yap Fook Fah's model-V4. The reference values have been verified and validated by the Inmarsat analysis [7]
23.3	A rough location is estimated at ~ (-11.8293S, 107.1668E). But because of the width of Arc-7, the point location precision would allow the points on the arc of circle centred on the "Arc6 crossing" with a radius of ~42NM and within Arc-7. ***data:*** No data but computations, cartographic measurement and location measurements from our simulations paths. This is one of the points at 42NM and at heading 135° from Arc-6 ***Interpretation:*** This is a realistic location.
23.4	The heading was probably ~135° ***data:*** A sensitivity analysis shows that the heading minimising the BFO error is ~180°. But a heading almost in continuation of the previous path at ~135° leads to a BFO=184Hz which is in the acceptable margin ***Analysis:*** Our simulations showed that once all engines have stopped and the gliding has started the aircraft always turns. The side is random. The sensitivity analysis shows that a right turn leads to compatible BFOs from 192Hz down to 182Hz while a left turn increases the BFO above 192Hz.
Conclusions	***Time: ~00:19:29 - 00:19:37 next day***
23.I	***-11.8293S, 107.1668E) The flight was gliding with an instantaneous RoD of -2700fpm (its starting altitude was ~ 5,000ft)***
23.II	***The heading was ~135°***
23.III	***The estimated speed is KIAS=240kn with a ground speed at about gs=~300kn***
24.IV	***BTO=18,363µs and BFO=184Hz*** ***compared to Inmarsat measured BTO=18,400µs and BFO=182Hz***

Interpretation of 23.2:

This handshake-7 means that the left engine stopped about 1 min earlier. The aircraft was gliding.

Our simulations proved that the aircraft reached easily RoD close to -3,000fpm, which has been also experienced during the real-time simulation performed on a professional Level-D Training simulator. This means that the People in Command faced similar rate of descent, which is within acceptable limits but requires human intervention to reduce it.

The choice of 135° is coherent with regards to the BFO. The leg Arc-6 to Arc-7 was probably on heading 135° which is not so far away from the head wind 155° as recommended by the standard emergency procedure.

Note: when both engines are lost, the recommendation from FCOM continental p265 [32] is to follow the "green dot" procedure. This is a visual help for the pilot to maintain the right attitude of the aircraft for an optimum gliding.

24- Sea-landing

The final phase of the flight is difficult to analyse due to the lack of data. Nevertheless two important factors must be considered first. The altitude derived at Arc-7 which is 5,000ft, its probable speed and vertical speed reveal that the aircraft was on its gliding phase more or less under control in a straight line.

Second, as only a few debris of small size were found afterwards, an emergency ditching is retained as the preferred option: the aircraft did not crash but very likely broke into two or three large pieces and a few pieces, such as the famous flaperon.

Location 22	***Sea-landing***	***Time: ~00:21:30 /00:25:00 Next day***
24.1	The aircraft did not crash but landed on the sea either relatively gently or breaking in two or three large pieces with only a few debris detached. ***data:*** The aircraft status at Arc-7 shows that the gliding was under way and relatively under control. ***Interpretation:*** The fact that only a few debris have been found advocate for a landing without any huge impact. In addition the BFO at Arc-7 does not fit at all with a vertical crash but more with gliding characteristics. The sensitivity analysis shows that a vertical speed of descent faster than RoD=-3200fpm leads to BFOs below 174Hz which are outside -and do not correlate with- the acceptable margins of Inmarsat [7].	
24.2	The sea-landing took place between 00:21:30 and 00:25:00 ***data:*** No proof. Computations only with simulations. If the aircraft was at 5,000ft and taking into account the first part of the descent at ~2700fpm, 2min remain to reach the sea level at that vertical speed, but with the "green dot procedure" it would take about 3:30min. ***Interpretation:*** These estimations are made with an average of RoD at ~1500fpm that could be realistic once the first minute is passed for the People in Command to understand how to make the aircraft properly gliding. The maximum distance covered during the glide can be estimated thanks to the Lift-to-drag ratio (~17-18). This approach leads to a maximum distance 5000ft x 18 = less than16NM. We don't assume that the aircraft took time or spent its fuel to climb.	
Conclusions	***Time: ~00:21:30 /00:25:00 Next day***	
24.I	***The aircraft has sea landed, heading was 135° (close to head wind direction)***	
24.II	***The estimated ditching point location is about ~(-12.025687S, 107.363234E) with an uncertainty of about ~16NM around Arc-7 crossing Location 23. (See discussion in Section 6).***	

Operational aspects

To minimise the landing speed the aircraft may have selected a heading close to 155° in order to maximise the headwind lift.

5- Fuel consumption

The next fundamental question is whether the aircraft could have flown such a Piloted Trajectory with the available fuel on board at take-off and if so, where and when the fuel was completely burnt.

The Piloted Trajectory profile is atypical but not complex. But the evaluation of the detailed fuel burning itself is complex for such a Piloted Trajectory because the descent in steps was lengthy and because the second half of the path was at a very low altitude, which is not a standard operating mode of the aircraft and thus it is not well documented. For this atypical profile, few numerical data are available for estimating the fuel consumption and even Boeing provides only partial information for much shorter flight paths. *This calls for a more in depth elaboration.*

Consequently, the fuel consumption was approached in two steps: a) flight simulations to get a rough order of magnitude, validate our assumptions and if positive proceed to b) a more precise fuel burn computation.

Table 3 presents the results of the CAT computation for the Piloted Trajectory using the model 9M-MRO Fuel Model provided by Dr Ulich in [13]. It provides the remaining fuel on board at the specific waypoints starting from the Top of Climb value as provided by the ACARS messages. Note that for better accuracy, the fuel estimation is actually computed at a much higher sampling rate (every second) along the flight than just the presented waypoints.

Location-Waypoint	***Fuel On Board (kg)***
Top of Climb	43800
IGARI	42255
KENDI	38706
Arc-1	34855
MEMAK	30895
Arc-2	28519
Arc-3	22809
POSOD	20871
Arc-4	17049
Arc-5	10023
EPGUP	9357
ISRAN-Arc-6	187
Arc-7	0

Table 3:
Fuel Consumption at key locations

The major outcome from this fuel burn estimation is that, as expected, the Piloted Trajectory profile leads to fuel consumption until exhaustion between Arc6 and Arc7. ***Hence the conclusion is that the end of the flight was actually caused by fuel exhaustion.***

Also this matches the operational aspects of the Piloted Trajectory and confirms that this is a valid profile since it does end in the vicinity of Arc7.

It should be noted that if the right engine had not consumed 150kg/h more i.e. about 1 extra ton of fuel for the full trip, the aircraft would have been able to get to Christmas Island. But the People in Command could not be aware of this over-consumption.

6- The new search area

Considering the estimated flight level at Arc-7 crossing i.e. 5,000ft and the lift-to-drag ratio of the B772 (~17 to 18), the probable ditching point location is about 16NM away from Arc-7. This means at (-12.025687S, 107.363234E) or (12°2'32"S, 107°22'48"E) if one assumes a constant heading at 135°.

Consequently using three specific points at the flown distance of 42NM (green segments in Figure 10) and using the gliding distance from there via circles, this defines a maximal search zone as depicted in Figure 10. This is a kind of trapezoidal zone which maximal width is 40NM and maximal length is 80NM. The area is around 10 000 km^2.

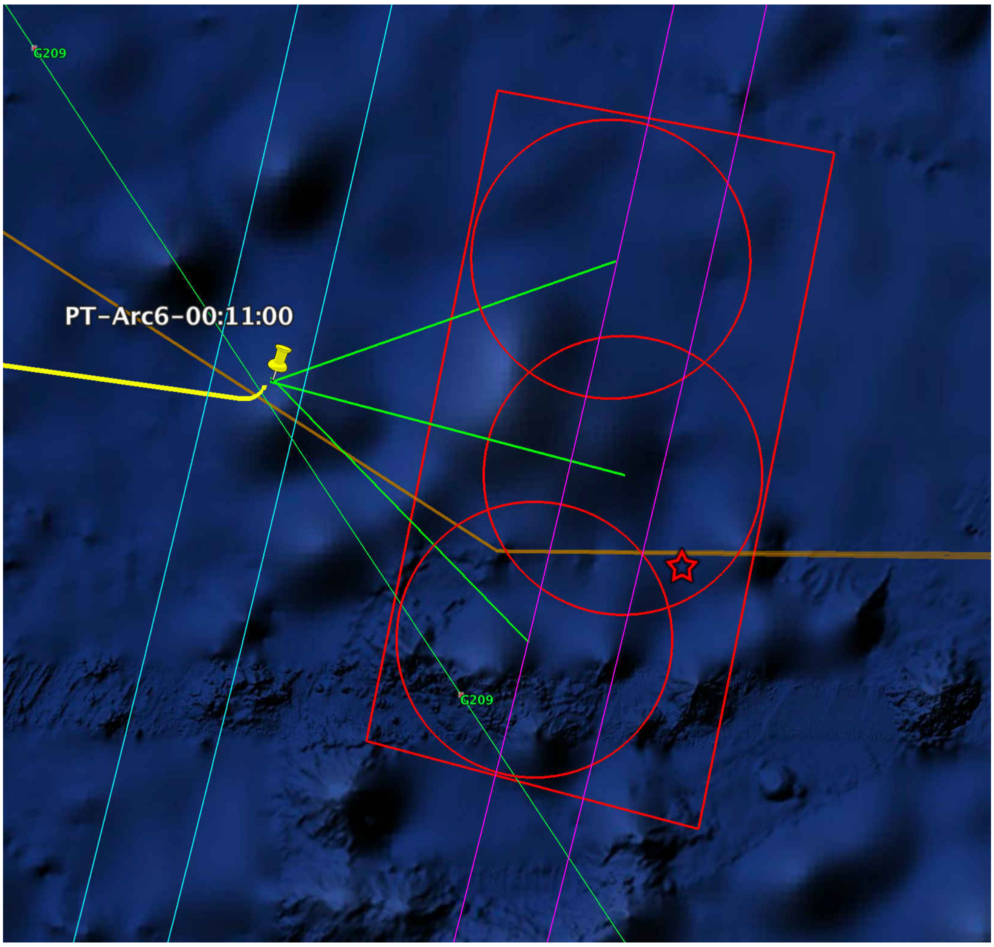

Figure 10:
Identification of the new search zone

This area has been searched from the 18th to 25th March 2014 by aircraft as explained on page 18 in [6]. In addition Hurricane Gillian disrupted the search. And later, the Australian coordination took over which led to more southern search areas.

As for waterborne search, on the day of the disappearance of MH370, several Chinese vessels were on the west side of Christmas Island while the proposed new search area is on the south-east at about 120NM from the island. Therefore none of the Chinese ships that subsequently participated into the surface search was present at the time of the crash in the immediate vicinity of the ditching position proposed in this paper.

The proposed search area has also never been searched underwater.

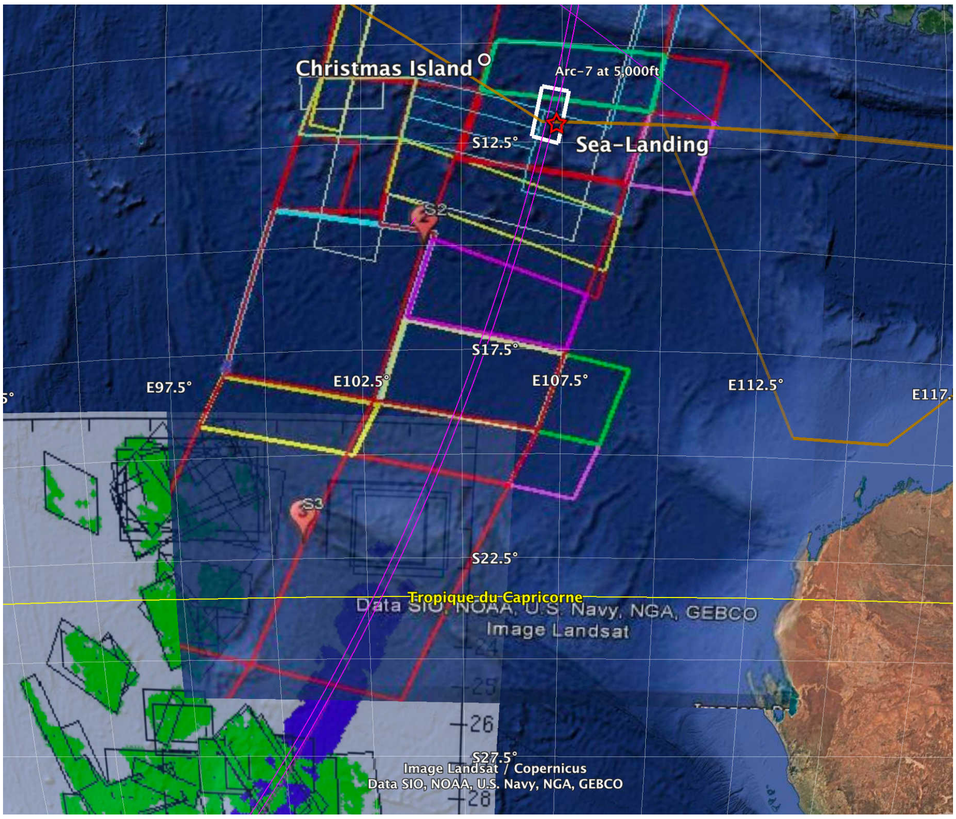

Figure 11:
The identified zone for the proposed new underwater search (in white)

7- Debris drift and Hurricane Gillian

Several experts, in particular GEOMAR and CSIRO have published very interesting study reports on the debris drift and how they could have reached places like l'Ile de La Réunion from specific areas on Arc-7 based on the BRAN2015 model [42].

Locations to the north of 30°S have been excluded on the ground that the flaperon would have travelled faster than the 15 months it took it to reach La Réunion.

To be able to figure out whether the area found by the Piloted Trajectory and located much more in the north could be a potential starting point of the drift, a simplified model of CSIRO [42] was integrated into the CAT with the same set of assumptions and drift model but computed on a shorter duration until 23rd November 2014. This was considered sufficient to draw convincing conclusions on the debris drift. The effort required to decompress the remaining meteo data for a longer period would have taken too much resources because of the change of its data compression format to a more complex one.

Our reverse drift study used data from and after the 8th March 2014, the very day when Gillian appeared.

The location of the sea-landing point is the vicinity of (-12.10°, 107.2°) and is far from the areas designated by the CSIRO Oceans and Atmosphere study which are located more to the south at ~(-30.5S, 97.9E) on the 7th arc. The distance between these two areas is approximately 1,200NM along Arc-7.

Hurricane Gillian [36] started on 8th March in the Gulf of Carpentaria offshore northern Australia and overflew Christmas Island on 22nd March (cf. Figure 12). Finally Gillian dissolved on 26th March at location ~(-21.0S, 103.5E). That is about 596 nautical miles west of Learmonth in Australia.

During that time, the SAR operations under Australian coordination [37] started on 18th March. Gillian affected the search from 21st until 25th as official reports show that it was suspended due to bad weather. And until 31st March the search areas were at the latitude of Perth i.e. 1,200NM in the south.

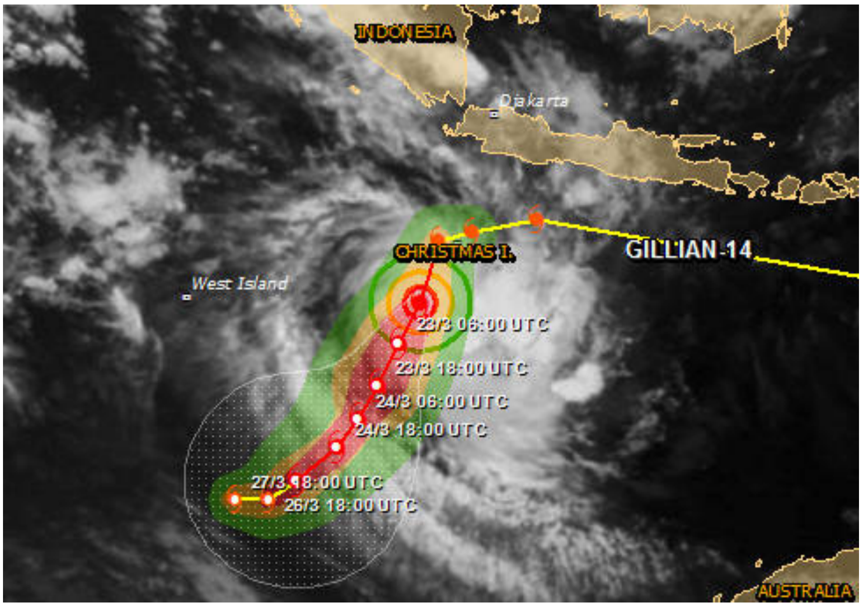

Figure 12:
Hurricane Gillian path.

During the 8 days of strong wind and waves, the debris would have most probably drifted southwards pushed by Gillian. It is estimated that they reached a sufficiently low latitude (~16°S / 18°S) to drift westwards in the Indian Ocean eventually. Figure 13 illustrates the results of the rough estimation produced by the CAT until 23rd November 2014.

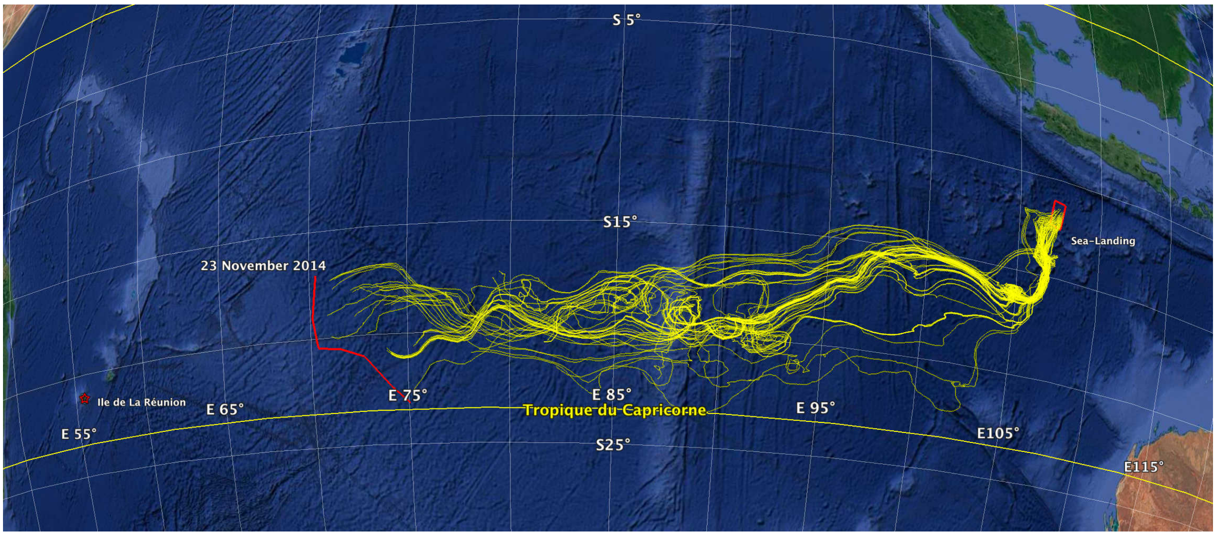

Figure 13:
Debris drift from the vicinity of the identified sea-landing zone

The drift analysis has been made for the debris with the same characteristics as the flaperon and in particular the specific additional angle of the drift due to the emerged part pushed by the wind.

Results of the simulations presented in Figure 13 confirm that taking into account the impact of Gillian supports the hypothesis that debris could have drifted from the vicinity of the identified sea-landing point towards actual locations where debris have been found in 2015.

So statistically, there is a high probability that the flaperon could have come from this area. But of course, this should be confirmed for the full time duration of the actual flaperon journey by more computations with better models with higher precision and more computing power.

It should be noted that, in this hypothesis, the estimated journey of the debris to the French and African coasts was constantly in the north of the Capricorn Tropic. This could be the reason why the type of molluscs found on them is from the tropical latitudes only.

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8- Annex 1: Systems powering and shutdown Issues

This document contains:

- a brief description of the electric power generation system on-board Boeing 777 aircraft ;

- a presentation of all the communication-and-surveillance (C&S) systems and events of relevance to flight MH370 ;

- an analysis of the possible causes of C&S service interruption/restart events observed during the flight in terms of cockpit-initiated actions and/or the loss/recovery of electric power due to systems failure or some voluntary actions on circuit-breakers.

a. Electric power and Electric Load Management System (ELMS)

The ELMS is a system whose function is to dynamically adapt the distribution of electricity on-board to what quantity of energy is available.

Since the objective of this document is to discuss MH370-related events, we will leave aside the issues related to the provision of electricity from external sources when the aircraft is in at the airport.

When in flight, the Boeing 777 uses two main sources of electric power driven by the two engines (and accordingly identified as Left and Right), which are called the Integrated Drive Generators (IDG). These IDG provide 120 kVA of 3-phased 400 Hz alternative current at 115 / 200 Volts to the corresponding main electric bus (Left Main Bus and Right Main Bus).

When one of these two main buses is no longer powered (due to engine or IDG failure) the Auxiliary Power Unit (APU) with the same power as either IDG, is started automatically or through a switch located in the cockpit. The APU motor burns fuel coming from the aircraft tank and therefore can be started only if there is some fuel left.

Two Back Up Generators (BU GEN) are also powered by the aircraft engines but they can deliver only 20 kVA, which still allows a single BU GEN to keep some of the equipment running in the case when the three main sources of energy (L-IDG, R-IDG and APU) would become simultaneously unavailable.

If one engine stops, both its IDG and BU GEN become unavailable, but the other engine's BU GEN may replace the non-running IDG by providing additional electricity through the transfer bus, which is useful in cases when the APU is unavailable. Only one BU GEN can be running at any time.

In any case, a single generator (be it an IDG, a BU GEN or the APU) can feed both main buses. Bus tie breakers close automatically when one of the main bus is no longer powered by its own nominal source of energy. The ELMS sheds the provision of services by ascending order of priorities so as to keep as many services as possible and shedding non-essential services (eg galley services) first.

The minimum quantity of electric power required to feed the DC circuit for navigation systems, the fuel pump and maintain the temperature of the navigation window is 14 kVA according to [43].

The whole system is designed to provide a high level of redundancy, but in a situation when all the main and backup systems would become unavailable (eg when no fuel is left to power the engines and the APU), a last resort windmill called the Ram Air Turbine (RAT) is deployed and it can provide enough electrical energy to operate all essential navigation services to the cockpit, including one VHF radio and one SSR transponder. As the RAT relies on aircraft speed, it can work without time limitation.

Mobile parts (flaps, fin) have their own individual batteries to limit the overall load on this last resort system (the main battery acts as a buffer to allows for a no-break transition to full RAT deployment.)

The two following diagrams (borrowed from [43]) show the overall architecture of the electric generation and distribution system and the control switches available in the cockpit.

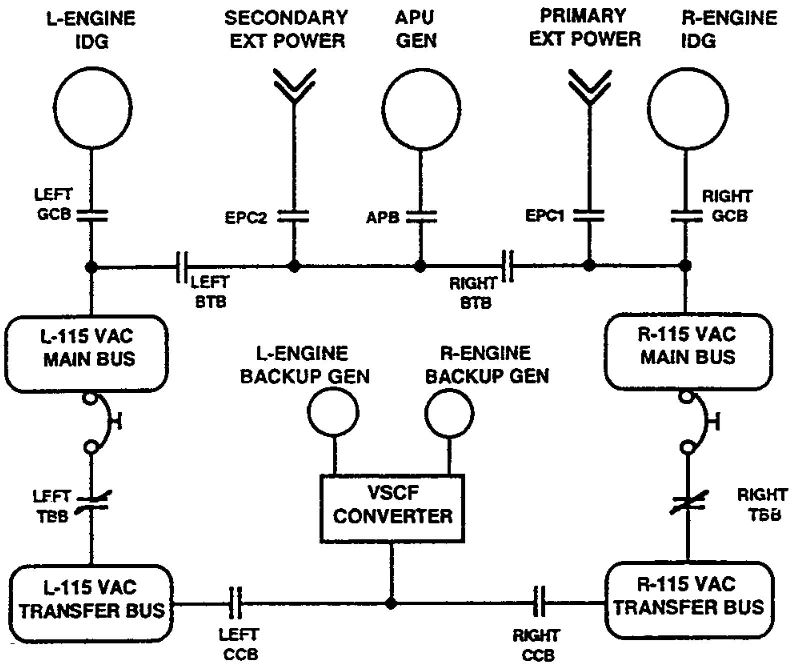


Fig. 1. Main and AC Backup Power

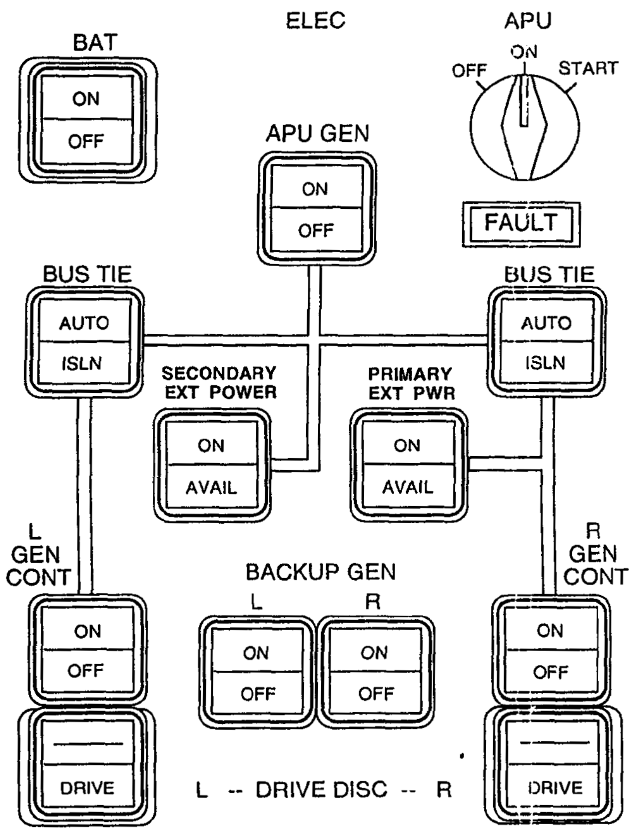


Fig. 3. Flight Deck Control Panel, Electric Power System

b. C&S Systems and Key Events during flight MH370

i. MH370 communication and surveillance systems and services

3- 2 Secondary Surveillance Radar (SSR) Transponders denoted as Left and Right, which also provide the Automatic Dependent Surveillance Broadcast (ADS-B) service ;

4- 3 VHF Analogue Radio (for voice communication with Air Traffic Controllers) denoted as Left, Right and Centre ;

5- 1 Airborne Earth Station (AES) and Satellite Datalink Unit (SDU) connected to the Perth Ground Earth Station (GES) via the Inmarsat IOR (Indian Ocean Region) geostationary satellite to provide a SatCom service ; when the AES-GES link is left unused for about 60 min, a timer in the GES checks that the link is still operational by sending a short message to the AES which then acknowledges reception. This is called a “handshake”. Any communication attempt (either successful or not) by some service using the SatCom link restarts the 60 min timer in the GES.

6- 1 ACARS Terminal for communication between the pilots and the company via the SatCom ;

7- Flight Progress Monitoring (FPM) ACARS-based applications for doing automatic event-based reporting to signal progress through the main flight phases from departure to arrival ;

8- an Engine Health Monitoring System (EHMS) ACARS-based application for doing automatic or event-based periodic reporting ;

9- A SatCom Telephone Service (available only in the cockpit) ;

10- SMS and BITE services available through the In-Flight Entertainment (IFE) system.

The multiplicity of VHF Radios and SSR transponders is part of the safety-related redundancy scheme already described in the section on electric power sources. Some of these components, like the navigation systems, are powered at all time, even when only the last resort RAT is available.

More precisely, one of the two SSR transponders is connected to the left electric bus and the other one to the right electric bus. Two of the three VHF radios are connected to the left electric bus and the other one to the right electric bus. By contrast, the SatCom system and ACARS services are connected only to the left electric bus and may be shut down by the ELMS when not enough electricity is available. The IFE Services to the passengers have an even lower priority. Based on the redundancy scheme between the different sources of electric power, we have the following table of nominal and back-up electric sources for communication and surveillance equipment:

	IDG-L	IDG-R	BU GEN-L	BU-GEN-R	APU	Battery	RAT
Left VHF	Normal	Xfer Backup	Backup IDG-L	Xfer Backup	Backup	Backup	Last Resort
Right VHF	Xfer Backup	Normal	Xfer Backup	Backup IDG-R	Backup		
Central VHF	Normal	Xfer Backup	Backup IDG-L	Xfer Backup	Backup		
Left SSR Tr.	Normal	Xfer Backup	Backup IDG-L	Xfer Backup	Backup	Backup	Last Resort
Right SSR Tr.	Xfer Backup	Normal	Xfer Backup	Backup IDG-R	Backup		
SatCom Link	Normal	Xfer Backup	Backup 1DG	Xfer Backup	Backup		

Table A2-1 : Electric Power Redundancy Scheme

“Xfer backup” denotes the possibility of transferring electric power from left to right (or from right to left). In the cockpit, the left position corresponds to the first officer, hence the last resort side.

We can see that at least one VHF Radio and one SSR Transponder should remain available at all time.

ii. Key communication and surveillance-related events

Based on the information provided by the official Malaysian report, the key events related to these communication and surveillance systems and services are:

Event N°	UTC Time	System or service	Description of the event
C&S-1	17:07	EHMS	Periodic ACARS report sent over the SatCom link
C&S-2	17:08	VHF	Pilot confirming cruise level at FL350 to the controller
C&S-3	17:19	VHF	Controller instructs pilot to contact Ho-Chi-Minh-Ville Control
C&S-4	17:19	VHF	Acknowledgement by the pilot (last VHF radio communication)
C&S-5	17:21	SSR	The transponder stops responding to SSR interrogations
C&S-6	17:21	ADS-B	ADS-B emissions stop
C&S-7	17:30	PSR	First detection by Kota Bharu primary radar
C&S-8	17:37	EHMS	Expected periodic ACARS report not transmitted
C&S-9	18:03	AES-SDU	SatCom link unavailable for a ground-originated phone call
C&S-10	18:22	PSR	Last detection by Penang primary radar
C&S-11	18:25	AES-SDU	AES-initiated Logon re-establishing the SatCom link (1st handshake)
C&S-12	18:27	IFE-SMS	Level 3 (X25) connection established for SMS (a) messages
C&S-13	18:28	IFE-BITE	Level 3 (X25) connection established for BITE (b) SMS messages
C&S-14	18:40	Sat Phone	A ground-originated phone call to the cockpit is left unanswered
C&S-15	19:41	AES-SDU	Second Handshake between the GES and the AES
C&S-16	20:41	AES-SDU	Third Handshake between the GES and the AES
C&S-17	21:41	AES-SDU	Fourth Handshake between the GES and the AES
C&S-20	22:41	AES-SDU	Fifth Handshake between the GES and the AES
C&S-21	23:14	Sat Phone	A ground-originated phone call to the cockpit is left unanswered
C&S-22	00:11	AES-SDU	Sixth Handshake between the GES and the AES
C&S-23	00:19	AES-SDU	Uncompleted AES-initiated Logon to re-establish the SatCom link

Table A2-2: List of key C&S events

(a) SMS : Short Message Service ; (b) BITE : Backward Interworking Telephone Event

In the above table, for the sake of brevity, we have skipped all the normal events preceding the last normal communications and we present only the first and last occurrences of aircraft detection by Malaysian Primary Surveillance Radars (PSR).

c. Analysis of the C&S events

The 4 first events listed in Table A2-2 show that until the last radio exchange at 17:19 UTC, all communications and surveillance systems and services were up and running.

After 17:21 UTC the following phenomena have been registered:

a) the end of SSR detection and ADS-B reports ;

b) the end of VHF communications ;

c) the non-transmission of an ACARS EHMS message ;

d) the reinitialisation of the SatCom link ;

e) the opening over this link of X25 circuits available to passengers;

a) The SSR and ADS-B events (C&S-4 and C&S-5 at 17:21) indicate that the loss of SSR detection was not caused merely by a transponder coding error in the cockpit (as may occur sometimes) because, if that had been the case, the ADS-B service would have remained active.

So the only possible actions for simultaneously triggering these two events are:

- - an erroneous or voluntary action in the cockpit setting the transponder on OFF or STBY,
- - a transponder failure,
- - a loss of electric power.

Since the backup transponder was not switched on in the following minutes, the possibilities are:

- - a voluntary or involuntary absence of action in the cockpit,
- - a failure of both transponders,
- - a loss of electric power impacting both transponders.

b) The end of VHF communications is not associated to any event. Indeed, no further attempt by the pilots to contact ATC authorities was detected. This can be explained only by:

- - a voluntary omission in the cockpit (the pilots were expected to contact the next control centre within minutes of their last radio communication with Kuala Lumpur)
- - a failure of the three VHF radios,
- - a loss of electric power impacting the three radios.

c) the non-transmission of the automatically-generated EHMS message (C&S-8 at 17:37) expected half-an-hour after the previous message (C&S-1 at 17:07) can be explained by:

- - an EHMS application failure,
- - an ACARS terminal failure,
- - a voluntary action in the cockpit disconnecting the ACARS terminal from the link,
- - a SatCom link failure.

d) The restart of the SatCom link (C&S-11 at 18:25) shows that the SatCom link had been abruptly shut down at some time between 17:07 (last ACARS message) and 18:03 (failure to transmit an upcoming phone call). Also, the absence of the Flight ID in the Logon message from the AES-SDU to the Perth GES shows that the Airplane Information Management System (AIMS) that monitors all the communication systems was also reset at some point, with the missing information having not been properly re-input from the cockpit.

e) the two X25 circuits opened over the SatCom link for providing passenger messaging services (C&S-12 at 18:27 and C&S-13 at 18:28) show that the IFE system had been restarted at the same time as the SatCom link, which means that the electric power had been more or less fully restored.

Since the hypothesis that simultaneous individual failures occurred for all the non-working components has an extremely low probability, and considering the behaviour of the aircraft after its U-turn, only two possibilities remain:

- 1) some massive failure in the electric system, followed by a (quasi) full recovery,
- 2) a series of voluntary actions so as to disable all communication and surveillance means.

A massive failure in the electric system followed by a full recovery about one hour later seems rather unlikely, especially because what we know about the diversion from the flight plan during this first hour reflects a deliberate intention to evade air traffic surveillance and control.

Therefore we consider that the most likely explanation for all the C&S events discussed above is that they were caused by one or more voluntary actions taking place just after the last radio communication.

The restarting of the SatCom indicates that these actions were probably not taken through the normal interface in the cockpit because, in order to close down the SatCom link, a pilot would have simply used the SatCom OFF command in the relevant menu of their Control Display Unit (CDU) interface.

But we know this is not what happened because no Logoff message from the AES-SDU was received by the GES. So we agree with the comment made in the official report that "*There is no evidence of a cockpit-initiated manual Log-Off of the SATCOM*".

If these voluntary actions were not taken through the control panels of the communication and surveillance systems in the cockpit, the only way to produce a multiple shutdown of so many redundant systems is by opening circuit-breakers, which are to be used only for maintenance purpose or in case of emergency (eg. if a motor is on fire, the pilot may isolate the corresponding IDG and BU GEN).

However, since the MH370 flight continued flying for almost seven hours after its U-turn, an emergency shutdown by the pilots in response to a major incident on one motor is not likely, all the less so that the absence of activation of the backup VHF and transponder shows that this shutdown should have impacted all the main sources of electricity which is impossible: if the aircraft is still flying, at least one motor is running and the corresponding IDG plus the APU can provide all the electricity that is needed. And even is both motors stop, the battery and the RAT can still provide electricity to all the essential equipment (including one VHF and one SSR transponder ; cf. Table A2-1).

The two main buses distribute power under the form of 400Hz 115 V alternative current (AC), but at a lower level, the Navigation, VHF and SSR electronics receive 28 V direct current (DC) from transformers that feed low voltage buses. Relying on low voltage DC makes it easier to transition to battery-and-RAT-provided power in case of failure of the main power feed.

By contrast with other communication equipment, the SatCom system, which is never fed by the battery and the RAT (cf. Table A2-1), directly receives 115 V AC from the Left Main Bus or from the other main bus or the APU through the Bus Tie. The AES-SDU is located at the bottom of the cabin, close to the Satcom antennas mounted on top of the aircraft neat the tail.

Shutting down individually each and every piece of communication equipment would have required several actions to be taken in the cockpit (setting the SSR Transponder controls on STBY, setting all the VHF radios on OFF) and then going to the rear end of the cabin to shut down the AES-SDU, because no dedicated circuit-breaker is available in the cockpit for selectively shutting down the AES-SDU: only global circuit-breakers (eg for isolating an IDG) are available there.

Shutting down abruptly the SatCom system from the cockpit would have required several high-risk actions:

1°) switching OFF the Left GEN (which is the primary source of electricity for the SatCom),

2°) switching OFF the associated BU GEN, to prevent it from replacing the IDG,

3°) Setting the Bus Tie switch on ISLN (to neutralise the transfer backup mechanism from the right side or from the APU which would be activated by the ELMS).

However the consequences of such actions on the availability of Navigation systems are unpredictable and no professional pilot would take so huge a risk, considering that a much simpler way of de-activating the SatCom link is at hand (by using the CDU SatCom OFF command).

So for a small number of actions to result quickly in the shutdown of all communication and surveillance systems, these actions must have been fairly global and should consist in opening maintenance-dedicated circuit-breakers upstream from individual components or in extracting electronic boards from their racks.

Therefore the electric/electronic compartment is the place of choice where shutting down all these systems despite their multiple redundancies would have been relatively easy for someone knowledgeable with the electric architecture of the Boeing 777 (e.g. an electronic systems maintenance technician).

Last but not least, the SatCom Logon and the subsequent opening of IFE-dedicated X25 circuits shows that the electric power came back after about one hour which is contradictory with the apparent objective of remaining incomunicado. So, it seems that the people who shut down all the communication systems did not realise that the AES-SDU would automatically reinitialise the SatCom link if the electric power came back.

Some kind of global interference with the left main bus leading to a reset of the left AIMS should be envisaged, based on the fact that the flight ID (normally provided by the left AIMS to the SDU) was absent for the Logon message emitted by the AES-SDU system.

Although some never-seen-before global failure of all the main electrical systems putting the three VHF and both transponders out-of-order cannot be definitely dismissed, it seems very unlikely and we suggest that Boeing experts try to reproduce the observed sequence of events by concentrating on scenarios involving the voluntary manipulation of global and/or more specific circuit-breakers in the electric/electronic compartment.

Regarding the last uncompleted Logon (C&S-23 at 00;19), we agree with other analyses that this event was caused by a reduction of electric power that occurred when the engines ran out of fuel.

Owing to some fuel remaining in its feeding pipe, the APU could start and trigger a SatCom Logon, which could not be completed because the APU soon stopped.

However, we cannot conclude that the aircraft would have plunged immediately into the Indian Ocean. Depending on its altitude at that time, it might have flown in a more or less controlled glide for some time, especially if the RAT had been deployed to provide minimal navigability.

But since the RAT does not power the SatCom, no conclusion can be drawn from the analysis of this last C&S event.

9- Annex 2: The Constraint Assessment Tools (CAT)

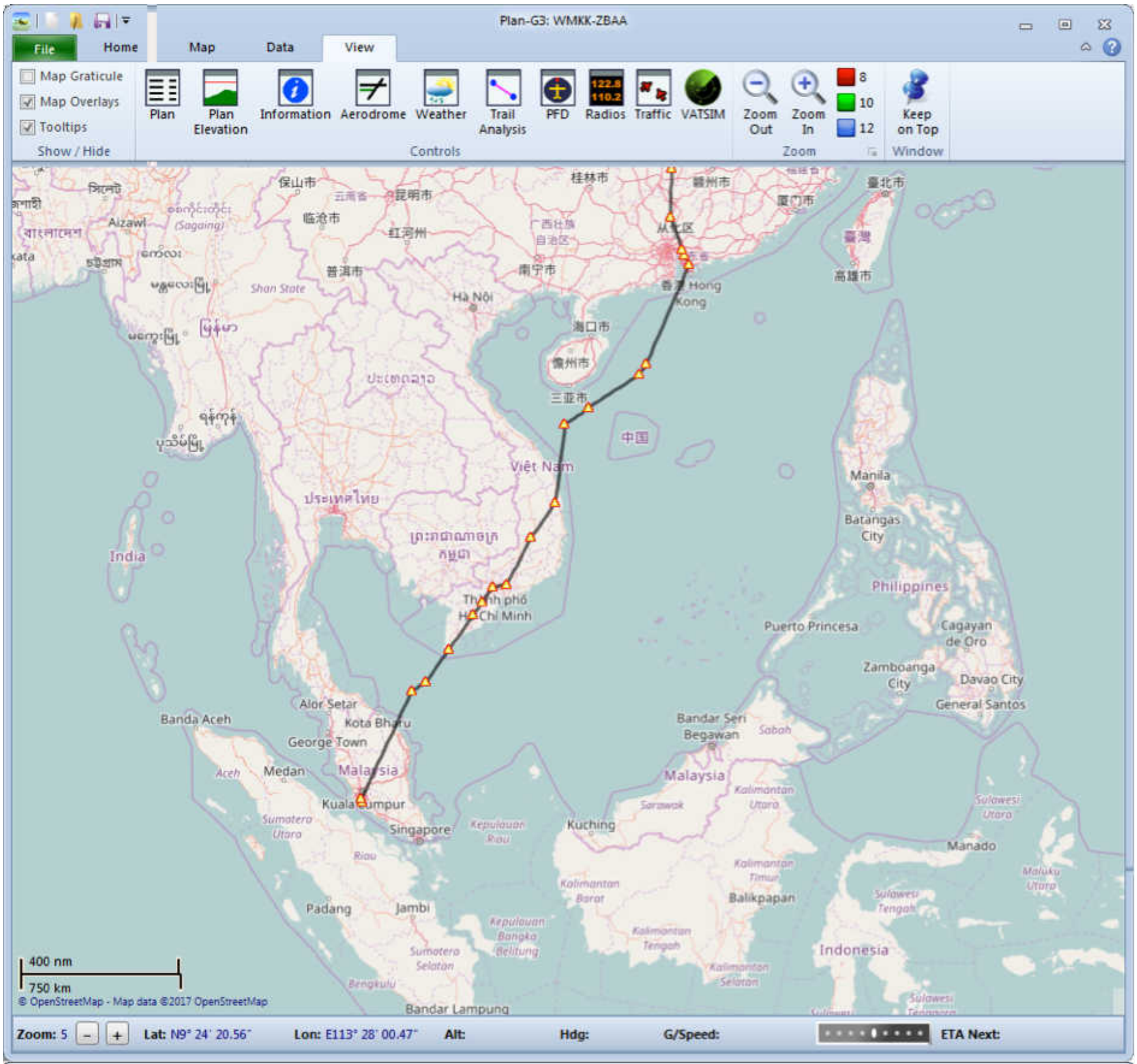
The purpose of this tool set is to:

1. Create and update a 3D flight plan in order display it using several tools and to capture simulation data for in depth analysis.
2. Generate 3D radar coverage
3. Capture and convert historical weather data
4. Refine trajectory and estimate best BFO, speed etc. values based on 3D (or 4D if time is known) trajectory and BTO ping information in combination with existing data e.g. meteo
5. Calculate the drift of the MH 370 flaperon
6. Generate Arcs based on BTO and altitude values
7. Estimate the remaining fuel for each point of the trajectory

This set of tools has been built with MS-Access Databases (2010 version - compatible with the 2002-2003 version). Functions and procedures included in modules have been developed in Visual Basic.

List of tools

- **The plans and simulations tool** inserts in a table trajectory data from trajectory information typed-in manually or copy-pasted from external tools; it recognises latitude/longitude (deg/min/sec, deg/dec), alt (ft) waypoints and airports ICAO codes and translates them in coordinates (deg/dec) . All of this data can be updated after translation and the plan can be updated and other points/segments can be inserted at a later stage. AIRAC 1501 data comes from Navigraph Data included in the PMDG 777 Model which has been used in our simulations. They have been inserted in the Microsoft Flight Simulator X (FSX) environment. Data can be exported in different formats: Google Earth (GE) .kml files, FSX .pln file and basic PMDG .rte file in order, first to display the 3D trajectory in GE (or in 2 D in Plan-G or FSX) and then they can be loaded as flight plans into aircraft flight management system (FMS) (for PMDG and other FSX compatible models).
  Each plan can be associated to one or more simulations which contain logs of key parameters (position, speed, direction, altitude, wind speed and direction …) . These data are the results of simulations performed using FSX models and recorded with Tiny Flight Tracker. These logs are imported and combined and provide a trace of how the simulation was conducted. A start time can be specified to derive a time-stamp for each sample according to this initial value.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Hong Kong
Hà Nội
Việt Nam
Manila
Batangas City
Philippines
Puerto Princesa
Cagayan de Oro
Zamboanga City
Davao City
General Santos
India
Thành phố Hồ Chí Minh
Alor Setar
Kota Bharu
Banda Aceh
George Town
Medan
Malaysia
Kuala Lumpur
Singapore
Kuching
Bandar Seri Begawan
Manado
Balikpapan
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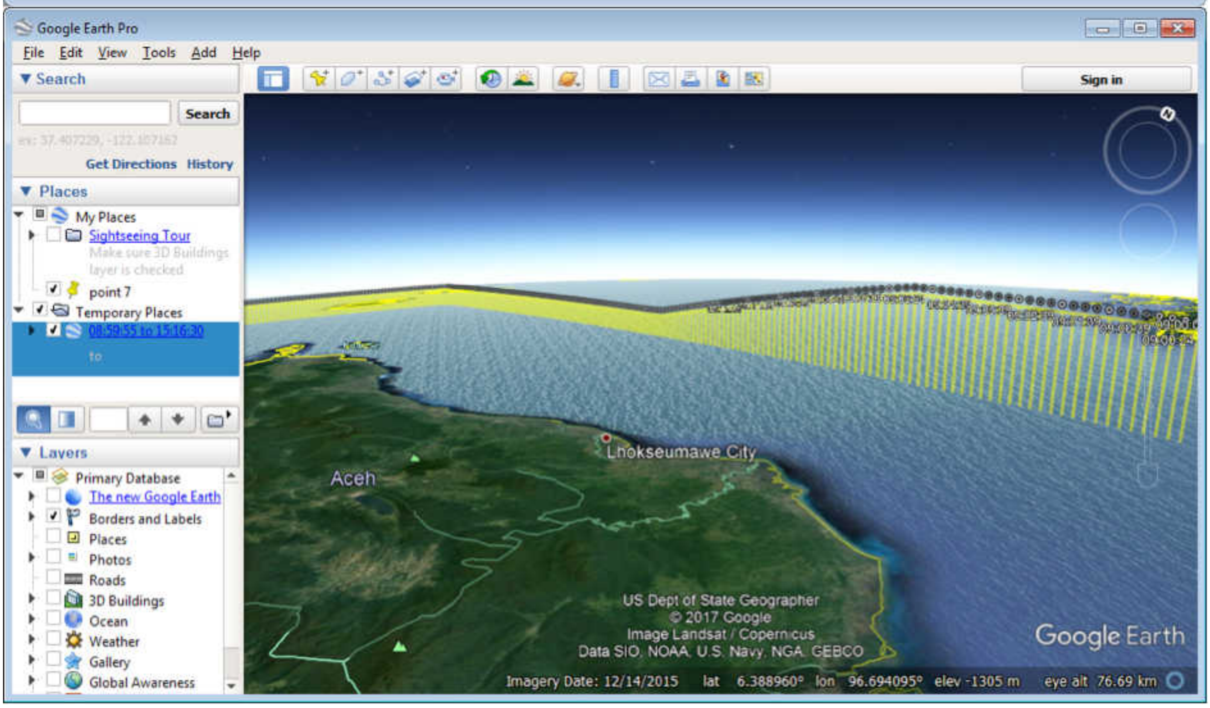
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Places
Photos
Roads
3D Buildings
Ocean
Weather
Gallery
Global Awareness
Aceh
Lhokseumawe City
US Dept of State Geographer
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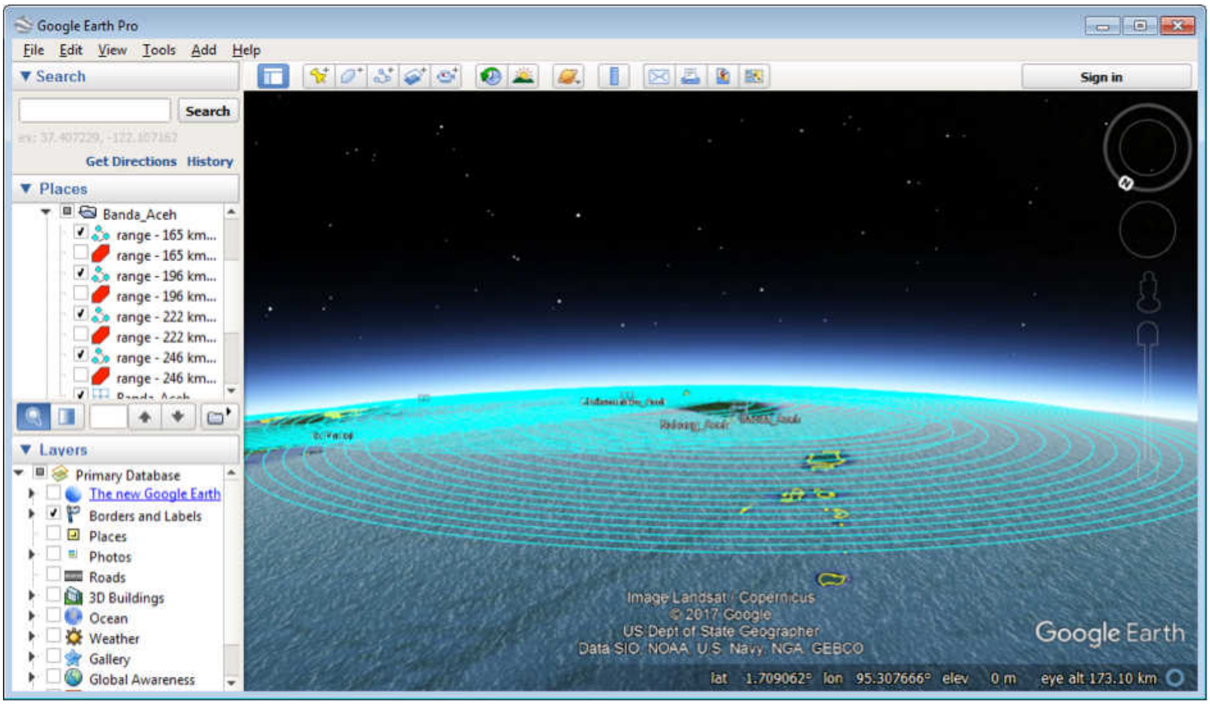
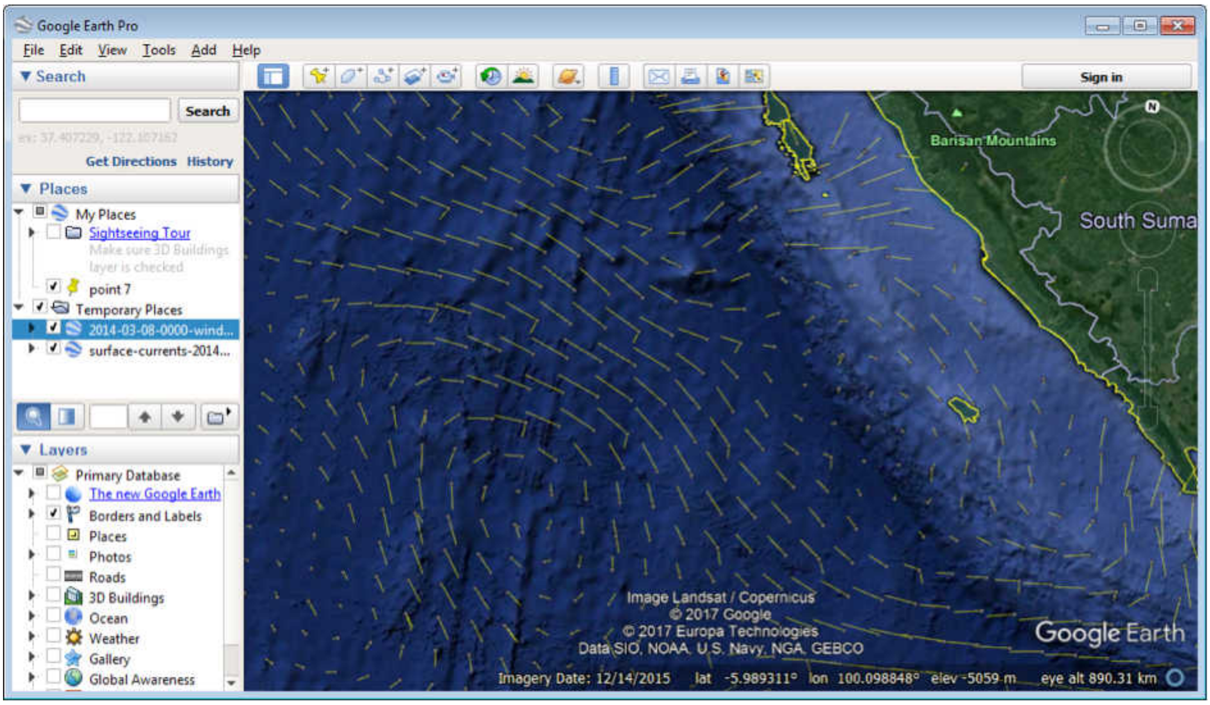
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google Earth
Imagery Date: 12/14/2015 lat 6.388960° lon 96.694095° elev -1305 m eye alt 76.69 km

- **The radars generator tool** generates kml files to display 3D radar coverage in GE. Data sources have been fetched from the ICAO GIS site (MH 370 story) and data provided by the MH370 Independent Group. Ranges for different altitudes are calculated and can be selected and displayed by using standard GE functionalities



- **The weather data transformer** downloads historical surface currents and wind data from Earth Nullschool (EN). That information has been produced by the Global Forecast System (GFS)

NOAA and Earth and Space Research Institute (ocean surface current analyses (OSCAR) derived from satellite data) and stored by EN. Some downloaded data had to be decompressed before transformations. The period considered is from the 7th of March 2014 until the 23rd of November 2014 for the wind and the current at surface level. From the 7th of March 2014 3pm to 8th of March 2014 3am addition wind information at isobaric 850hPa, 700hPa, 500hPa, 2050 and 1000hPa roughly and respectively equals to FL004, FL048, FL099, FL183 and FL340 because the barometric pressure was close the standard 1013hPa at sea level the day of the disappearance (source EN). Samples have been collected by the GFS and OSCAR each 3 hours for the wind and each 5 days for the current. Standard weather GRID (1 degree for wind and 1/3 degree for current) files have been converted and data have been used to populate many MS Access tables.

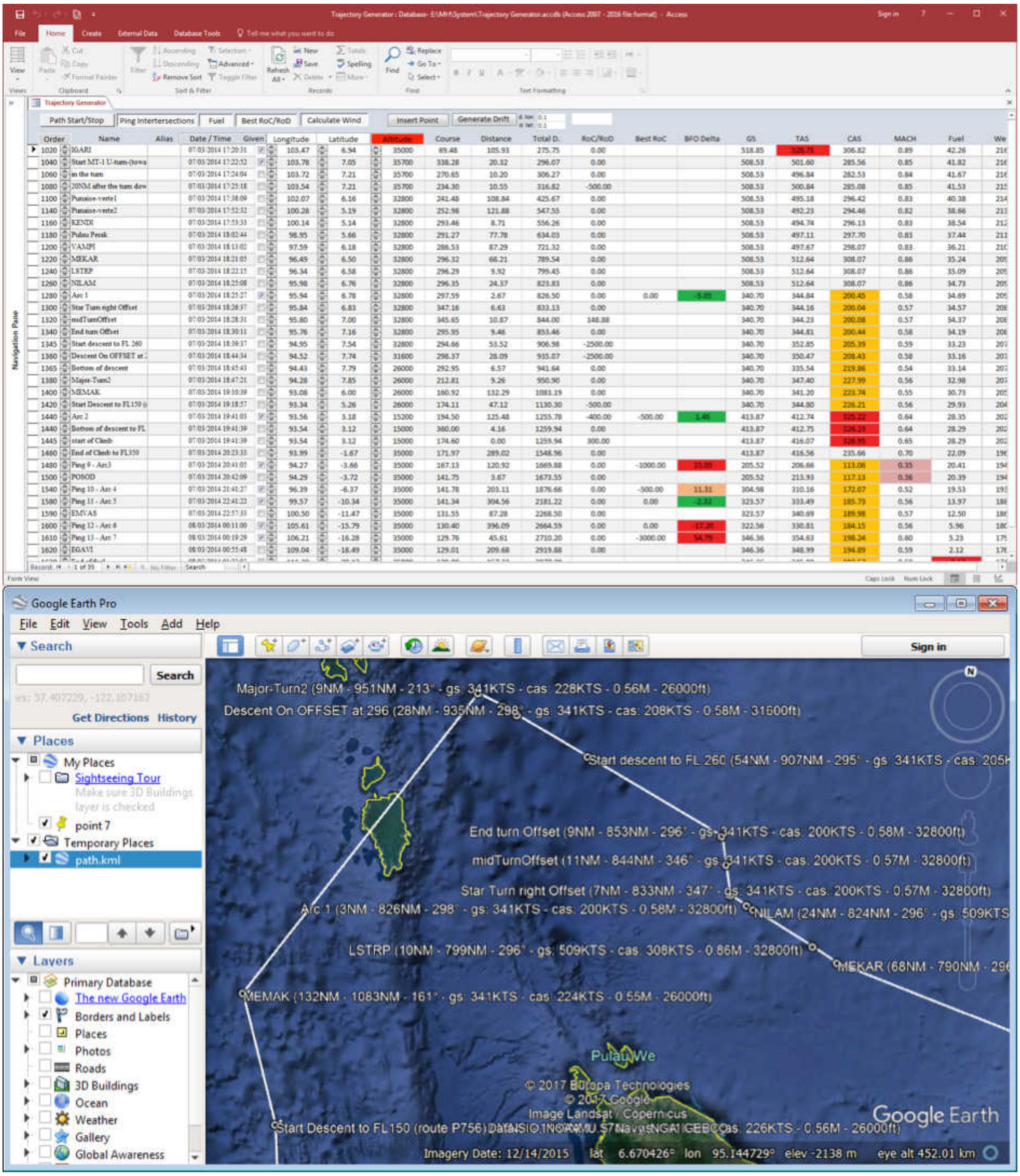


- **The trajectory calculator** yields a 4D trajectory (time constraint at specific points). Calculations include:

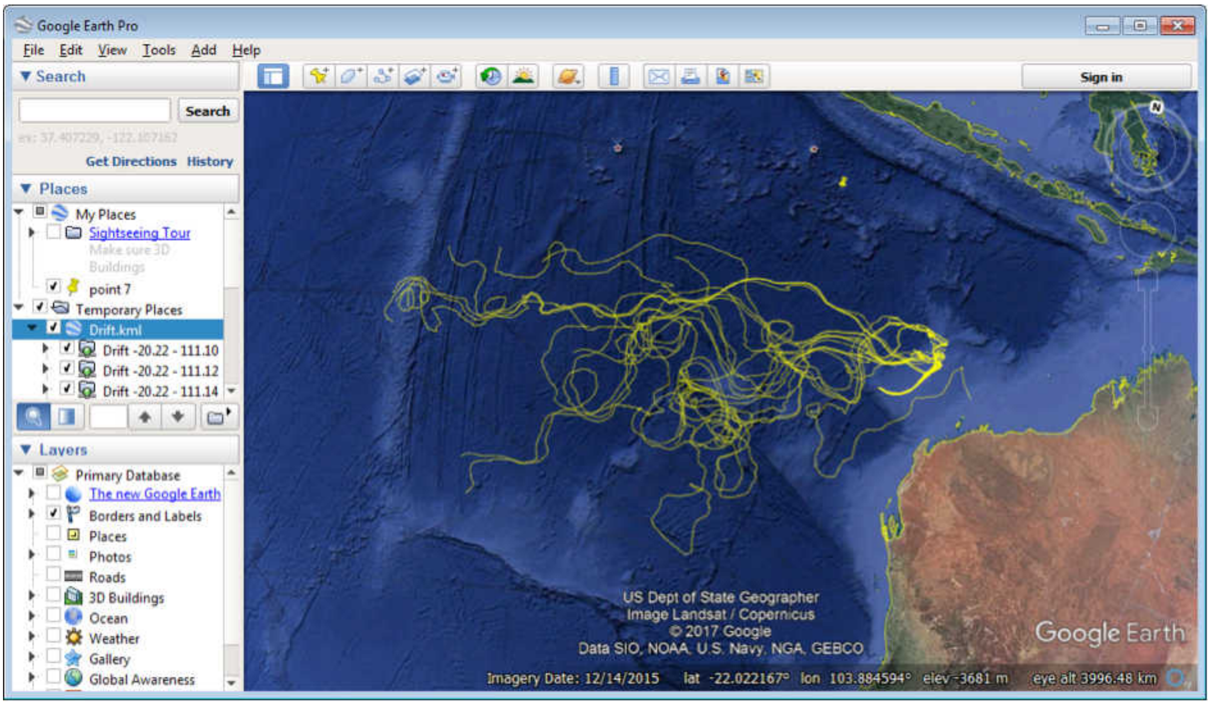
  - at a non-arc-crossing point: time (if not given), distance (and total distance from the starting point), course, ground speed, true airspeed (TAS) and direction (using weather data – see above – and 3D linear interpolation), calibrated airspeed (CAS), Mach number, equivalent airspeed EAS) (for delta ISA=13; mean in the latitude under consideration – source EN)

  - at arc-crossing points it calculates the 3D location of the intersection of a segment of flight path and the sphere having a radius equivalent at the corresponding BTO and the centre point located at the satellite position at this time. The altitude and Rate of Climb (RoC) or Descent (RoD) is calculated as a function of the two segment extremities. This calculation is based on the model developed by Yapp FF and on the longitude calculator developed by Barry Martin & Geoff Hyman. It calculates the best Rate of Climb or Descent as well (between -7 000 ft/min and +7 000 ft/min per step of 500ft) for the aircraft located on a specific arc and having a fixed speed and heading in order to get the best BFO at this position for this range of rates.

  - an interactive interface enables the user to dynamically modify and update the trajectory either by typing (or copy/pasting) data directly in the form or using the mouse and/or buttons. A kml file is generated by the tool at regular interval and is periodically read by GE which display trajectory changes on the map. Moreover data which are outside the aircraft flying envelop are highlighted.



- **The Drift Calculator** uses surface current and surface wind (source EN) as inputs to calculate the drift of the debris based on latest CSIRO report which specify that the flaperon drifted with the surface current plus the surface wind with 16 degree orientation to the right and an additional speed of 0.1m/s in the wind direction. This calculation is done using a linear interpolation of weather data with for the wind a 1 degree grid and delay of 3hours between samples and for the current a 1/3 degree grid and a 5 days period of time between samples. It starts the calculation from location of the last point of the trajectory defined in the trajectory calculator tool. It runs the calculation using samples from the 8th of March 2014 until the 23rd of November 2014. It uses linear interpolation to calculate values from one point to another. The zone is specified at the beginingn and 121 paths are calculated from this area.

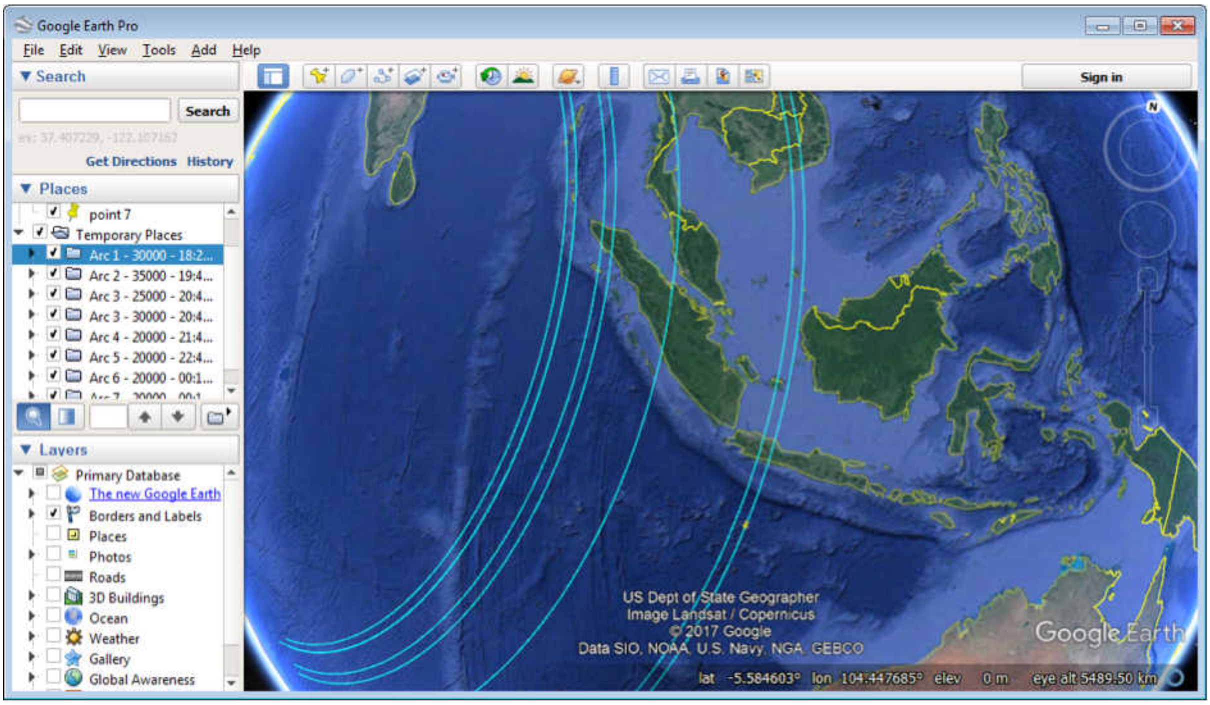


- **The fuel calculator** is based on the model (9M-MRO Fuel Model V5.X) developed by Bobby Ulich. The data sources come from the FCOM of the Boeing 777_200ER with RR Trent 982B engines. The fuel weight is manually introduced in the trajectory at a specific point and is used as the starting figure. The calculator integrates the fuel flow each second between two points of flight plan to calculate the remaining fuel via a bi-cubic interpolation. The model considers the speed, the weight, difference between sea level temperature and day temperature at the location (delta ISA), the conditional pack consumption[3], the flight level, the increase in fuel flow during climb and the decrease during descent, the idle consumption of the engine, the average performance degradation for the left engine and the right one.

[3] Pressurization Air Conditioning Kits : For any modern aircraft to fly at high altitudes, it must be equipped with an air conditioning and pressurization system, which provides a convenient environment for its passengers

Fuel	Weight
42.26	216.63
41.82	216.19
41.67	216.04
41.53	215.90
40.38	214.75
38.66	213.03
38.54	212.90
37.44	211.81
36.21	210.58
35.24	209.61
35.09	209.46
34.73	209.10
34.69	209.05
34.57	208.93
34.37	208.74
34.19	208.56
33.23	207.60
33.16	207.53
33.14	207.51
32.98	207.35
30.73	205.10
29.93	204.30
28.35	202.72
28.29	202.66
28.29	202.66
22.09	196.45
20.41	194.78
20.39	194.76
19.53	193.90
13.97	188.34
12.50	186.87
5.96	180.33
5.23	179.60
2.12	176.49
-0.17	174.37

- **The arc generator** is based on the longitude calculator developed by Barry Martin & Geoff Hyman. It generates arcs from BTO values and altitude; Arcs are displayed in GE


Google Earth Pro
File Edit View Tools Add Help
Search
Search
Get Directions History
Places
point 7
Temporary Places
Arc 1 - 30000 - 18:2...
Arc 2 - 35000 - 19:4...
Arc 3 - 25000 - 20:4...
Arc 3 - 30000 - 20:4...
Arc 4 - 20000 - 21:4...
Arc 5 - 20000 - 22:4...
Arc 6 - 20000 - 00:1...
Layers
Primary Database
The new Google Earth
Borders and Labels
Places
Photos
Roads
3D Buildings
Ocean
Weather
Gallery
Global Awareness
Sign in
US Dept of State Geographer
Image Landsat / Copernicus
© 2017 Google
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google Earth
lat -5.584603° lon 104.447685° elev 0 m eye alt 5489.50 km

10- Abbreviations:

OMR-2 :	Official Malaysian Report Issued on 8th March 2015 (Updated on 15th April 2015)
ACARS	Aircraft Communication Addressing and Reporting System
AES	Aircraft Earth Station (Satcom aircraft terminal)
ACC	Air Traffic Control Centre
ATC	Air Traffic Control
ATM	Air Traffic Management
ATSB	Australian Transport Safety Board
ATSB-3	The operational search for the MH370 (report, 3 oct 2017)
AIRAC	Aeronautical Information Regulation And Control (database used by a/c for navigation)
APU	Auxiliary Power Unit
EEB	Electronic Equipment Bay
EICAS Display	Engine Indication and Crew Alerting System
ETA	Estimated Time of Arrival
FIR	Flight Information Region
fpm	Feet per minutes (usually for vertical speed RoC or RoD)
FMS	Flight Management System
FSX	Microsoft Flight Simulator - X
ISA	International Standard Atmosphere
KTAS	True Air Speed in knots
KIAS	Indicated Airspeed in knots - usually the reference speed as defined by the FMS or manually engaged on the Mode Control Panel (MCP).
kn	knots (speed unit; 1kn = 1,852 km/h)
LRSP	Last Radar Spot Point (location of the a/c when the radar spot vanished) on Route N571 10NM away westward from MEKAR
LOR	Logon Request from the AES to connect to the network
MCDU	Master Control Display Unit
MCP	Mode Control Panel (Auto Pilot Board)
MYT	Malaysian Time
µs	Micro second = 10^{-6} second
PFD	Primary Flight Display (including the digital artificial horizon)
PMDG	Precision Manuals Development Group
RoC	Rate of Climb (vertical speed in fpm)
RoD	Rate of Descent (vertical speed in fpm)
RVSM	Reduced Vertical Separation Minima (allowing 1000ft between flight levels instead of 2000ft)
SAR	Search and Rescue operations
SDU	Satellite Data Unit
SLO	Strategic Lateral Offset Procedure
SSR	Secondary Surveillance Radar
TAC	Thrust Asymmetry Compensation of the B777 when an Engine fails
TAS	True Air Speed
TOC	Top of Climb
TRI/TRE	(Aircraft) Type Rated Instructor / Type Rated Examiner

References:

In the text the original sources are referenced in square brackets and listed at the end of the paper. Text quoted from original documents is shown in italics.

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For reference:

The coded waypoints and specific points of the planned trajectory are the following:
WMKK (Kuala Lumpur) –IGARI - short leg towards BITOD -U-turn-towards WMKC (Kota Bharu) – KADAX – PUKAR – KENDI – VAMPI – MEKAR – NILAM - Offset IGOGU – Major Turn 2 - ***MEMAK – POSOD – (Major Turn 3) – EPGUP – (Major Turn 4) – ISRAN – (Major Turn 5) – YPXM (Christmas Island)***

Change Log:

P37 Event19	Conclusions: Correction erroneous values of BTO