Analysis of Flight MH370

From waypoint VAMPI until the estimated touch down

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Executive Summary:

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

The following elements have been addressed:

1. The reconstructed trajectory using proven aeronautical computations based on:
    a. The fuel quantity at 02h28 MYT[1] estimated and reported by Boeing in the Appendix 1.6E of the official report in 2018 [2].
    b. Inmarsat satellite arcs which are considered trustworthy.
    c. Meteo information of the day used by pilots (wind maps, temperature reports etc.)
    d. In Flight Performance tables for the B777-200ER with Rolls-Royce Trent 892 engines.
    e. Specific technical data to 9M-MRO like the "performance factor" of the fuel consumption

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

The following conclusions were drawn:

1. The reconstructed trajectory is similar to Inmarsat's example published in the report "the Search for MH370" [3]. Figure 1 below allows comparing the reconstructed trajectory in yellow with Inmarsat's example in red.

2. Inmarsat "loss of contact point" is very close to the reconstructed trajectory path and coincides well with our estimated location where the second engine was voluntarily shut down (cf Figure 3).

3. The northernmost probable point of impact (POI) identified in this study is located at [35°39'S ; 93°01'E]. It is very close to the POI computed by CSIRO forward drift analysis reported in their report n°III of 26 June 2017. In addition, potential debris have been photographed by the French CNES Pléiades 1A satellite in this area.

4. For the end of flight, two slightly different possible scenarios have been elaborated. Both include a gliding phase with a final controlled ditching producing little debris. Scenario 1 is illustrated in figure 2.

5. From these scenarios, a zone for a new search of the wreckage is proposed (yellow area in figure 3) which extends the already searched area in 2018 to the south by about 38Nm. Its width is ~16Nm. The estimated duration to scan this area of ~600Nm2 is approximately 10 days according to recent information provided by Ocean Infinity which was the last company searching in the field in 2018.

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[1] *MYT: Malaysian Time*

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

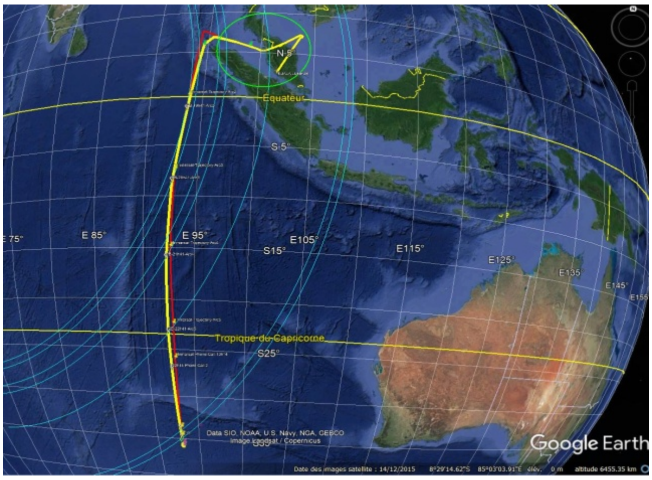

Figure 1: Reconstructed trajectory (Yellow) and Inmarsat example (Red)

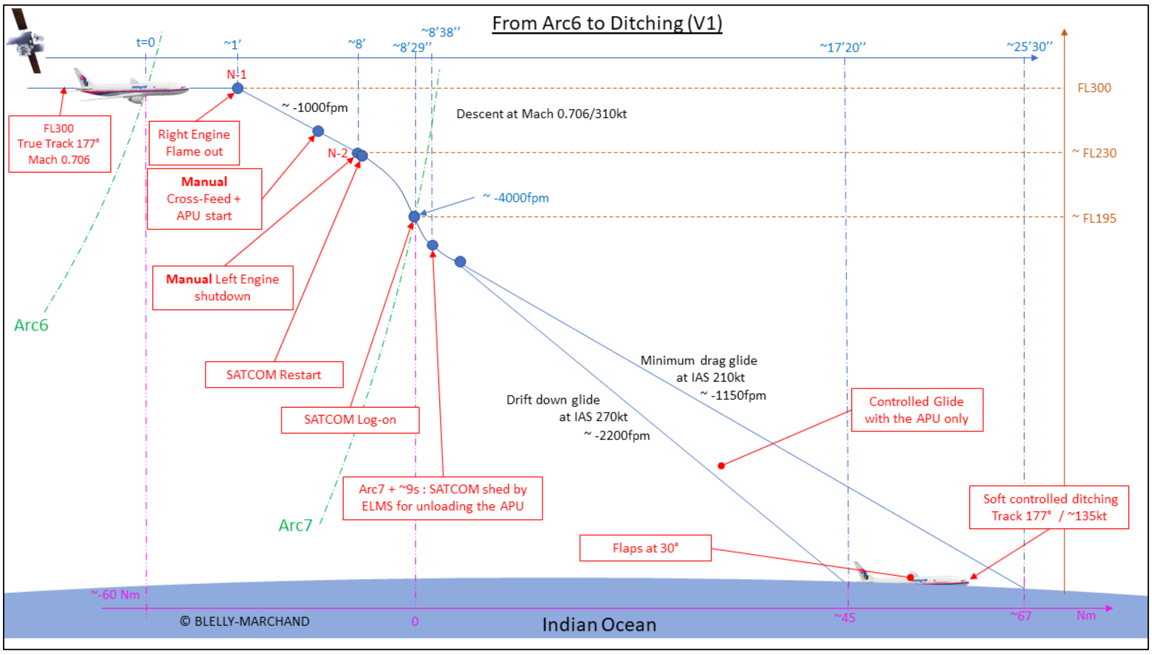

Figure 2: Scenario 1 of the probable final descent of MH370 with a glide

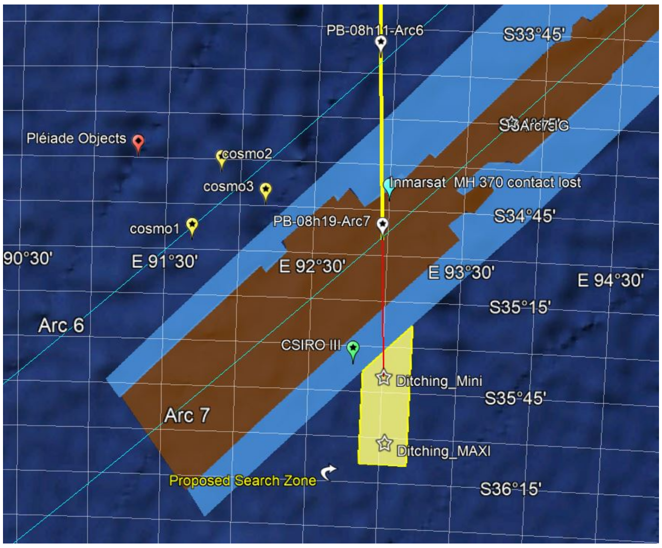

Figure 3: Proposed search zone (Yellow, ~600Nm²) and CSIRO III estimated Point of Impact

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1 Introduction

This paper presents the findings of a study focused on reconstructing the portion of the trajectory, which starts shortly before 02h22 MYT when the aircraft exited the Malaysian radar coverage. The previous portion of the trajectory does not need a specific aeronautical analysis. Thanks to the radar data it is almost certain that the aircraft overflew waypoint *VAMPI* located in the north-west of Sumatra. Then its radar blip was lost few minutes later after passing close to waypoint *MEKAR.*

Thus, to ease the understanding, the starting point of this analysis was chosen to be waypoint *VAMPI* as it is the last precisely known location of the aircraft with its timing at 02h13' MYT on March 8th, 2014:

1. Section one addresses the leg from passing waypoint *VAMPI* until the phone call of the ground at 02h40'. It includes a slow turning manoeuvre to the south which is commonly called FMT (Final Major Turn).
2. Section two details the reconstructed trajectory after the FMT which is almost a straight line to the south. The selected flight settings and characteristics are provided here.
3. Section three aims to identify the scenario of the final descent and the related actions performed by the pilot in command leading to a probable soft ditching creating a minimum number of pieces of debris.
4. Section four concludes on the characteristics of the identified zone where to search the wreckage and which is proposed as a viable candidate for future underwater search campaigns.
5. Finally, complementary and relevant elements are brought to attention in Section 5.

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

2 The « Final Major Turn[3] » (FMT)

Figure 4: The Final Major Turn (FMT) in the north-west of Sumatra: a succession of 2 light turns

Preamble

- Back to the first part of the flight and just after the U-Turn after IGARI, one should remember that the pilot in command (PiC) most probably performed several actions affecting the aircraft trajectory. The main actions would be: a probable descent to FL300 (~30000ft) and, following the loss of the electrical power, to leave the throttles untouched resting in their current position. This is in line with Boeing report [2]. Together, these actions led to a progressive increase of the ground speed up to 516kt. At ISA +14°, the Indicated Air Speed (IAS) would have been at ~310kt with possible peaks at 330kt.
- The PiC changed flight level down to FL300 because he knew that usually at this late time in the night in this region this level was not much used. In addition, this induced a higher ground speed as well as a less cold temperature inside the cockpit [1].
- In addition, the current high speed would have allowed him to exit the Malaysian radar coverage quickly in the vicinity of waypoint *MEKAR* after overflying *VAMPI*.

From *VAMPI* to the 1st Phone call from the ground at 02h40' MYT (cf figure 4):

- It appears that after overflying waypoint *IGARI*, *VAMPI* has been the last waypoint exactly overflown by the MH370. This implies a well-controlled navigation by the pilot in command to turn around FIR Jakarta (Sumatra Island) while staying outside the alert surveillance zone.
- From waypoint *VAMPI*, the route is found constant at 287° until about 02h29' MYT i.e. shortly after the bursts at 02h28' MYT. The identified trajectory passes slightly north of waypoint *MEKAR*. This is in accordance with the famous picture presented to the families at the Lido Hotel by the Malaysian authorities. Until about 10Nm after MEKAR, at 02h22' MYT, the

[3] *FMT: commonly used terminology to designate the manoeuvre to the south considered as the last turn*

estimated ground speed was ~516kt. This corresponds well with the loss of contact by Western Hill radar. Figure 4 sketches this manoeuvre.

- Clearly, the pilot in command aimed to turn around Sumatra as fast as possible and as discreetly as possible at the limit of mid-range radar coverage.
- Considering Inmarsat findings [3], a left turn has probably been executed at 02h29’ (or just after) towards waypoint POVUS approximately, possibly at the limits of Banda Aceh radar and avoiding entering Indian FIR Chennai. After the turn and considering the wind, the estimated ground speed would have slightly decreased down to ~503kt and still at ~310kt IAS. This gradual decrease of speed was probably due to a transition phase towards a stable flight at a constant Mach.
- At 02h40’ MYT which is the time of the first phone call from the ground to the aircraft, in the vicinity of waypoint POVUS, the ground speed (GS) is estimated at ~456kt.
- This helps identifying the approximate location of the aircraft at the time of this unsuccessful phone call (Cf. Table 4).
- From that moment, computations show that the estimated speed was basically constant all the way long to the south at a constant Mach of 0.706. The analysis presented in [1] demonstrates that this corresponds to an indicated speed (IAS) equal to 265kt at FL300. This could appear as a paradox, but it is not. Mach 0.706 is 5% lower that the Long-Range Mach and also well below the Maxi Range Mach. But most probably, by experience, the PiC took advantage of the correlation between the decrease of speed and the subsequent decrease of fuel consumption of the same amount (-5%). These effects produce a net result of the same flown distance as in the Long-Range mode but in a slightly longer time at no extra fuel cost in the absence of climb. During this particular flight and contrary to normal operational practices, the fuel was practically fully consumed at cruise level and no consideration of the descent is necessary as it glided. From a pilot experience, it is believed that the chosen mode was “Mach Selected” as no route input was possible in the FMC.
- Concerning the electrical power status, all facts during the leg starting at waypoint IGARI concur to conclude that it was switched off voluntarily in a reversible way. This would have triggered the deployment of the RAM Air Turbine (RAT) which satisfied the essential electrical power needs. Thus, the aircraft could have been piloted with the basics systems alone but with the full hydraulic power - still available at that time - from the running engines.
- In order to recover the full functionality of the systems, the PIC switched the electrical power back on at about 02h23’ MYT triggering the reboot of the SATCOM and its Logon request at 02h25’27 MYT according to the Inmarsat data. In order to maintain the aircraft “invisibility” and to avoid to be recognised by the ground, a “data link reset” has been completed just after the power was switched back On via the “com manager” followed by an “auto message off” command. These actions erased the Flight ID (which was missing in due places in the subsequent bursts) and also instantaneously blocked the sending of ACARS messages. Thus, no identification nor any exchange of information were possible anymore. Nevertheless, the SATCOM was still powered and continued to respond to the (almost) hourly handshakes initiated by the ground.

The details of the FMT are posted in Table 4.

Table 4: Detailed characteristics of the reconstructed trajectory during the FMT

Waypoint	longitude °	latitude °	longitude °	latitude °	True Track °	Ground Distance Nm	Wind kt	temperature °C	ISA °C	Air Distance Nm	Delta Time min s	Total Duration min s	Mach	True Airspeed kt	Ground Speed kt
VAMPI	97°35'01.00"E	6°10'09.00"N	97.5836	6.1692									0.845		
					287	68.5	14	-31	14	67	8'	-		502	516
MEKAR	96°29'05.00"E	6°30'02.00"N	96.4847	6.5006									0.832		
					287	10	14	-31	14	10	1'10"	-		502	516
02h22' *	96°19'46.41"E	6°33'31.83"N	96.3296	6.5588									0.832		
					287	18	9	-31	14	24.7	3'	3		494	503
Arc1 02h25'27"	96°02'24.37"E	6°39'01.23"N	96.0401	6.6503									0.814		
					287	22	9	-31	14	24.7	3'	6		494	503
Arc1.2 02h28'15"	95°41'13.35"E	6°45'22.48"N	95.6870	6.7562									0.814		
					287/223	81	9	-31	14	78.2	9'30"	15"30"		494	503
POVUS	94°39'55.80"E	6° 00'02.40"N	94.6655	6.0007									0.734		
					197	18	10	-31	14	18.6	2'30"	18"		446	456
Phone Call 1 02h40'	94°37'37.44"E	5°42'34.56"N	94.5771	5.7096	187								0.706		

* Time is given in Malaysian time (MYT)

3 The Southern Part of the Trajectory

3.1 Speed and Altitude Computation

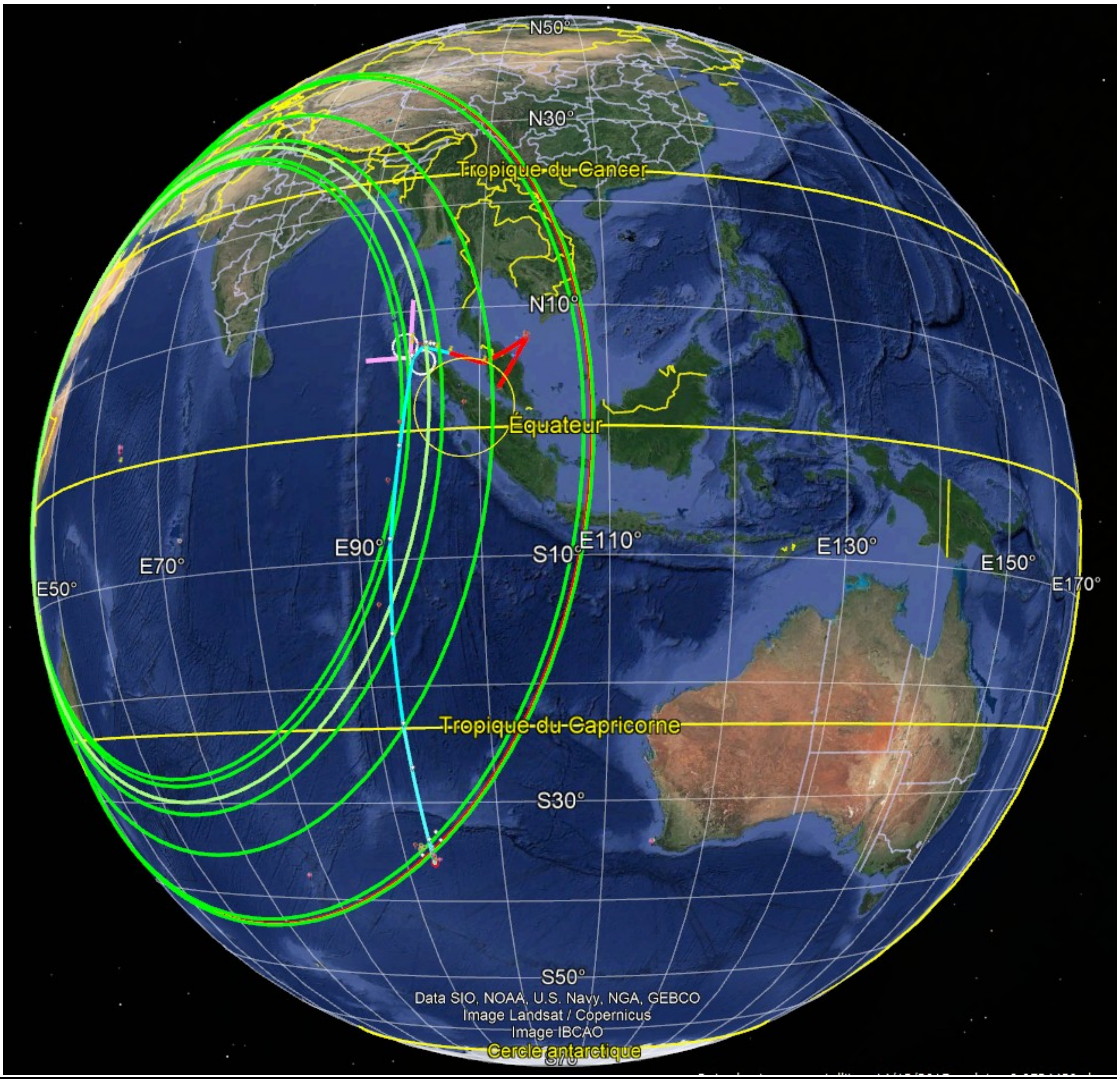

Figure 5: Southern part of the reconstructed trajectory (Cyan)

The first point of the southern part of the trajectory (we will also call it "Southern leg") is the location of the aircraft at 02h40' MYT when the 1st phone call took place. The last point is taken as the crossing point at Arc 6. This last point is specifically addressed in the next section where it is considered as the starting point of the final leg.

In order to reconstruct the southern part of the trajectory (illustrated in Cyan in figure 5), the following hypotheses were made and the following data was used:

1. At 02h28' MYT, the amount of fuel remaining on board has been officially evaluated by Boeing at 33524 kg.
2. An assumption is made here that a speed decrease took place (justified below in this report) from M0.814 at ISA +14° (M0.838 at ISA cf Boeing in [2]) within approximately 12 minutes before the phone call. During this time about ~1120kg of fuel was burnt when considering an averaged Mach and the fact that the engines were idle during approximately 1.5 minutes as experimented during simulations.
3. Thus, at 02h40 MYT, the amount of fuel remaining on board is estimated at ~32400kg.
4. Arcs have been precisely constructed per altitude using Inmarsat official reported data.
5. For that day, Meteo and wind data and temperature data for ISA correction have been used for FL300.
6. "Performance in flight" data of the B777-200ER powered by R&R Trent-892 engines has been used.
7. Corrections for the overall fuel overconsumption were applied as follows: +1.5% of perf factor (aging of the engines) and +1.2% due to a high temperature on that day based on an estimation of an average ISA +12° and following Boeing's recommendation to add +1% per 10° of extra ISA.
8. The flight time estimated by the ATSB between 02h40' MYT and the supposed flame out of the second engine – two minutes before the last logon request at 08h19'39 MYT – is 5h37'30"" i.e. 5.625 decimal. *Note: This is a starting working hypothesis as in our actual End of Flight scenario the logon request comes approximately ~30 seconds after the left engine manual shut down with the APU operating.*

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

1. The hourly consumption is equal to the average (33524kg – 1120kg) /5.625h = 5760kg/h. This represents the actual hourly fuel consumption on that day including the +2.7% of overconsumption coming from the two factors identified above.
2. At mid-term of the southern route i.e. ~05h28' MYT, the aircraft **average** mass is estimated at ~190.6 tonnes. For the sake of simplification, we will truncate this value down to 190t. The actual impact on the final result of the following computation is negligeable.
3. In Boeing's look-up table "performance Inflight Long Range" for the B777-200 ER, one has to look for the value 5760 kg/h for reference weight of 190t. Unfortunately, this entry does not exist nor does FL300 exist. Thus, a double cross-interpolation is required. A relevant extract of the lookup table is provided in figure 6 along with the details of the computation.
4. The interpolation results in 5904kg/h for Mach 0.743 in Long Range mode at FL300. In order to match the value of 5760 kg/h for 190t, one must deduce 5% and then add +2.7% because of the overconsumption (cf above) since the look-up table is provided for brand new engines at ISA.
5. Considering this result and reading the point -5% of fuel flow from the nominal point (1;1) on the curve "B777-200ER Cruise Mach, Fuel Flow, and Ratio of Specific Air Range to LRC Specific Air Range" given in figure 7, one can see that the ratio is also 1 at this other point. Thus at -5% fuel flow, the air range is identical to LRC range according to Boeing. On the abscise axis, one can read that the ratio of Mach to LRC Mach is 0.95 i.e. a 5% reduction.
6. Thus, applying this reduction to the speed, one can conclude that for FL300 the Mach number becomes M 0.743([4]) – 5% = M 0.706. It must be noted here that the corresponding computed air range value is in adequacy with the Mach of the MRC mode indicated par Boeing in table 4 of Appendix 1.6E [2].

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

FL300

WEIGHT (1000 KG)		PRESSURE ALTITUDE (1000 FT) 25	27	29	31	33	35	37	39	41	43
300	EPR										
	MACH										
	KIAS										
	FF/ENG										
240	EPR										
	MACH										
	KIAS										
	FF/ENG										
220	EPR										
	MACH										
	KIAS										
	FF/ENG										
200	EPR			1.048	1.068						
	MACH			0,745	0,772						
	KIAS			287	286						
	FF/ENG			3100	3098						
190t	FF/2xENG			6200	6196						
180	EPR			1.032	1.047						
	MACH			0,714	0,740						
	KIAS			275	273						
	FF/ENG			2834	2775						
	FF/2xENG			5668	5550						
160	EPR										
	MACH										
	KIAS										
	FF/ENG										

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

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

Figure 6: Extract of the look-up table from the FCOM - Long Range Cruise Control Trent 892 (Source PMDG and Airlines [5])

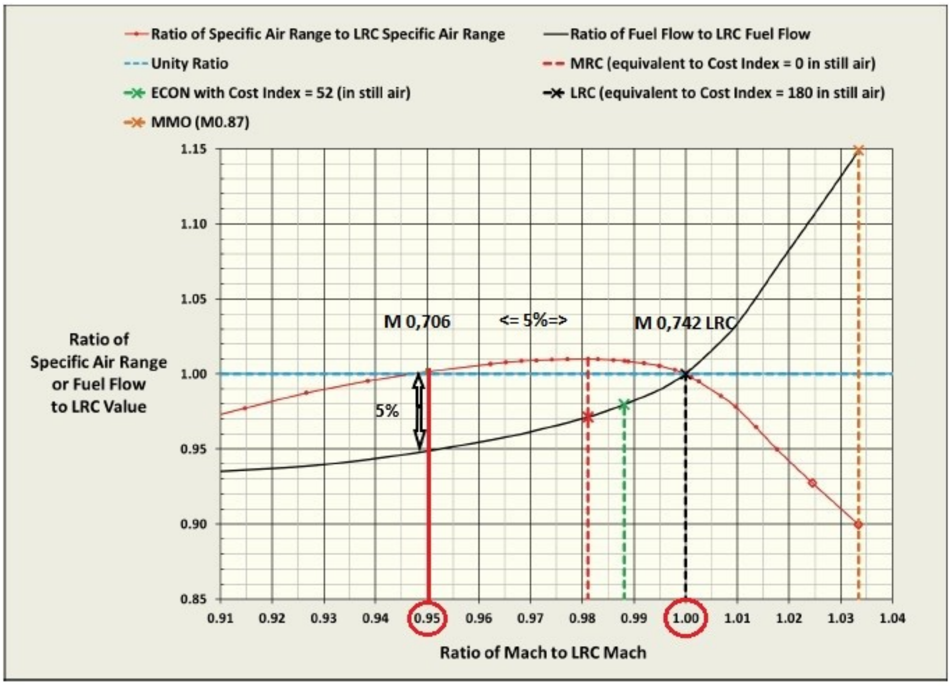

Figure A-1. B777-200ER Cruise Mach, Fuel Flow, and Specific Air Range

Figure 7: Specific consumption-distance for the B777-200ER (Source: Independent Group [6])

Under these conditions, one can conclude that the flight level was indeed FL300 with a Mach equal to 0.706 (i.e. IAS of 265kt) and that, during the southern leg of the trajectory, the hourly fuel consumption was indeed 5760kg/h in average.

3.2 Reconstructing the “Southern Leg”

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

1. From 02h40 to 03h41 (arc 2) = 61’ => TAS[5] = 429 kt, GS = 435 kt and Distance = 442 Nm. The great circle distance of 442Nm is “drawn” from the location of the 1st phone call at 02h40’ to intercept arc 2.
2. From 03h41 to 04h41 (arc 3) = 60’ => TAS = 429 kt, GS = 436 kt with distance = 436 Nm
3. From 04h41 to 05h41 (arc 4) = 60’ => TAS = 429 kt, GS = 440 kt with distance = 440 Nm
4. From 05h41 to 06h41 (arc 5) = 60’ => TAS = 428 kt, GS = 437 kt with distance = 437 Nm
5. From 06h41 to 08h11 (arc 6) = 90’ => TAS = 426 kt, GS = 419 kt with distance = 629 Nm

The detailed characteristics of the southern leg of the reconstructed trajectory are posted in table 9. Figures 1 and 5 graphically illustrate this southern leg.

Making an “aeronautical reading” of the data show that probably in the first place the pilot input a magnetic track reference at 187° on the MCP[6] and that later, somewhere south of the Tropic of Capricorn between 23°S and 25°S, he input a true track reference at 177° making the southern leg a quasi-straight line.

The initial selection of 187° magnetic heading is justified by the presence of adverse cumulonimbus clouds off the north-west coast of Sumatra as depicted in Figure 8.

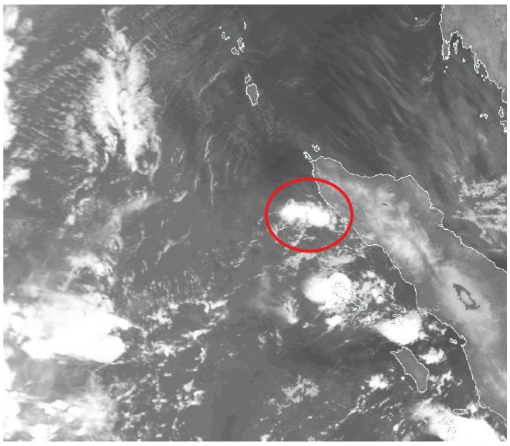

Fig. 8a

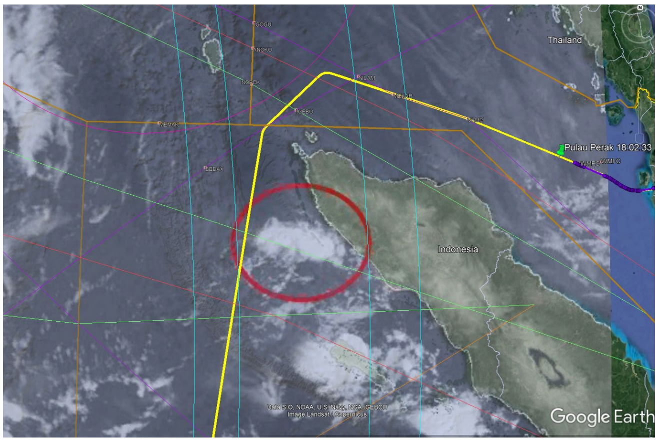

Fig. 8b

Figure 8 : Heading selection to avoid meteo obstacles when exiting the FMT

[5] *TAS: True Air Speed*

[6] *MCP: Mode Control Panel*

Table 9: Detailed characteristics of the "southern leg"

Arc MYT	Longitude °	Latitude °	Longitude °decimal	Latitude °decimal	True Direction °	Ground Distance Nm	Wind °/kt	Tempera-ture °C	ISA °C	Air Distance Nm	Delta Time h min s	Total Time min s	Mach	True Air Speed kt	Ground Speed kt
02h40'	94°34'37.44"E	5°42'34.56"N	94.5771	5.7096									0.706		
					187	442	023/6	-31	14	436	1h01'	1h01"		429	435
03h41' arc2	93°37'28.56"E	1°31'17.76"S	93.6246	-1.5216									0.706		
					187	436	050/10	-31	14	429	1h00'	2h01'		429	436
04h41' arc3	92°40'37.20"E	8°45'28.80"S	92.6770	-8.7580									0.706		
					183	440	000/11	-31	14	429	1h00'	3h01'		429	440
05h41' arc4	92°18'41.76"E	16° 7'25.32"S	92.3116	-16.1237									0.706		
					180	437	052/15	-32	13	428	1h00'	4h01'		428	437
06h41' arc5	92°22'33.60"E	23°24'29.88"S	92.3760	-23.4083									0.706		
					177	629	260/40	-34	11	639	1h30'	5h31'		426	419
08h11' arc6	92°54'2.16"E	33°54'50.04"S	92.9006	-33.9139									0.706		
					177	60	260/25	-41	8	60.5	8'30"			430	423
08h19'29" arc7	92°57'53.65"E	34°54'53.58"S	92.9649	-34.9149								5h39'30"	0.702		
					177									440	436
08h19'38"	92°58'07.22"E	34°56'29.49"S	92.9687	-34.9415									0.7		

3.3 Validation of the "southern leg" with Inmarsat data

The next necessary step is to answer the question: how does the reconstructed trajectory compares to Inmarsat data? Table 10 presents the detailed characteristics of the full reconstructed trajectory. To ease the comparison, the same format has been used as in Table 9 of Inmarsat paper [3] when presenting their example of possible trajectory. This level of details offers the possibility to better understand the different components of the offsets (the BFOs[7] in particular). Extra elements have been also included like the BTOs[8] as additional waypoints allowing a more accurate comparison.

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

In Table 10, one can see that the reconstructed trajectory complies with the two Inmarsat defined constraints: its BTOs are within the error margin of +/-50µs and its BFOs are within the error margin of +/- 7Hz. Thus, this makes it an acceptable candidate.

Please note that Table 10 does not include the BFO (-2Hz) of the last burst emitted by the SATCOM at 08h19:38 MYT. This peculiar case is addressed as a variant of the scenario presented in the next section. Its details can be found in Annex 1 of this report.

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

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

Table 10: Captain Blelly/Jean- luc Marchand's Reconstructed Flight Path Results (same formatting as Table 9 in Inmarsat report)

Reconstructed Flight Path Results (ref. Inmarsat paper Table 9)																				
									Δ Fup						Total Burst Freq. Offset BFO (Hz)			Burst Time Offset BTO (μs)		
	Time UTC *	Lat°N	Lon°E	Altitude (100ft)	True Track (°ETN)	Speed (kt)	Speed (km/h)	Vertical Speed (fpm)	Aircraft (Hz)	Satellite (Hz)	Δ F down (Hz)	δ f comp (Hz)	δ Fsat + δ AFC (Hz)	δf bias (Hz)	Pred.	Meas.	Error	Pred.	Meas.	Error
Nominal-1-Inmarsat	16:30:00	2.70	101.70	0	0	0	0	0	0	-6	-84	0	29	150	88	88	0	14893	14920	27
Nominal-2-Inmarsat	16:42:31	2.80	101.70	20	333	235	435	1200	194	-6	-80	-180	27	150	130	125	-5	14931	14900	-31
Nominal-3-Inmarsat	16:55:53	4.00	102.20	280	25	461	854	1500	-424	-4	-75	453	25	150	155	159	4	15212	15240	28
Nominal-4-Inmarsat	17:07:19	5.30	102.80	350	25	468	867	0	-461		-71	488	24	150	130	132	2	15587	15660	73
Arc1	18:25:27	6.65	96.00	300	287	503	932	0	774	-1	-37	-761	10	150	136	142	6	12560	12520	-40
Arc1.2	18:28:15	6.76	95.69	300	287	503	932	0	769	-1	-36	-755	10	150	137	143	6	12430	12480	50
Phone Call 1	18:40:33	5.71	94.58	300	187	428	793	0	165	-2	-30	-203	8	150	89	88	-1	11910	N/A	N/A
Arc 2	19:41:03	-1.52	93.62	300	187	435	806	0	11	-1	0	-51	-2	150	108	111	3	11520	11500	-20
Arc 3	20:41:05	-8.76	92.68	300	185	436	807	0	-169	6	29	130	-2	150	145	141	-4	11750	11740	-10
Arc 4	21:41:27	-16.12	92.31	300	182	440	815	0	-364	17	56	331	-18	150	171	168	-3	12820	12780	-40
Arc 5	22:41:22	-23.41	92.38	300	179	437	809	0	-533	30	78	508	-29	150	204	204	0	14560	14540	-20
Call 23h14	23:14:30	-27.22	92.55	300	177	419	776	0	-590	38	88	570	-33	150	224	217	-7	15700	N/A	N/A
Arc 6	00:11:00	-33.91	92.90	300	177	413	765	0	-681	50	100	670	-37	150	252	252	0	18040	18040	0
Arc 7	00:19:29	-34.91	92.96	195	177	433	783	-4000	-782	52	102	701	-38	150	186	182	-4	18430	18400	-30

* UTC = Malaysian Time – 8h

Figure 11 replicates Figure 9 of Inmarsat paper [3] for comparison. The red plot represent Inmarsat data as provided by Inmarsat in [3]. The blue curve represents the computed estimation of the BFOs of the reconstructed trajectory. The matching is very good as the standard deviation of the BFORs is σ ~3.9Hz. Furthermore, when considering the available extra BFOs (like the one we name Arc-1.2 for example) which are not usually considered by the other studies the BFOR σ becomes ~4.3Hz.

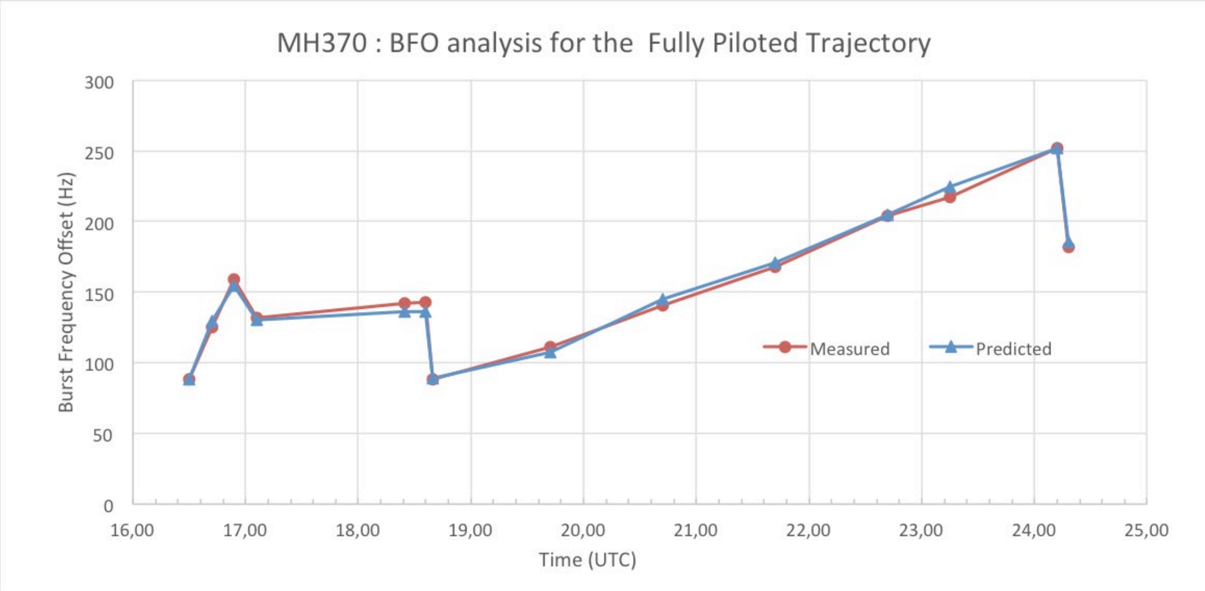

Figure 11: Comparison of Inmarsat BFO versus Captain's Blelly trajectory BFO (BFOR σ ~3.9Hz)

The comparison of the reconstructed trajectory with Inmarsat's example is presented in figure 12. Their similarity between arc 2 and arc 6 is striking. Nevertheless, the arc crossing points are different except those at arc 7 which are very close i.e. only 10Nm apart.

However, Inmarsat's final major turn (FMT) is wider and is located ~75Nm further to the northwest compared to the turn found here. The difference is explained by a greater average speed as well as a higher altitude in Inmarsat example.

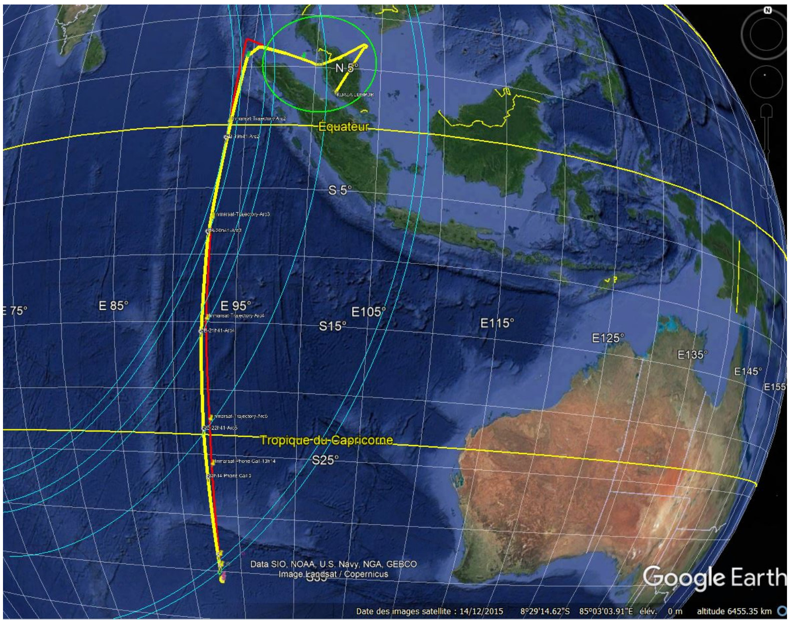

Figure 12: Trajectories comparison - the reconstructed trajectory (Yellow) and Inmarsat example (Red) (source Inmarsat)

4 The Final Descent to the End of Flight

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

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

1. The hypotheses and the required basic parameters are:
   1.1. The shortest straight-line ground distance between arc 6 and arc 7 is 60 Nm flown by the aircraft in 8’30”.
   1.2. The top of descent was at FL300 at Mach 0.706 with both engines running
   1.3. At the arc 6, the Inmarsat handshake was complete and normal.
   1.4. At the arc 6, the ground speed was GS=413 kt at ISA +4° (which increased to ISA +8° at sea level)
   1.5. The wind decreased from 260°/40kt towards 235°/25kt at lower flight levels
   1.6. At the arc 6, the quantity of fuel is estimated at about ~800 kg.
   1.7. The true track at 177° was kept from the top of descent to sea level
   1.8. In this method, the computations actually consider the crossing point of arc 7 as the starting reference location for measuring distances. This is where the logon request to the Inmarsat network was made within approximately 30 seconds following the power switch off. It occurred due to a “break power transfer” which automatically triggered a reboot followed by a logon request. It is assumed that the OCXO[9] of the SATCOM did not cool down in such a short time.
   1.9. Going backwards from the arc 7 to the arc 6, the average speed could be computed taking into account the auto pilot automation and the management of the remaining fuel.
   1.10. The hypothesis is made that ***the pilot in command managed to keep the necessary quantity of fuel for the APU until touch down thus keeping all control surfaces operational for a well-controlled gliding descent*** and ensuring a full flaps configuration for a controlled ditching.

2. The different steps of the descent are sketched in figure 13. By setting a reference initial time at T_0=08h11’ MYT, they can be detailed as follows:
   2.1. T_0= 0’: at arc 6, both engines were running and the SATCOM answered the satellite ping. The remaining fuel is estimated at ~800kg. It was not evenly balanced between the tanks because the right engine was more consuming than the right one. At this point in time, the total fuel consumption of both engines was about 88kg/min i.e. 5280kg/h according to Boeing fuel performance table for the B777-200ER with a mass of 175t.
   2.2. T_1=+1’: at about +1 min, the right engine flamed out because of a shortage of fuel in the right tank. This is illustrated by the “N-1” tag in figure 13. Thus, from this moment and for all aircraft systems, the power was supplied by the left engine only. Subsequently the auto pilot and the flight director were still functioning and available to the pilot who most likely kept the “Mach selected” mode active (it was being used in cruise until now). Thus, during the coming descent, the IAS will progressively increase and stay at 310kt which is the speed limit imposed by the flight envelop. The only reference setting input made by the pilot on the MCP for the A/P was a constant reference vertical speed value of V/S=-1000fpm. As a consequence, the TAS is estimated around ~430kt when the aircraft crossed FL210. This basically confirms that the aircraft did fly 60Nm in 8’30’’ with an average ground speed of 423kt, wind considered. A key element to keep in mind is that the aircraft accelerated, which is only

[9] *OCXO: Oven Controlled Crystal Oscillator*

possible if the "Mach selected" mode is active. At a rate of descent of ~-1000fpm, the consumption of the unique running engine is estimated at ~71kg/min i.e. ~4300kg/h.

2.3. At the beginning of the descent after the right engine flame-out, ***the pilot started the APU and opened the fuel cross-feed valves*** to be able to use all of the remaining fuel and to dry out the tanks (the aircraft was descending with a negative pitch with a small quantity of fuel).

2.4. T_2 = +8'00": close to FL230/FL225 **the left engine was voluntarily manually stopped** as illustrated by the "N-1" tag in figure 13. Thus, the aircraft started gliding with a slight increase of the pitch. At this point, either by surprise or in a short period of inattention, a short lack of pitch control increased the vertical down speed during few seconds up to ~-4000fpm. This would have led the aircraft down to ~FL195 (19500ft).

2.5. T_3 = +8'29": Logon request from the SATCOM producing an estimated BFO of 186Hz compared to Inmarsat measured 182Hz. Remember that following the left engine cut-off few seconds ago, no more power was available to the left AC bus which powers the SATCOM. Thus, the APU – the sole remaining source of power – took over from the left engine and powered the left AC bus in addition to the right AC bus. This left AC bus power Off/On sequence induced a power-off/power-up of the SATCOM automatically leading to a logon request initiated at T_3.

2.6. T_4 = +8'38": within the 9 seconds after T_3 the SATCOM logon to the network was properly completed according to the protocol. But, contrary to the previous logons, no other airborne system could logon subsequently and in particular the IFE[10]. This leads to conclude with confidence that the ELMS (Electrical Load Management System) shed the low priority utility buses and loads for dedicating the power to the high priority systems like the demanding pumps providing the hydraulic power to the control surfaces. Subsequently the SATCOM was shed to avoid overloading the APU which was the sole source of power operating at that time.

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

2.7. T_5 = +8'40" and later: The pilot could have used one of the two procedures he had been probably trained for:

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

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

2.8. The minimum crash zone coordinates are: **-35.6650° S and 93.0130° E**

2.9. The maximum crash zone coordinates are: **-36.0269° S and 93.0364° E**

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

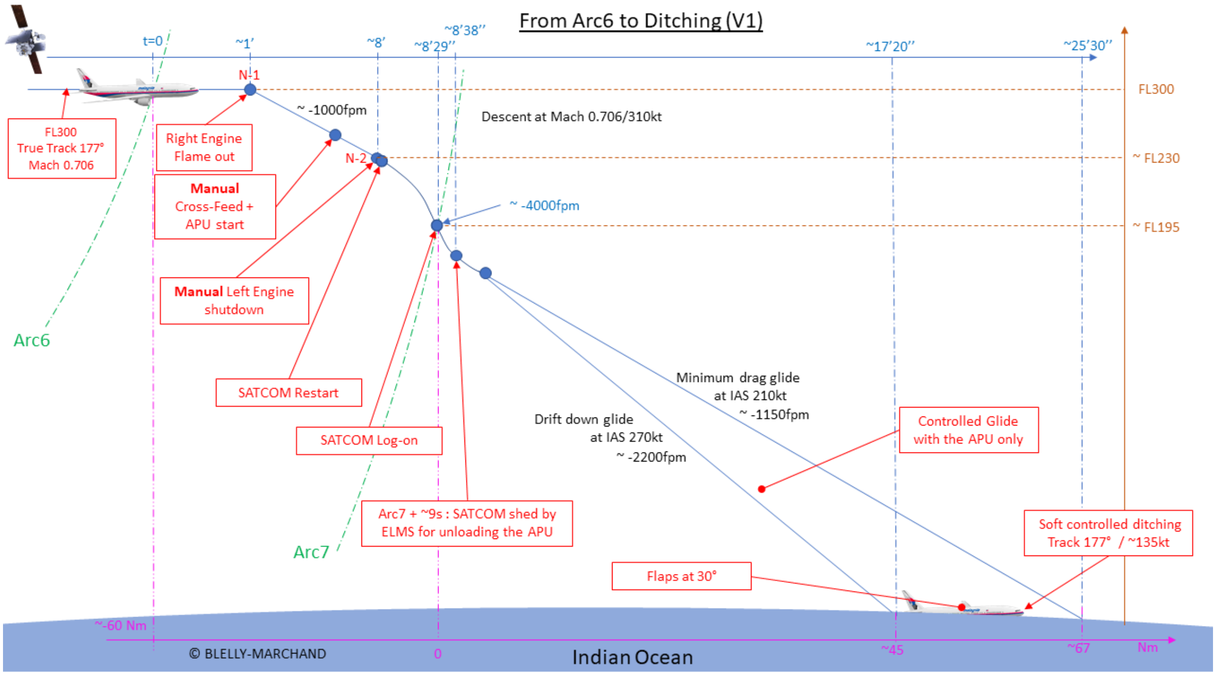

Figure 13: Considered end of flight scenario (Blelly-Marchand) – Variant 1

Figure 14 sketches the location of the northern and southern points which have been determined in function of the arc 6 and the arc 7.

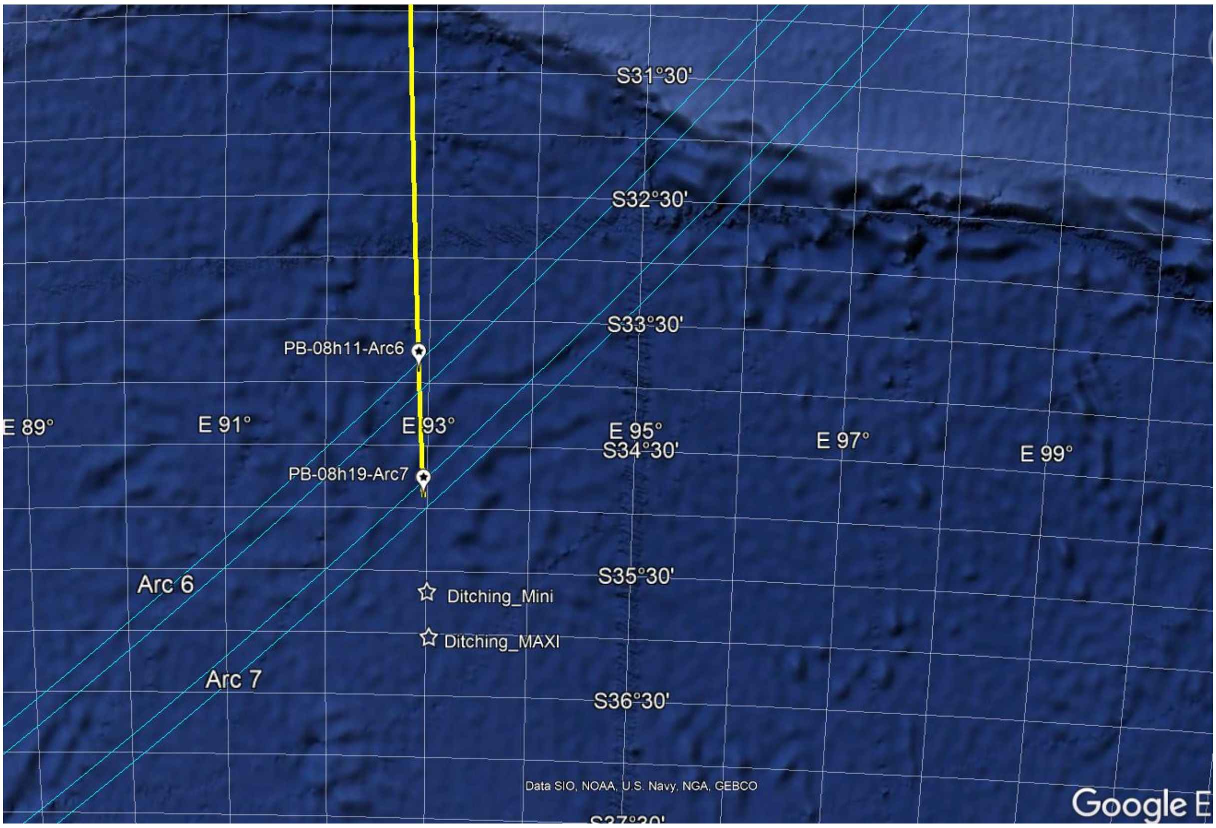

Figure 14: Estimated northern and southern locations of a controlled ditching (white stars)

5 The proposed new search zone

Not far from the identified locations of the potential ditching, two under-water search campaigns have covered areas on both sides of the arc 7 as illustrated in figure 15 in Brown (Fugro) and in Blue (Ocean Infinity). They have been unsuccessful because we think that the very good gliding capability of the plane had not been considered nor the possibility that a pilot was still in command.

The proposed new search zone is depicted in Yellow in figure 15. It is 14 Nm wide trapeze shape prolongating the already scanned zone to the south by ~37 Nm. The zone includes a contingency margin of ~7Nm on each side of the true track of 177° and on the southern limit to cover the case where the aircraft could have deviated slightly. This search zone is valid for both End of Flight scenarios presented in this report.

The proposed new search zone surface is estimated of ~600 Nm^2 approximately. It is small compared to the potential search zone of 10 000 Nm^2 envisaged by Ocean Infinity (sketched by the two Orange rectangles in figure 15) during a future 100-day campaign in 2023 or 2024. According to this daily rate, the proposed search zone would be scanned in less than 10 days.

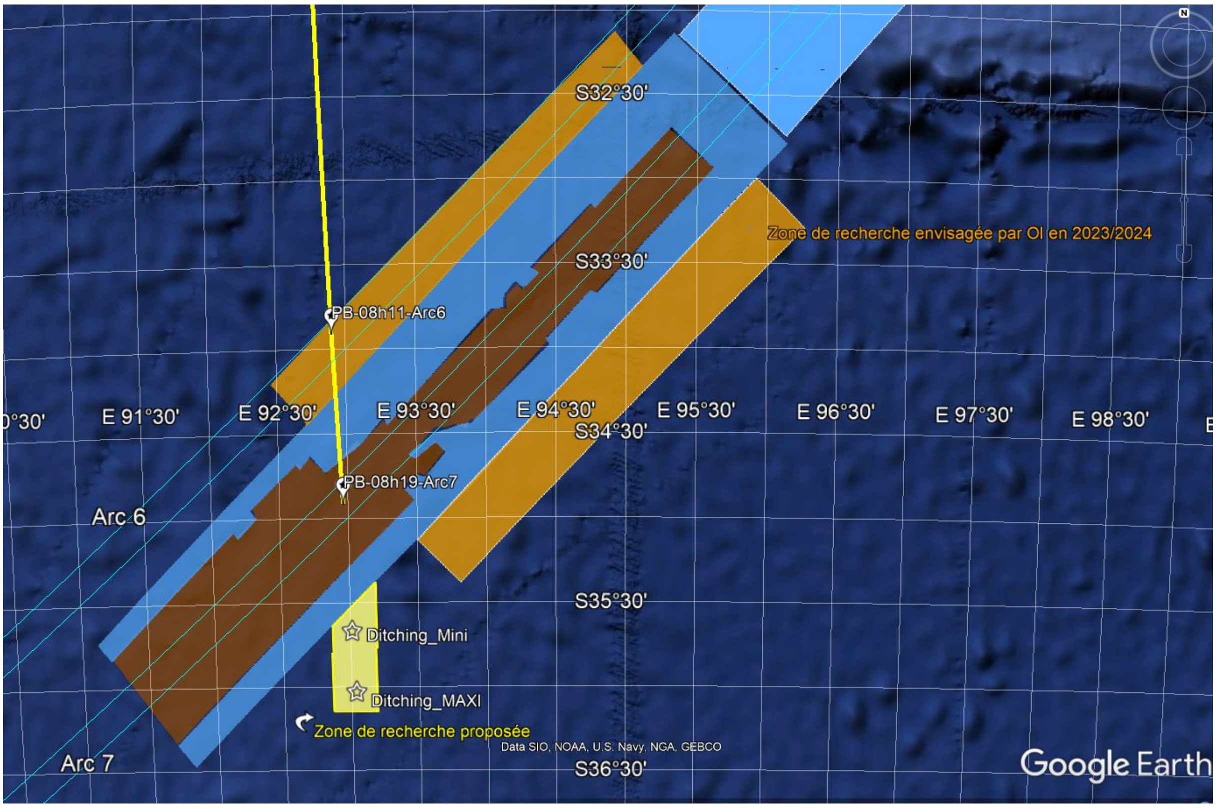

Figure 15: Proposed new search zone (Yellow area) potentially covered in less than 10 days

6 Additional elements of interest …

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

The first element comes from the report on the analysis of the "optical" images captured by the French satellite PLEIADES 1A on 23 march 2014 [4]. From these images, a set of approximately 12 objects were identified as "possibly man-made". All of these objects include a top surface of 20 m^2 or larger. Their geographical location is pinpointed as "Pléiades objects" in figure 16. This is in coherence with the results of one of the drift studies from the Australian organisation CSIRO (CSIRO report III).

In addition, Italian satellite COSMO-Skymed provided Synthetic Aperture Radar (SAR) data acquired on 21 March 2014. The geographical location of the objects identified as "possibly man-made" is illustrated by CosmoX tags in figure 16.

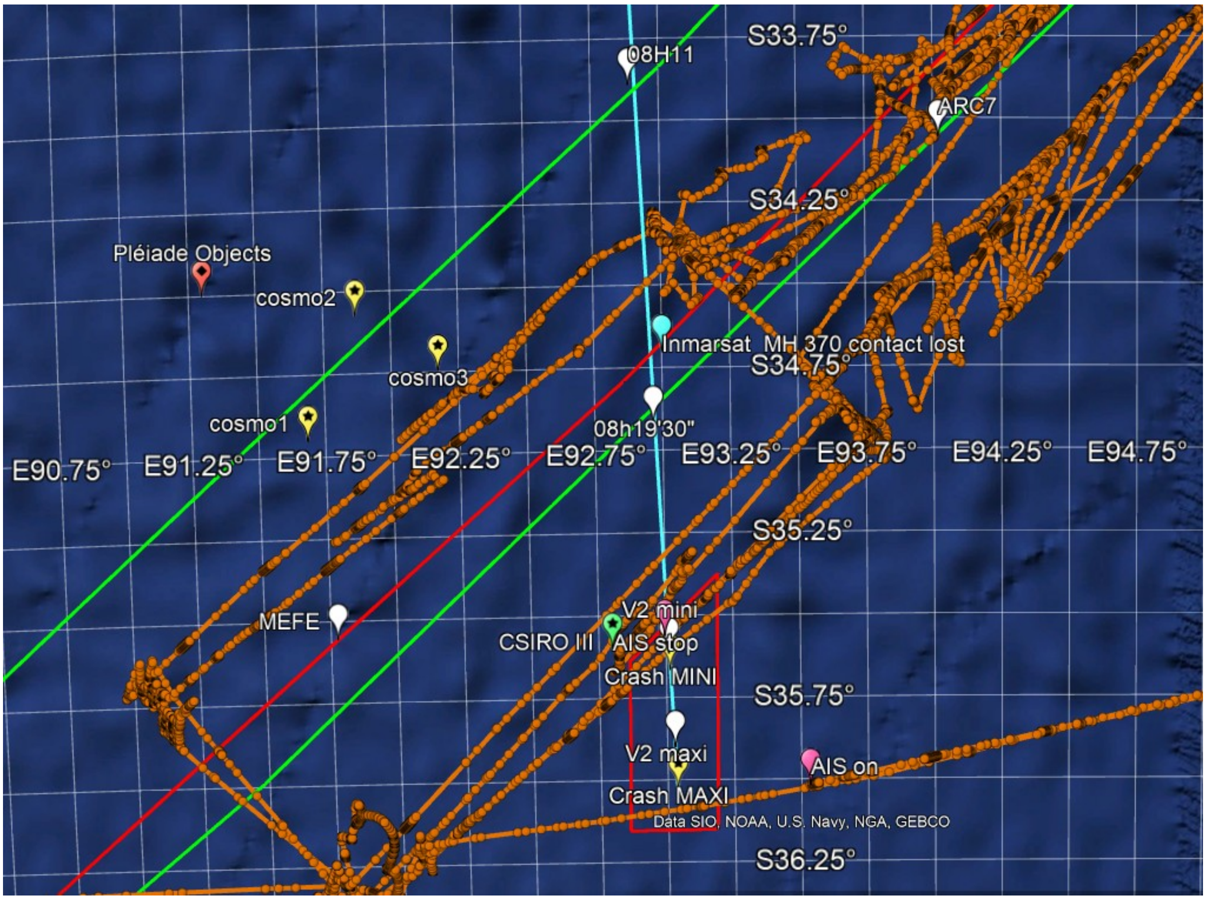

Figure 16: Additional elements of consideration in the vicinity of the ditching location (Pléiades, Cosmo, CSIRO, AIS …)

Annex 1: Variant 2 of the End of Flight

At 08h19:29 MYT the arc 7 exists because the SATCOM of the aircraft sent a burst requesting the logon to the Inmarsat network. This provided the arc 7 BTO/BFO doublet. In the few seconds that followed, the logon procedure proceeded normally with the expected second burst from the SATCOM at 08h19:38 MYT but providing a measured BFO of -2Hz.

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

If one considers a human presence in the cockpit, there is another possibility which is envisaged here and sketched in Figure 17. The small number of found debris and their type lead to conclude that the aircraft did not violently crashed into the water at a high speed. Otherwise, it would be similar to crashing into a concrete wall spreading thousands of pieces around. In our view, it is perfectly possible that after the start of a dive – being it voluntarily or involuntarily – the pilot recovered very quickly. The voluntary cut-off of the last running engine (the left one) and the management of the subsequent events in the cockpit might have triggered this temporary dive. For example, computations show that if the aircraft dove during 10 seconds shortly before the arc 7, the recovery manoeuvre sketched in figure 17 would last 50 seconds with a flown distance of 6 Nm. Then a descent would take place similarly to the one described in Variant 1 and recalled in figure 18.

The noticeable difference between the End of Flight Variants 1 and 2 is the estimation of the minimum and maximum distances flown by the aircraft. The minimum distance in Variant 2 would be ~42 Nm while the maximum would be ~59 Nm. These would be ~45 Nm and ~67 Nm respectively in Variant 1 as posted in figure 18.

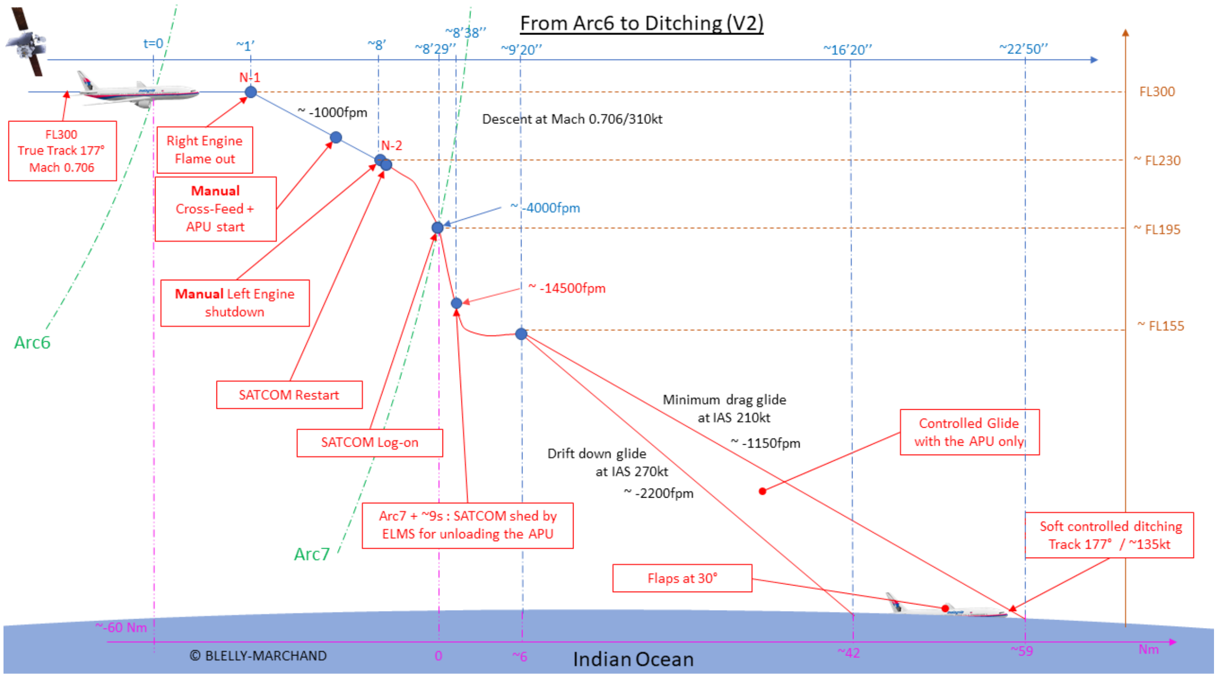

Figure 17: Variant 2 of the end of flight including a dive followed by a quick recovery (Blelly/Marchand)

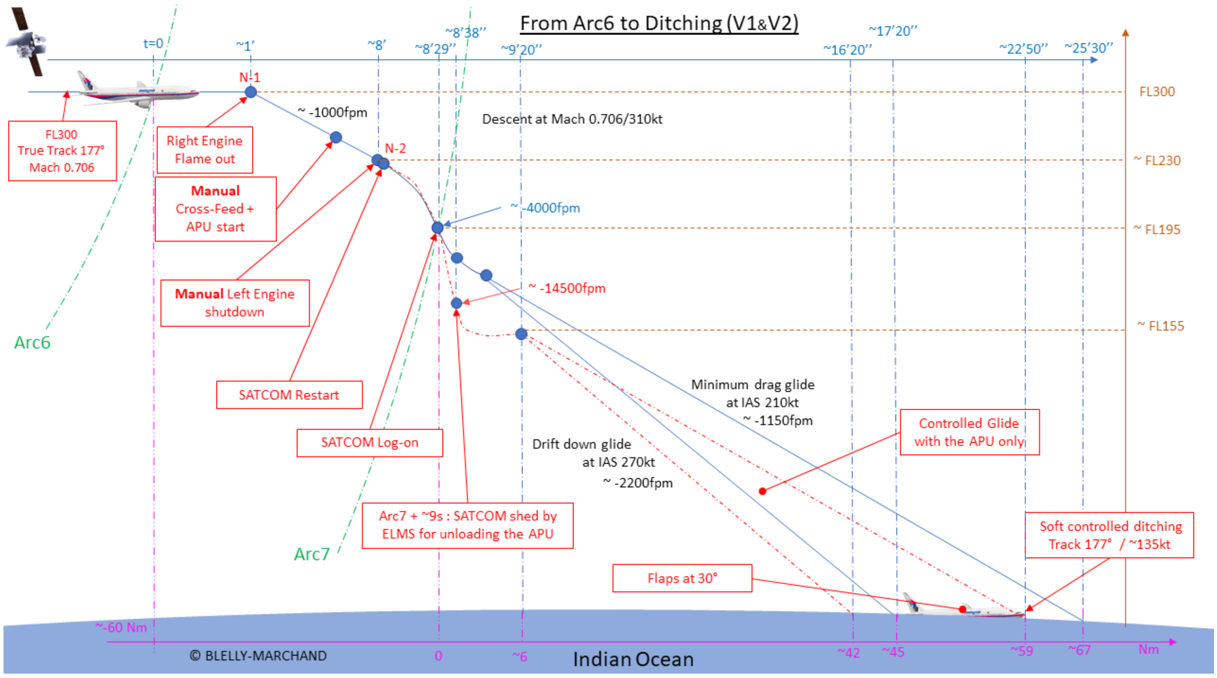

Figure 18: Synopsis of the End of Flight scenario (Variants 1 & 2)

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