Further Analysis of Simulator Data Related to MH370

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Introduction

Recently, the MH370 Independent Group (IG) released a preliminary assessment of data recovered from Captain Zaharie Shah's home computer that were related to the Microsoft Flight Simulator (MSFS) game [1]. The data are in the form of fragments of "flight files", which a user may create during a game to record the state of a game for future reference or to resume play at a future time. The particular flight files of interest were one of hundreds found on the computer on several drives; however, the files of interest were deleted and later recovered by investigators from a "shadow volume" on a single drive that was found disconnected from the computer. This makes the set unique among all the flight files found.

The flight files recovered include flight and navigation parameters that are "snapshots in time" and are associated with six coordinates. Flight parameters derived from the raw data from the simulator are presented in Table 1 [1]. If these coordinates were all from a single simulation, it suggests that a user created a simulation of a flight of a B777-200LR aircraft with a departure from Kuala Lumpur International Airport (KLIA), a flight up the Malacca Strait, a turn to the south, and a termination in the Southern Indian Ocean near 45S 104E. It was also found [1] that if a great circle path that connects the final points is extended past the final point, the great circle would cross the McMurdo Station, Antarctica. (McMurdo is the largest and most populated research station in Antarctica.) This raises the possibility that McMurdo was used as a waypoint in the simulation with the understanding that there was insufficient fuel to reach it. In a subsequent paper [2], the McMurdo waypoint was used to reconstruct a path that also satisfies the available satellite and radar data. By combining all these data sets, the predicted terminus for the flight path was estimated to be 26.9S, 100.6E, which falls outside of the current search area. This flight path is shown in Figure 1, together with the flight path defined by connecting the points found on the captain's simulator.

In this paper, we present further findings regarding how the simulation might have been created by a user. We also present more evidence that deleted data sets recovered from the captain's computer were from the same simulated flight.

The list of parameters included in each flight file is long. An abbreviated list can be found in Table 2, where we have rounded some of the values for convenience. Here we refer to the identification of each data set by its latitude, i.e., as 2N, 3N, 5N, 10N, 45S1, and 45S2, where the position for data set 2N is Runway 32R at KLIA. Each data set has an associated coordinate number that was assigned by investigators. There were two other data sets found on the captain's computer showing the aircraft parked at KLIA. One (Coordinate 6-2) had all the available aircraft tanks, including the left and right auxiliary tanks, fueled to 100%. The other (Coordinate 7) had the four side tanks (main and auxiliary) fueled to 80.3% and center tank at 0%. As these fuel levels were not consistent with the levels for data set 3N (Coordinate 1), these data sets are not analyzed here. These levels might have been intermediate values before the final values were selected and the simulation was initiated.

<u>Recreation of Simulated Flight</u>

When the captain's computer was recovered, there were several drives with different versions of Microsoft Windows and Microsoft Flight Simulator installed. It was previously reported [1] that the deleted flight files were created using FSX, as FSX is referenced extensively throughout the Malaysian police report. In fact, the aircraft model used in the simulation was a "PSS Boeing 777-200LR No VC", which refers to an aircraft model developed by Phoenix Simulation Software, now known as BlackBox Simulation. This aircraft model is only available for Flight Simulator 2004, also known as FS2004 and FS9. (The "No VC" designation refers to a version of the model that doesn't use a "virtual cockpit"', which was probably chosen because the captain used external hardware and additional monitors for pilot inputs.) The turbine engines in the model are two GE-90s. In order to reproduce how the user might have created the simulator data, we created new simulations using FS9 and the PSS 777-200LR aircraft model.

The position coordinates in Table 1 suggest a flight that departs from KLIA, proceeds up the Malacca Strait towards the Andaman Sea, and then turns with a 20-deg left bank towards the south and terminates with fuel exhaustion in the Southern Indian Ocean. Although the coordinates do not correspond to standard named waypoints, we have recreated the approximate path from the following series of waypoints: WMKK, AGOSA, GUNIP, TASEK, VAMPI, MEKAR, NILAM, IGOGU, LAGOG, DOTEN/-30, NZPG, where the designation DOTEN/-30 refers to a fix that is 30 nm before the waypoint DOTEN. The flight path following the waypoints as well as coordinates from Table 2 are shown in Figure 2. For the recreated flight, the Flight Management Computers (FMCs) were programmed using a Control Data Unit (CDU). The recreated flight path was flown using LNAV and VNAV (lateral and vertical) navigation modes with a Cost Index (CI) of 85. The weather conditions were selected as "Clear Skies", which effectively sets the atmosphere to standard conditions with no wind. As the aircraft consumed fuel, a stepped climb profile was followed to a flight level of FL400 (pressure altitude of 40,000 ft).

The stabilizer trim (called ElevatorTrim in the flight files) allows the determination of the indicated airspeed (IAS). At 3N and 5N the values recorded match an IAS of 280 kn. This would be the VNAV climb speed of a Cost Index (CI) of 0 as implemented in the PSS FMC. CI=0 gives maximum range, but at a lower speed. At 10N at FL 400 and 20-deg bank angle, there is a high consistency with the stabilizer trim at Mach 0.806, which is the ECON cruise speed at CI=0. It is therefore possible that the choice of CI=85 for the reconstructed flight was slightly less fuel efficient than what the user had selected.

Weight and Fuel Consumption

The recovered data in Table 2 suggests that the aircraft was fueled so that the left and right tanks were at 100% and the center tank was at 15%, where the levels are expressed as a fraction of the tank capacity. The actual fuel quantities are not listed in Table 2. However, we can infer the fuel quantities by observing that in the configuration file for this aircraft model, each side tank on the left and right side tank is assigned a capacity of 9,300 gal (35,204 l) and the center tank is assigned a capacity of 26,100 gal (98,799 l). Using a fuel density of 0.803 kg/l, the capacity of each side tank is 28,263 kg and 79,319 kg for the center tank. Therefore, the total fuel when the aircraft was positioned on the runway before takeoff was 68,424 kg (150,714 lb). We assume the zero fuel weight (ZFW) was 179,886 kg (396,225 lb), which is the default value for the aircraft model, resulting in a takeoff weight (TOW) of 248,310 kg (546,938 lb).

During the course of the recreated simulation, the program was stopped as the aircraft was close to the coordinates for each of the recovered data sets and flight files were created and saved for later analysis. The fuel at each location is shown in Table 3 for the recovered flight files as well as for the recreated flight.

Figure 3 shows the remaining fuel plotted versus the distance traveled along the flight path for the recovered data sets and the recreated flight. The slope of the line between the data points represents the average fuel efficiency, expressed as kilograms (kg) of fuel consumed for each nautical mile (nm) of that flight segment. We observe that:

- From the departure at KLIA to point 3N, the recovered data and the recreated flight show similar fuel consumption.
- For the segment between 5N and 10N, the fuel efficiency for the recovered data was 2.8 kg/nm, while that for the recreated flight was 14.4 kg/nm. This suggests that during this segment, either the user positioned the aircraft forward along the path, or fuel was added.
- For the segment between 10N and 45S1, the fuel efficiency for the recovered data was 18.5 kg/nm, while that for the recreated flight was 13.8 kg/nm. This suggests that fuel was removed by the user during this segment, reducing the range and leading to fuel exhaustion at 45S1.
- In the recreated flight, the aircraft flew an additional 449 nm past 45S1 before the tanks were empty.

Manual Changes to Flight Parameters During Simulated Flight

Using the fuel data from the recovered flight files as evidence, we can confidently say that flight parameters were changed during the course of the simulation. There is other information embedded in the flight dynamic variables that provide additional clues about what changes were made.

First, we need to briefly describe how velocity is recorded in flight files in FS9. The velocity is reported in both the "body coordinate system" and the "world coordinate system" [3]. By definition, in the body coordinate system, the X, Y, and Z axes are orthogonal; the Z-axis is parallel to the longitudinal axis of the fuselage and represents the forward-back axis; the Y axis represents the up-down axis; and the X-axis represents the left-right axis. For the "world coordinate system", the Z axis is along the true north direction; the X axis is along the true east direction; and the Y axis is along the up-down axis. The two coordinate systems are related through a series of Euler rotations. For instance, knowing the pitch, bank, and heading allows the transformation from world coordinates to body coordinates.

The sign convention in MSFS (and verified by testing) is that a positive value of pitch is down and a positive value of bank is to the left (left wing down, right wing up). For the turn rate variable HVelWorld, a positive value indicates increasing values of heading, i.e., to the right. Therefore, for an aircraft in a stable turn, the sign of the bank angle and HVelWorld are opposite. This can be seen in Table 2 for data sets 10N, 45S1 and 45S2.

When we look at the values in Table 2, we observe that for data sets 3N, 10N, 45S1, and 45S2 (but not 5N), all of which were created when the aircraft was airborne, the speeds as reported in the body coordinate system have XVelBodyAxis = YVelBodyAxis = 0, and the values of ZVelBodyAxis are non-zero. This means that the aircraft body is aligned perfectly with the flight path, and the angle of attack, relative to the body, is zero.

In MSFS, the flight characteristics of an aircraft model (in this case, the PSS 777-200LR), are embedded in model-specific configuration files [3]. By studying the parameters that describe the performance of the wing, and in particular, the parameters that describe the relationship between the lift coefficient and the angle of attack, we determined that positive lift is generated for angles of attack greater than -4.2°, where the angle of attack is defined relative to the body axis of the aircraft.

Now, since lift is generated for angle of attacks greater than -4.2°, even at an angle of attack of zero, lift is generated, and therefore it is possible that the aircraft was stable at this attitude. However, what is interesting is the angle of attack is EXACTLY zero for multiple data sets, which would be very unlikely. This led us to suspect that the variables in the recovered flight files represented something different than the MSFS documentation might suggest.

Much time was spent trying to find the conditions for which the variables stored in the flight files might show the body perfectly aligned with the flight path. This included the investigation of flight files that were both manually and automatically created. Finally, we succeeded in finding the sequence of operations in FS9 that produced saved values of XVelBodyAxis and YVelBodyAxis equal to zero. The steps are:

- Pause the simulation (e.g., press the "P" key).
- While paused, change one of the values listed in the Map window under the World menu item. The list of values that could be changed are indicated airspeed (IAS), heading, altitude, latitude, and longitude. After making the change, the value can be returned to the original value, if desired.
- While still paused, create a flight file.

Figure 4 shows a representative Map window and the parameters that may be changed by the user during a flight simulation session.

After following this specific series of operations, the values before and after the change in flight parameters are related in the following way:

- The new values of pitch, bank, and heading are the same as the old values. If the heading is manually changed, the flight file reflects the changed value.
- The new value of altitude is the same as the old value. If the altitude is manually changed, the flight file reflects this changed value. However, the new value of altitude above ground level (AGL) remains the same as the old value.
- If the new values of latitude, longitude, altitude, heading or speed are manually typed into the map fields, the seconds of the latitude and longitude coordinates are (approximately) rounded to the nearest 0.01 minutes when the map is closed. The plane then changes its position by some meters. The rounding does not happen if the plane symbol is dragged to a new position.
- The new airspeed is different than either the old airspeed or the new selected airspeed. For the standard atmosphere, there is an increase in airspeed that is a function of altitude (it may be that the increase is a function of the outside air temperature, producing the altitude dependence). At a pressure altitude of 35,000 ft, the increase is 8.3%. At a pressure altitude of 4,000 ft, the increase is about 2.3%. If the airspeed is manually changed, the new value is increased relative to this value.
- The angle of attack (relative to the aircraft body) is set to zero so that YVelBodyAxis = XVelBodyAxis = 0.
- The flight path angle of the aircraft is set equal to the pitch angle.
- A negative (up) value of pitch will translate to a positive (up) value of vertical speed, even if the aircraft was flying with zero or negative vertical speed before the change.

It is not clear why MSFS exhibits this anomaly, but the behavior has been consistently reproduced for multiple FS9 installations that are completely functional (FSX behaves in a similar way.) When the simulation is restarted, the changes in speed and attitude induced by modifying values in the Map window places the aircraft in an unsteady configuration and induces transients in speed and pitch.

In the recovered flight files, the plane was probably dragged directly before saving at 3N, 10N and 45S1, as there was no rounding of the coordinates. The only indication of rounding occurs is for data set 45S2, where the latitude is S45° 7' 39.5993" (S45° 7.6600') and the longitude is E104° 8' 26.9998" (E104° 8.4500'). The rounding was likely triggered by entering 4000 ft in the altitude field in the map, which is also confirmed by the unchanged value of AGL (altitude above ground) in the flight file.

As the map shows the projected path of the aircraft consistent with the waypoints that are entered in the native flight planner, it would be convenient to drag the aircraft icon forward along the planned path. It is also possible that the slew mode of FS9 was used. In slew mode the plane can be moved from the cockpit with a very high speed. But in any case, slew mode was off when the flights were saved, as slew mode sets several parameters to zero.

With these discoveries, we make the following observations about the recovered flight files and how the user might have created these files:

- Before manually creating the flight files at 3N, 10N, and 45S1, one of the following parameters were changed using the Map window: latitude, longitude, speed, heading, but not altitude.
- Before manually creating the flight file at 45S2, the altitude was manually changed from 37,654 ft to 4,000 ft in the Map window. Other parameters might have also changed.
- The positive values of vertical speed (YVelWorld > 0) and negative values of pitch seen for data sets 3N, 10N, 45S1, and 45S2 indicate that the aircraft was pitched up relative to the horizon before the flight parameters were changed. The vertical speed suggested by YVelWorld is not the vertical speed before the change. The values do, however, accurately represent the transient state of the aircraft after the change in flight parameters.

For the data sets after fuel exhaustion (45S1 and 45S2), the increase in pitch angle from 1.0° to 5.9° (up) is consistent with stable flight conditions and decreasing speed. The positive values of vertical speed of 663 and 2,029 fpm were transient in nature and induced by the unsteady aerodynamic state imposed on the aircraft after the change in flight parameters.

<u>Maximum and Minimum Values as Flight Markers</u>

During the course of a simulated flight, FS9 keeps track of the minimum and maximum values of g-force (variables MinimumGForce and MaximumGForce) and also the maximum values of revolutions per minute (rpm) for each engine (MaxReachedEngineRPM). The g-force is a measure of structural loading for the wings, where a value of 1.0 indicates steady flight with the wing providing the vertical force to balance the weight of the aircraft. The maximum engine rpm is related to the maximum rotational speed attained by the engine. Because these values are not reset during the flight, and because it would be rare for two flights to have the same values, they can serve as a marker that can link two flight files to the same simulated flight.

For a GE-90 engine, 100% of N1 is 2,262 rpm and 100% N2 is 9,332 rpm. In the configuration file for the PSS 777-200LR, a value of 29,920 rpm is erroneously used for the rated value of N2. As such, all the recorded values of N2 are too high. Nonetheless, the values can still be used as flight markers.

It can be seen in Table 2 that points 3N and 5N share the same values for MinimumGForce, MaximumGForce, and MaxReachedEngineRPM (red boxes), and therefore are likely from the same flight simulation. Similarly, points 10N, 45S1, and 45S2 share the same values for these parameters (blue boxes). The marker values shared by 10N, 45S1, and 45S2 are very useful because they definitively link the position of the aircraft in the Andaman Sea with the two positions in the SIO, and leave little doubt that a user created a simulation in which a B777 is successively positioned in the Malacca Strait, the Andaman Sea, and the SIO.

Conclusions

The data recovered from Captain Zaharie Shah's home computer provide clues as to how a user might have created a simulated flight leading to fuel exhaustion. In particular:

- The parameters related to fuel and flight dynamics show that the aircraft was manually positioned along the flight path.
- The data files were manually created after certain parameters were manually changed.
- The simulator appears to be fully functional, and the rates of climb after fuel exhaustion suggested by the flight parameters can be explained and repeated.
- The data points in the Andaman Sea share some of the same values as the data points in the SIO, suggesting the flight files came from the same simulated flight.

The evidence presented here should be viewed in the context of other evidence previously presented [1], where it was shown that:

- The flight files were deleted and later recovered by investigators as a set from a "shadow volume" on a single drive that was found disconnected from the computer.
- The point in the Andaman Sea (10N) shows an aircraft banked left at 20° and turning towards the south.
- When a great circle path that connects point in the Andaman Sea (10N) and the points in the SIO (45S1 and 45S2) is extended past the final points, the great circle

would cross the McMurdo Station, Antarctica, suggesting that McMurdo was used as a waypoint in the simulation.

The totality of the evidence suggests that it is likely that a user created a simulation on Microsoft Flight Simulator to create a flight that passed over the Malacca Strait to the Andaman Sea and to the SIO in a way that is similar to the flight path that investigators believe was followed by MH370.

References

[1] Iannello, V. et al., "Captain Zaharie Shah's Recovered Flight Simulator Information: Preliminary Assessment from the MH370 Independent Group", Aug 15, 2016, https://www.dropbox.com/s/07kwlf9znxmjn6x/2016-08-14%20Prelim%20Assessment%20of%20IG%20on%20Simulator%20Data.pdf?dl=0

[2] Iannello, V., and R. Godfrey, "Possible Flight Path of MH370 towards McMurdo Station, Antarctica", Aug 25, 2016, https://www.dropbox.com/s/u20xs8e977d9ogy/2016-08-25%20MH370%20Path%20Towards%20McMurdo%20Station.pdf?dl=0

[3] Guillaume, Y., "Flight Dynamics in Microsoft Flight Simulator", Version 1.0, July 2012, http://www.fsdeveloper.com/forum/resources/flight-dynamics-in-msfs-v1-0.169/ or https://www.dropbox.com/s/ss2k2786zxzutos/Flight%20Dynamics%20in%20MSFS%20V1.0.pdf?dl=0

Edits and Corrections

Dec 4, 2016. The sentence "It can be seen in Table 2 that points 3N and 5N share the same values for MinimumGForce, MaximumGForce, and MaxReachedEngineRPM (red boxes), and therefore are likely from the same flight simulation." was corrected. Previously, the reference was to points 5N and 10N. The data in Table 2 is unchanged.

Table 1. Flight Parameters Derived from Raw Simulator Data* [1]

Latitude	(deg)	2.7480	3.4151	5.1116	10.1831	-45.0852	-45.1277
Longitude	(deg)	101.7223	100.8856	98.5879	90.2245	104.1455	104.1408
Altitude	(ft)	70	23,247	32,246	40,003	37,651	4,000
Heading	(deg)	326.2	305.3	314.8	255.5	178.2	193.0
Ground Speed	(kt)	0.0	403.1	433.6	469.5	363.8	195.1
Vertical Speed	(fpm)	0	3,507	1,456	3,570	663	2,029
Turn rate	(deg/s)	0.000	0.000	0.001	-0.888	0.584	0.169

*The fuel quantities derived in [1] are omitted in favor of the updated values presented in Table 3. These changes represented differences between the PMDG 777-200LR and the PSS 777-200LR aircraft models.

Table 2. Abbreviated List of Parameters Recovered from Deleted Flight Files

Data set ID		2N	3N	5N	10N	45S1	45S2
Coordinate Number		6	1	2	3	4	5
[SimVars]							
Latitude	(deg)	N2° 44' 52.6561"	N3° 24' 54.5139"	N5° 6' 41.8671"	N10° 10' 59.2526"	S45° 5' 6.8357"	S45° 7' 39.5993"
Longitude	(deg)	E101° 43' 20.3843"	E100° 53' 8.0655"	E98° 35' 16.6071"	E90° 13' 28.2634"	E104° 8' 43.9576"	E104° 8' 26.9998"
Altitude	(ft)	70	23247	32246	40003	37651	4000
AGL	(ft)	70	23244	32245	40003	37653	37654
Pitch (>0 = down)	(deg)	-0.1	-4.91	-3.46	-4.29	-1.03	-5.86
Bank (>0 = left)	(deg)	0	0.034	0.014	20.09	-10.92	-2.87
Heading	(deg)	-33.85	-54.7	-45.25	-104.53	178.22	-167.01
XVelBodyAxis	(ft/s)	0	0	29.62	0	0	0
YVelBodyAxis	(ft/s)	0	0	-19.87	0	0	0
ZvelBodyAxis	(ft/s)	0	682.78	731.34	794.61	614.09	330.95
PVelBodyAxis	(rad/s)	0	0	0.0011	0	0	0
BVelBodyAxis	(rad/s)	0	0	-0.0011	0	0	0
HVelBodyAxis	(rad/s)	0	0	0	0	0	0
XVelWorld	(ft/s)	0	-555.17	-498.44	-767.03	19.06	-73.99
YVelWorld	(ft/s)	0	58.4477	24.26	59.5	11.0572	33.81
ZvelWorld	(ft/s)	0	393.1438	535.82	-198.8	-613.69649	-320.8
PVelWorld	(rad/s)	0	0.00027	-0.001067	0.000284	-0.000871	-0.001455
BVelWorld	(rad/s)	0	-0.00030317	-0.001113	-1.87E-05	-0.008335	0.00052119
HVelWorld	(rad/s)	0	-1.63E-06	1.79E-05	-0.0155	0.0102	0.0029496
MaximumGForce	(g)	1	1.4397	1.4397	2.2032	2.2032	2.2032
MinimumGForce	(g)	1	0.5958	0.5958	0.1453	0.1453	0.1453
[Engine Parameters]							
ThrottleLeverPct1	(-)	0	0.7865	0.8768	0.9811	0.5523	0.5562
Pct Engine RPM1	(-)	0.3158	0.9768	1.0065	1.093	0.001	0
ThrottleLeverPct2	(-)	0	0.7865	0.8768	0.9811	0.5252	0.5252
Pct Engine RPM2	(-)	0.3158	0.9768	1.0065	1.093	0.001	0
MaxReachedEngineRPM1	(rpm)	0	31517.5	31517.5	32968.9	32968.9	32968.9
MaxReachedEngineRPM2	(rpm)	0	31909.4	31909.4	32968.9	32968.9	32968.9
[Fuel]							
Fuel Center	(%)	15	10.8455	9.9778	7.7843	0	0
Fuel Left Main	(%)	99.9991	99.9966	99.9966	99.9966	0	0
Fuel Right Main	(%)	99.9991	99.9966	99.9966	99.9966	0	0
Fuel Left Aux	(%)	0	0	0	0	0	0
Fuel Right Aux	(%)	0	0	0	0	0	0

Table 3. Fuel Remaining Along the Flight Path
(Values in kg)

	2N	3N	5N	10N	45S1
Recovered Data	68,424	65,129	64,440	62,700	0
Recreated Flight	68,424	64,617	61,206	52,400	6,274

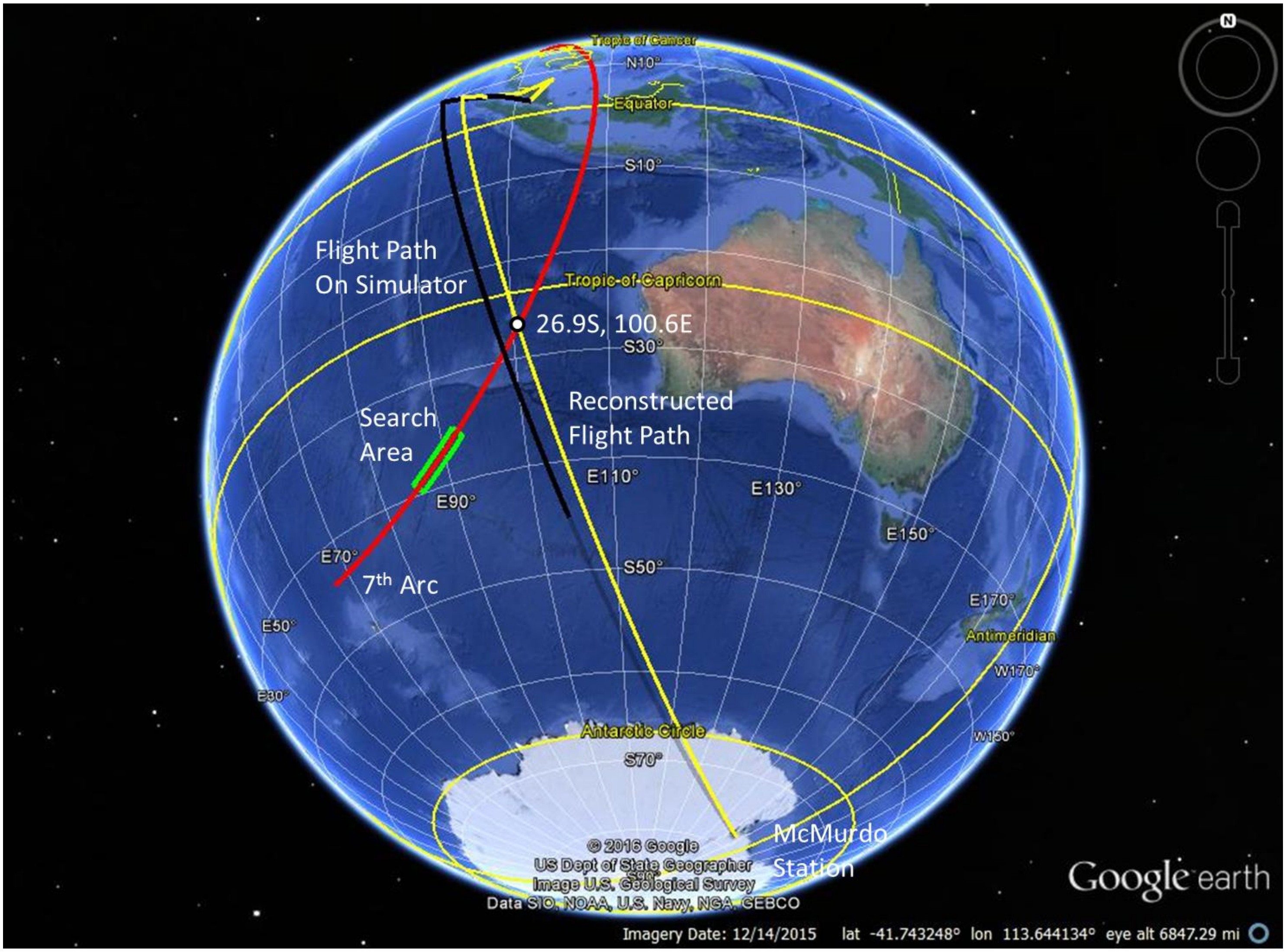

Figure 1. Comparison of flight path on simulator (black) and reconstructed flight path (yellow) of MH370, both leading to McMurdo Station, Antarctica [1].

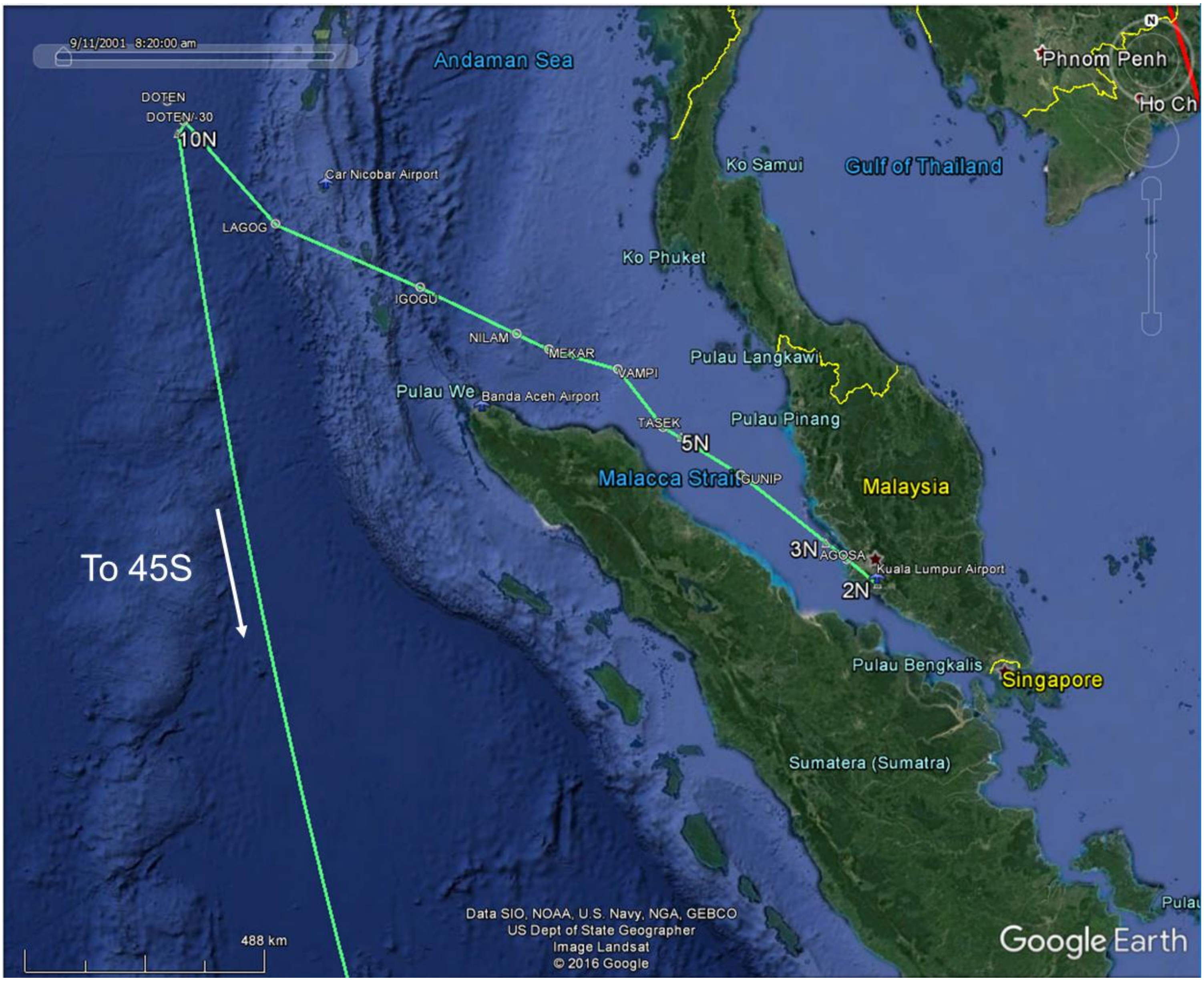

Figure 2. Flight path following waypoints in the Malacca Strait and Andaman Sea and then turning towards coordinate 45S and aligned with McMurdo Station, Antarctica.

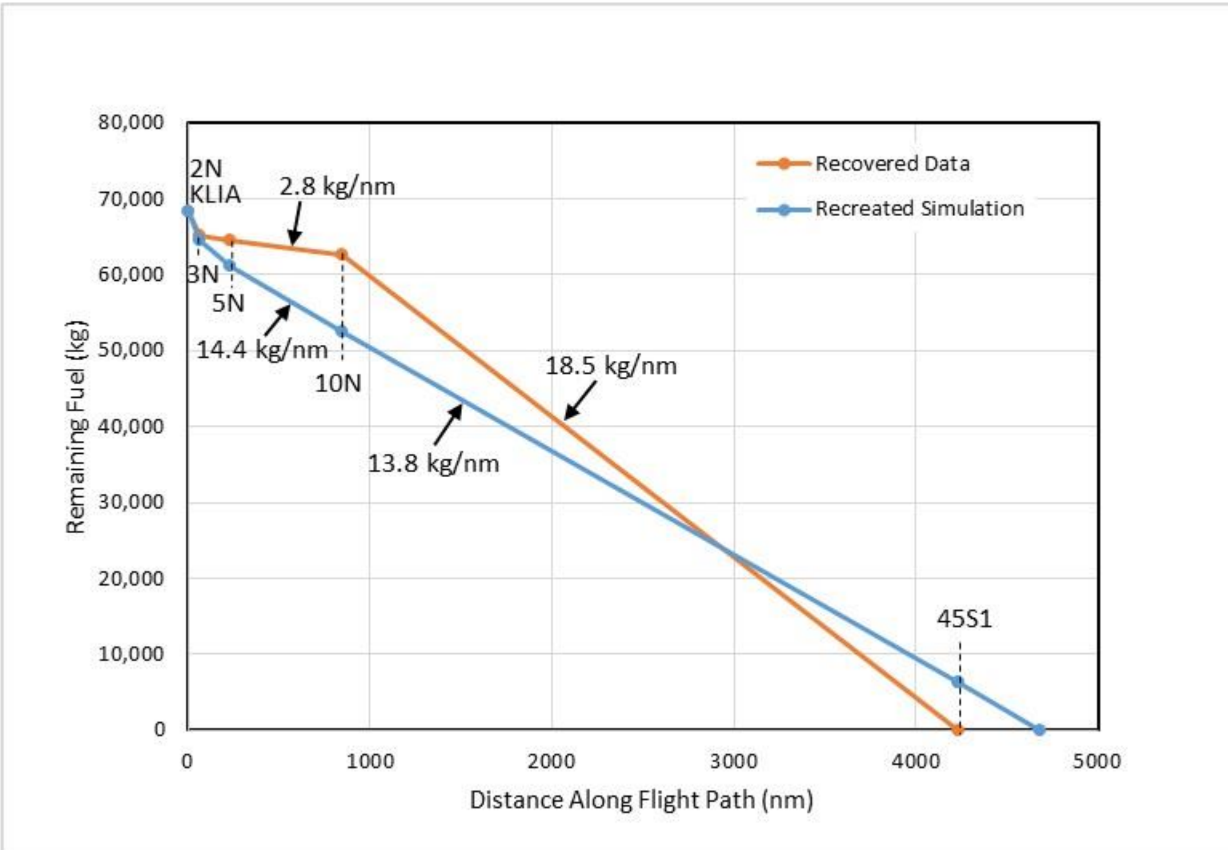

Figure 3. Remaining fuel along flight path.

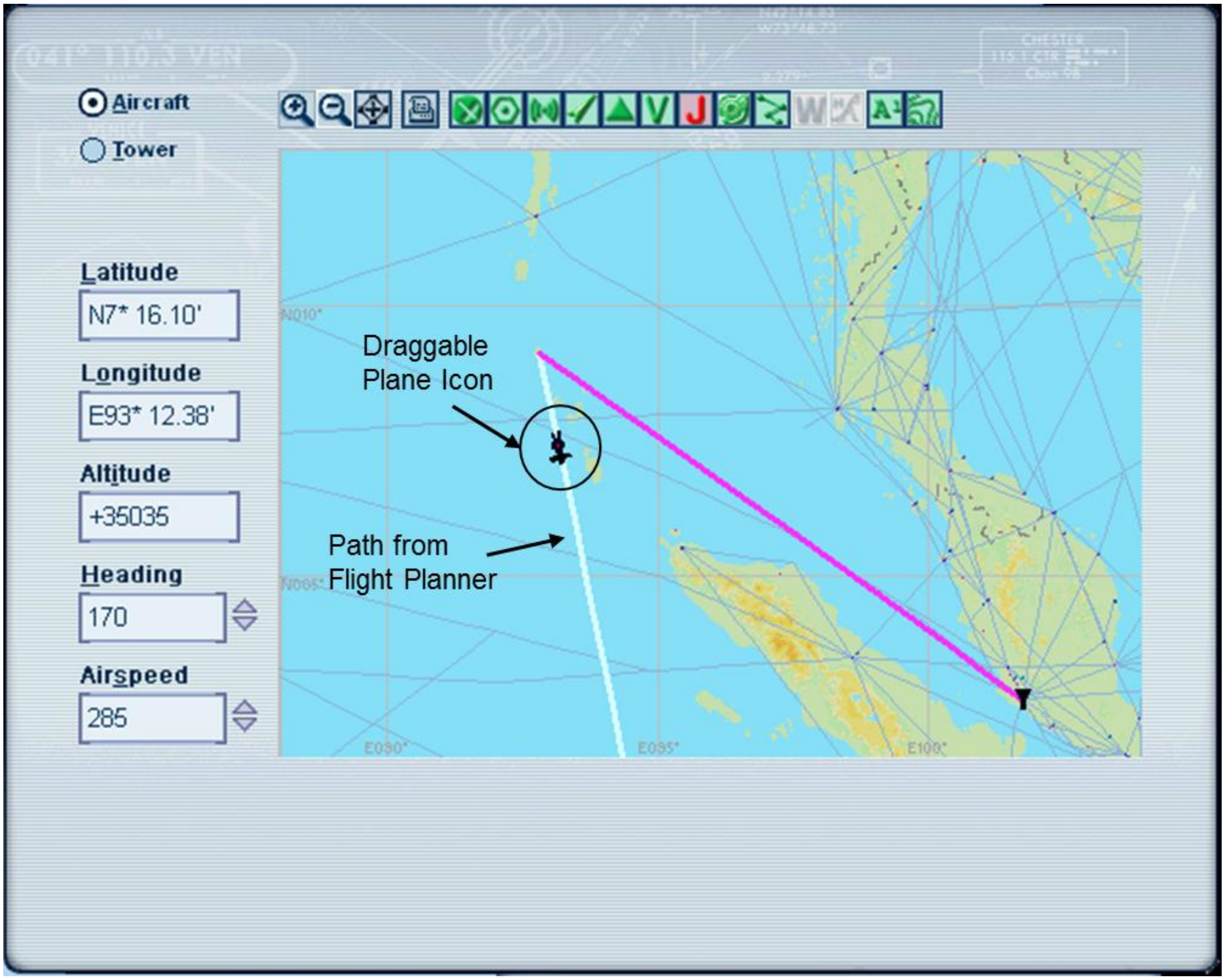

Figure 4. Map window for changing flight parameters in FS9.