Event Report
Malaysia Airlines (MAS) reported that a 777-200ER (WB175/9M-MRO) operating as flight MH370 en route from Kuala Lumpur, Malaysia to Beijing, China lost communication over Vietnam airspace after leaving Malaysia airspace on 8 March 2014.

This event is being investigated by the Malaysian Ministry of Transportation (MOT) with the assistance of accredited representatives from the United States National Transportation Safety Board (NTSB), the Australian Transportation Safety Board (ATSB), and the United Kingdom Air Accidents Investigation Branch (AAIB). Boeing is providing technical support to the US NTSB. As of the date of this report, flight data from the flight data recorder (FDR) and quick access recorder (QAR) are not available for analysis. The data currently available consists of aircraft communications addressing and reporting system (ACARS) data, radar data, and satellite data. The analysis presented in this report will focus on the performance of the airplane and describe how the ACARS data were used to analytically determine position and fuel consumption over the Malay Peninsula, how the radar data were used to track the path of the airplane off its charted course and estimate the amount of fuel used through that segment of flight, and how performance range capability augmented analysis to the satellite data to determine the possible flight profiles.

Available Airplane Position Data
The flight departed Kuala Lumpur International Airport – Sepang (KUL) on March 7, 2014 at 16:42 Coordinated Universal Time (UTC). The airplane lost contact with air traffic control (ATC) at 17:22 UTC during transition from Malaysia to Vietnamese airspace. The last ACARS transmission occurred at 17:06:43 UTC. Primary radar continued the tracking of the flight through time 18:22:12 UTC. Satellite data provided communication data through time 00:19:29 UTC on March 8.

Aircraft Communications Addressing and Reporting System (ACARS)
ACARS data provided time history position via latitude and longitude, along with altitude, computed airspeed, wind speed and direction, total fuel weight, and gross weight of the airplane in 300-second time intervals. The fuel recorded prior to takeoff at time 16:41:43 UTC was 49,200 kilograms (kg) (108,467 pounds [lb]), and the gross weight was 492,520 lb. For reference, the maximum takeoff weight for WB175 is 650,000 lb. The last data point transmitted by ACARS was at time 17:06:43 UTC. At that time, the airplane was positioned approximately 165 nm northeast of KUL with the fuel weight recorded at 43,800 kg (96,562 lb) and gross weight at 480,600 lb.

Radar Data
The radar data originated from two sources and provided time history position information of the airplane in terms of latitude and longitude, along with altitude in 10-second time intervals. One of the sets also provided altitude and ground speed information; however, they were ultimately determined not to be entirely reliable due to their inconsistent values. The radar data originated from two sources and began at KUL, tracked the airplane over the Malay Peninsula, then over the Gulf of Thailand before a left turn was completed taking the airplane back over the Malay Peninsula and over the Malacca Strait where the radar tracking of the airplane ended at time 18:01:19 UTC. One final data point of the position of the airplane was determined through analysis of radar playback that placed the airplane over the waters north of Indonesia at time 18:22:12 UTC. There were a few breaks in the radar data including a 50-second break around the time of the left turn, a 42-second break between the two radar sources, and a 20-minute, 53-second break to the final radar data point.

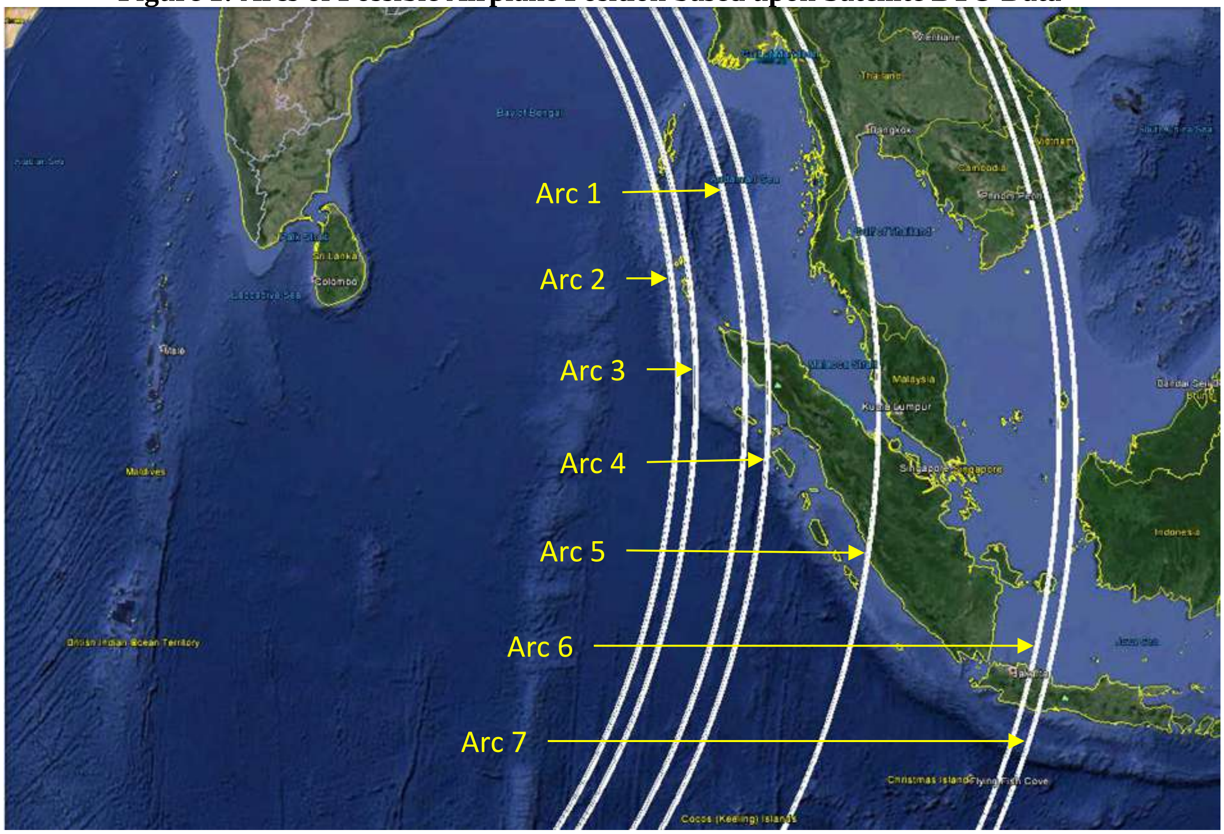
Satellite Data
The satellite communication (SATCOM) system on WB175 was in periodic communication with the Perth Ground Station during the flight starting prior to takeoff until the last signal at time 00:19:29 UTC. The SATCOM system is used for voice and data communications between the airplane and the ground station, and includes transmittal of data such as ACARS and communication between the crew and ATC. As part of the communication mechanism which allows voice and data communications, the airplane and the satellite periodically exchange signals. The fact that SATCOM

signals were received from WB175 until time 00:19:29 UTC indicated that the airplane was still powered, and because the response time changed, that the airplane was still moving. Three key pieces of information used to track WB175 came from the satellite data: 1) UTC time of the communication, 2) burst timing offset (BTO), and 3) burst frequency offset (BFO). BTO is the time for the airplane to respond to a message and was used to determine distance from the satellite to the airplane. BFO is the difference between the expected frequency and the measured frequency when received at the ground station and was used to help determine relative motion of the airplane with respect to the satellite. The BTO was used to create arcs along the earth representing the set of possible airplane positions at the time of communication, but provides no information about where along the arc the airplane was located. The BTO was associated with a UTC time which allowed for path constraints to be applied to the airplane position due to speed limitations. However, the BTO data did not provide direction of travel, and it was unknown if the airplane took a northern route over the Andaman Sea or a southern route over the Indian Ocean after the last radar signal. Analysis of the BFO data (not discussed in this report) eliminated the northern routes. The first satellite communication timing used to define the arcs after the end of the radar data occurred at time 18:28:06 UTC with the last transmission occurring at time 00:19:29 UTC, with 5 transmissions in between. The BTO data from the satellite communications are listed in Table 1. The arcs of possible airplane position defined by the BTO from the 7 transmissions are shown in Figure 1.

Table 1: Satellite BTO Data

UTC Time	BTO (microseconds)	Arc
18:28:05.90	12,500	1
19:41:02.91	11,500	2
20:41:04.90	11,740	3
21:41:26.91	12,780	4
22:41:21.91	14,540	5
00:10:59.93	18,040	6
00:19:29.42	18,440	7

Figure 1: Arcs of Possible Airplane Position based upon Satellite BTO Data



Wind Data
Wind data during the time period and covering the region of the flight were obtained for two time periods during the flight (18:00 UTC and 00:00 UTC) and at 8 altitudes (400 feet, 2500 feet, 4800 feet, 9900 feet, 13,800 feet, 18,300 feet, 23,500 feet, and 30,000 feet). The data contained time, latitude, longitude, wind speed, wind direction, and altitude. These data were applied to the available radar data to calculate the true airspeed of the airplane that would be used in the fuel burn analysis. The wind data were also incorporated into the analysis to determine the possible paths of the airplane using the constraints of the satellite data. Linear interpolation of the wind data occurred at the location and time of the assumed flight path in cases where known wind data was not available.

Assumptions
Not all of the parameters needed to calculate the performance range capability of the airplane were available, and many assumptions had to be made to complete this calculation. Below is a list of the general assumptions made about the airplane, its flight path, and the atmosphere:

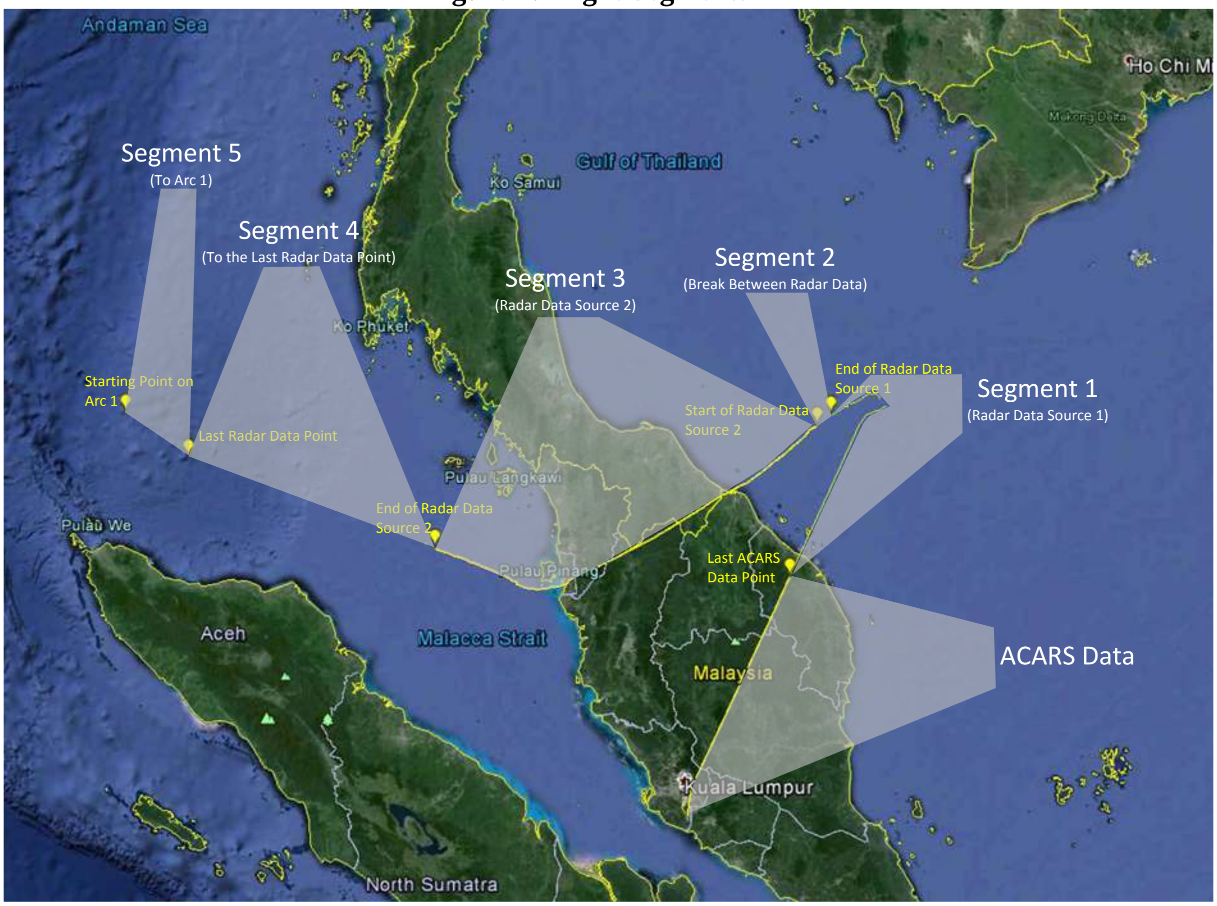
- The airplane weight information (including fuel weight) contained in the final ACARS report was valid and accurate
- Constant last known altitude from ACARS until higher speeds forced altitude restriction
- Constant altitude for each segment after end of ACARS data
- Constant speed during each segment
- No turns during flight segments where data were not available
- Standard day atmosphere

The segments referred to above are in reference to the data sources available that defined the flight path of the airplane from the end of the ACARS data to the first satellite arc. Each segment of data/flight path were analyzed and compiled to arrive at a fuel weight at the first satellite arc. The fuel weight was known at the last ACARS transmission, so the fuel burn analysis started at that point. The flight segments were defined as follows in Table 2 and depicted in Figure 2:

Table 2: Flight Segments

Segment	From	To
1	Last ACARS point	Radar Data Source 1 – End
2	Radar Data Source 1 – End	Radar Data Source 2 – Start
3	Radar Data Source 2 - Start	Radar Data Source 2 – End
4	Radar Data Source 2 – End	Final Radar Data Source 2 Point
5	Final Radar Data Source 2 Point	First Satellite Arc

Figure 2: Flight Segments



<u>Analysis of Fuel Burn</u>

ACARS Data

The airplane departed with 49,200 kg (108,467 lb) of fuel. At the last ACARS transmission, the amount of fuel onboard was recorded at 43,800 kg (96,562.5 lb).

Radar Data

Time and location information from the radar data determined the ground speed along the segments of flight. The ground speed, along with the wind data, allowed for the calculation of true airspeed. During Segment 1, an average ground speed was calculated based on time and distance traveled. The airplane was assumed to remain at 35,000 feet altitude (FL350) through this entire segment based on the last ACARS transmission. The radar data during this portion of the flight also indicated that the airplane was at FL350 for nearly the entire path. The end of the radar data deviated from constant altitude, with unrealistic changes in ground speed, and were considered unreliable and not incorporated into the fuel burn analysis.

Segment 2 consisted of a break between the two radar sources. Knowing the location and time at the end of the first radar source and the location and time at the beginning of the second radar source, the distance between the points was determined and an average ground speed was calculated. The altitude was assumed to remain constant at FL350.

The third segment of the flight consisted of the second radar source that contained unreliable altitude information. The average ground speed increased during this segment of flight, and after incorporating a tailwind, the true airspeed was estimated to be 510 knots. At FL350 and true airspeed of 510 knots, the Mach number would be 0.885 which is above the maximum operating Mach (MMO) of 0.87 at that altitude. While operating above MMO is technically feasible, the condition was considered unlikely as it would induce an overspeed warning, and the overspeed protection control laws would activate. Activation of the overspeed protection control law results in trailing-edge-up elevator to increase the pitch attitude, thereby slowing down the airplane. Pilot intervention would need to occur by pushing forward on the column to keep the airspeed above MMO. During Segment 3, the assumed altitude of the flight path was reduced to 30,000 feet altitude (FL300) to keep the Mach number below MMO.

Segment 4 comprises of the flight path between the end of the second radar source and the last radar data point. The average ground speed was slightly slower than Segment 3 but high enough for the assumed altitude to remain at FL300 for the performance fuel burn calculation to avoid exceeding MMO.

Segment 5 of the flight path continued a northwesterly route from the last radar data point to the first satellite arc. The altitude during this segment was assumed to remain at FL300 for analysis purposes. Boeing 777 performance models were used to determine the fuel flow for each segment. Table 3 shows the details at the end of each flight segment and includes the fuel burn analysis results.

Table 3: Flight Segment Details and Fuel Burn

Segment	Travel Time (hours)	Distance (nm)	Assumed Flight Level	Average Wind Component (+headwind/ -tailwind)	Average True Airspeed (knots)	Mach	Ending Fuel Weight (lb) (Beginning Fuel Weight = 96,563 lb)
1	0.36	175.3	FL350	-14	478	0.829	91,242
2	0.023	11.1	FL350	-19	470	0.815	90,911
3	0.54	282	FL300	-13	510	0.865	81,104
4	0.34	173.5	FL300	-14	502	0.852	75,425
5	0.092	46.4	FL300	-9	494	0.838	73,908

Performance Range Capability and Path Creation

Boeing used 777 performance data to analytically determine range capability during the satellite data portion of the analysis. WB175 was equipped with two Rolls Royce RB211-Trent-892B high-bypass turbofan engines. An engine efficiency analysis using the fuel burn information provided in the ACARS data was performed by the engine manufacturer, Rolls Royce. This analysis showed that the specific fuel consumption of the right engine is slightly greater as compared to the left engine. The analysis results in this report have taken this difference into account.

At the first satellite arc, the calculated fuel on board WB175 was 73,908 lb (see Table 3). At each successive arc point, the satellite data provided a UTC time and the response time (BTO) but did not provide a precise location of the airplane or any information about altitude or airspeed. A series of altitude/speed profiles were analyzed to determine the range capability of the airplane. The speed at each altitude ranged from the top of the amber band (minimum operating speed) to the bottom of the upper barber pole (maximum operating speed) and included the maximum range cruise (MRC) speed. Table 4 shows the results of the performance analysis for the altitude/speed combinations that were analyzed, along with travel time and range from Arc 1 with the MRC speed denoted with a "*".

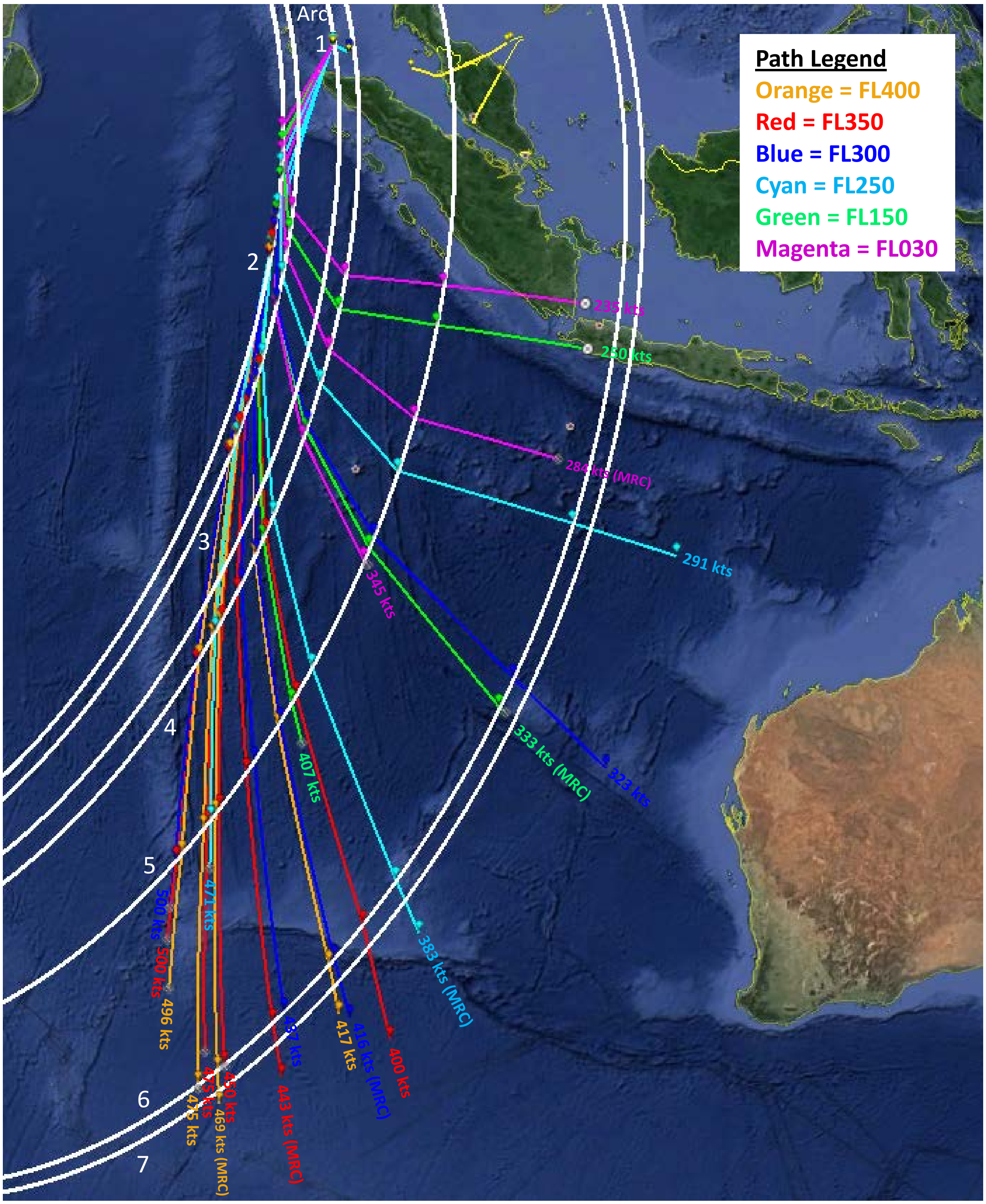
Table 4: Range Capability for Altitude/Speed Combinations (from Arc 1)

Flight Level	True Airspeed (knots)	Mach (*=MRC)	Time (hours)	Range (nm)
FL400	494	0.861	5.0	2491
FL400	475	0.828	5.9	2803
FL400	469	0.818*	6.0	2806
FL400	417	0.727	6.1	2538
FL350	500	0.867	4.7	2356
FL350	475	0.824	5.6	2657
FL350	466	0.824	5.9	2747
FL350	443	0.769*	6.2	2711
FL350	400	0.694	6.6	2624
FL300	500	0.848	4.5	2270
FL300	437	0.742	5.7	2523
FL300	416	0.706*	6.1	2552
FL300	323	0.548	6.8	2181
FL250	471	0.782	4.6	2151
FL250	383	0.642*	6.1	2363
FL250	291	0.483	6.8	1970
FL150	407	0.65	4.5	1835
FL150	333	0.532*	5.8	1923
FL150	250	0.399	6.75	1662
FL030	345	0.535	4.2	1446
FL030	284	0.437*	5.7	1534
FL030	235	0.359	6.2	1464

Using the time constraints of the satellite data and the wind data to back out ground speed from true airspeed in the performance analysis in Table 4, flight profiles for each altitude/speed combination were created and depicted in Figure 3. There are numerous possible paths that could have been taken between the arcs, and taking these variations into consideration would have resulted in an endless number of possible solutions. To constrain the problem, it was decided to include the following assumptions: 1) an assumption that changes to the flight path heading could only be made at the arc crossings, and 2) the altitude and true airspeed remained constant throughout the flight path. With those constraints in place, a number of possible flight paths were created that met the conditions of the satellite data in terms of time and position. Each color in Figure 3 designates a flight level, and within those flight levels there are several different true airspeeds.

Based on the performance range calculation for each altitude/speed combination, some paths were range-limited, meaning that they did not have enough remaining fuel to make it to the 7th arc. A few paths were time-limited, meaning they couldn't make it to an arc before exceeding the time constraint from the satellite data. Other paths met both the range capability and time constraints to reach the 7th arc.

Figure 3: Possible Flight Paths (from Arc 1)



<u>End of Flight Scenarios</u>

Simulation Session: Engine Flame-Out

A simulator session was held to determine possible outcomes of an engine flame-out at the point of fuel exhaustion with no manual intervention. A Boeing 777 fixed-base simulator using the same certified aerodynamic model as a Level D simulator for crew training was used during this session. As such, from a systems and aerodynamic/airplane behavior perspective, the simulator is representative of the expected behavior of WB175 assuming the conditions used in the simulator session existed during the event flight. The initial conditions in some cases were derived from information collected supporting the investigation (i.e. atmosphere, airplane center of gravity [CG]), and in the other cases, the initial conditions were assumptions required to run the simulator that may not be representative of the actual event airplane settings (i.e. autopilot modes, latitude and longitude, heading). Where assumptions were required, there was an attempt to select initial conditions that were considered possible for WB175. The fuel on board was selected to result in the right engine flaming out first due to the performance difference of the right engine stated previously. The simulation was prepared such that the left engine flamed out approximately 4 to 5 minutes after the right engine flame-out. This portion of the simulation was not intended to be representative of WB175 but to provide sufficient time to observe the system effects from the single engine flame-out prior to assessing the dual engine flame-out characteristics.

The simulator session results are as follows. Upon flame-out of the right engine, the thrust asymmetry compensation (TAC) function input left rudder to minimize the yaw asymmetry caused by the asymmetric thrust, per design. TAC is a control law on the 777 that commands rudder when a thrust asymmetry is detected, and the result is representative of what would have occurred on WB175 given an asymmetric engine shutdown. After flame-out of the right engine, the left engine also flamed out as a result of fuel exhaustion. Following the spool-down of the left engine and resulting electrical power loss, the autopilot disconnected. The ram air turbine (RAT) deployed which enabled a few of the flight deck displays to continue functioning as well as provided hydraulic pressure to a reduced number of control surfaces. As the left engine spooled down, TAC reduced the amount of left rudder input, per design. However, the rudder did not completely return to zero deflection before total loss of power. As a result, a residual amount of rudder, approximately 0.2 degrees to the left, remained. This residual rudder caused a slow roll to the left after the autopilot disconnected.

After the autopilot disconnect, the airplane was allowed to freely respond without any commanded inputs from the flight deck. In each case, the airplane began a descending, spiral turn to the left. It was generally a low bank angle turn that lasted for up to 12 minutes as the airplane descended to sea level. In many cases, but not all, a Phugoid oscillation was observed. This caused the airplane to pitch up and down at low frequency during the spirals. Some of the oscillations were large, but the airplane never stalled during the Phugoid cycles. Some exceedances of design dive speed (VD) were observed.

The simulator session flight paths from the point of the final engine flame-out to sea level were contained within a 100 nm^2 box. That box was observed to extend 10 nm beyond the point of fuel exhaustion and 10 nm to the left of the original flight path (at the point of fuel exhaustion) due to the roll to the left.

Possible Additional Range due to Driftdown

The 100 nm^2 box defined by the simulator session at the point of the dual engine flame-out was obtained assuming no inputs were commanded from the flight deck. To quantify the maximum range the airplane could have traveled, the distance covered during driftdown was estimated. The driftdown range is the additional range that the airplane could have achieved after fuel exhaustion if manual control inputs were commanded from the flight deck to maintain wings level flight throughout the glide distance. In general, the airplane could achieve an estimated driftdown range of 0.0034 nm per foot of altitude. Therefore, at FL350 the additional range after the dual engine flame-out would be approximately 120 nm and at FL400 it would be approximately 136 nm.