Northern Routes for MH370 Ending at Airports, by Victor Iannello, April 29, 2015

Notice: The views expressed here are solely mine and do not represent the views of the Independent Group (IG), Jeff Wise, or any other group or individual.

Summary

Paths were reconstructed for MH370 using the available radar and satellite data. Paths to the north of Malaysia were studied by relaxing the constraint of matching the Burst Frequency Offset (BFO), which is appropriate if the BFO data was either corrupted or misinterpreted. The choice of paths was constrained by matching the Burst Timing Offset (BTO) data. Three airports were identified that are located near the 7th arc, as defined by the last BTO data point at 00:19 UTC: Kyzlorda, Almaty, and Kuqa Qiuci. The viability of each airport was determined based on fuel requirements. A fuel flow model was developed by reverse engineering performance data at Long Range Cruise (LRC) and Holding speeds, and then extrapolating the data to other speeds and temperatures.

The fuel flow model coupled with the path reconstruction model predicts that a flight ending at Kyzylorda is unlikely due to the high speeds and unfavorable headwinds. A flight ending at Almaty was deemed viable even when considering the uncertainty in the fuel consumption model. Alternatively, Boraldai Airport, which is close to Almaty Airport, is also viable. Finally, a flight ending at Kuqa Qiuci is considered possible, although the fuel margin is small. The paths to the airports are shown in Figure 1.

The possibility that the plane reached a runway at Yubileyniy was also considered. As Yubileyniy is 237 km (128 nm) beyond Kyzylorda, a landing there is predicted to be very unlikely.

Introduction

A number of analysts have studied the Burst Timing Offset (BTO) and Burst Frequency Offset (BFO) data from flight MH370, as relayed by Inmarsat I3F1 satellite and received by the Ground Earth Station (GES) in Perth, Australia. The aircraft was a Boeing B777-200ER registered as 9M-MRO. The satellite data suggests that the aircraft flew to the South Indian Ocean (SIO) and exhausted its fuel. The constraint of matching the BFO data within any reasonable limit on error eliminates the possibility of a northern path. Performance constraints such as fuel consumption and unattended (autopilot) navigation also limit the range of possible end points for southern paths. Indeed, in the past, I have proposed two endpoints ending in the SIO. In one scenario, I assumed the flight path was uninterrupted and straight after 18:34 UTC and the aircraft was flying at air speeds close to the Long Range Cruise (LRC) condition. As one of the contributors to the Independent Group (IG) study, I predicted an end point of 37.24S, 89.56E, which is close to the prediction of other researchers such as the IG's Richard Godfrey. In another scenario proposed in July 2014, I studied the possibility that the plane "loitered" when it was in the vicinity of the Aceh province of Sumatra, and I showed that the data allows a possible landing and takeoff at Banda Aceh Airport. For this scenario, the predicted end point in the SIO is 34.24S, 93.78E.

Since the time of these predictions, the ATSB has led an extensive underwater search using advanced deep sea techniques to first conduct a bathymetric survey of a priority zone of 200,000 km^2, which was then followed by a multi-beam sonar search of this same area. To date, there has been no physical evidence of MH370 discovered even though the vicinity of the end points suggested by me and others has been searched. Additionally, no evidence has been recovered on the sea surface or washed up on shore.

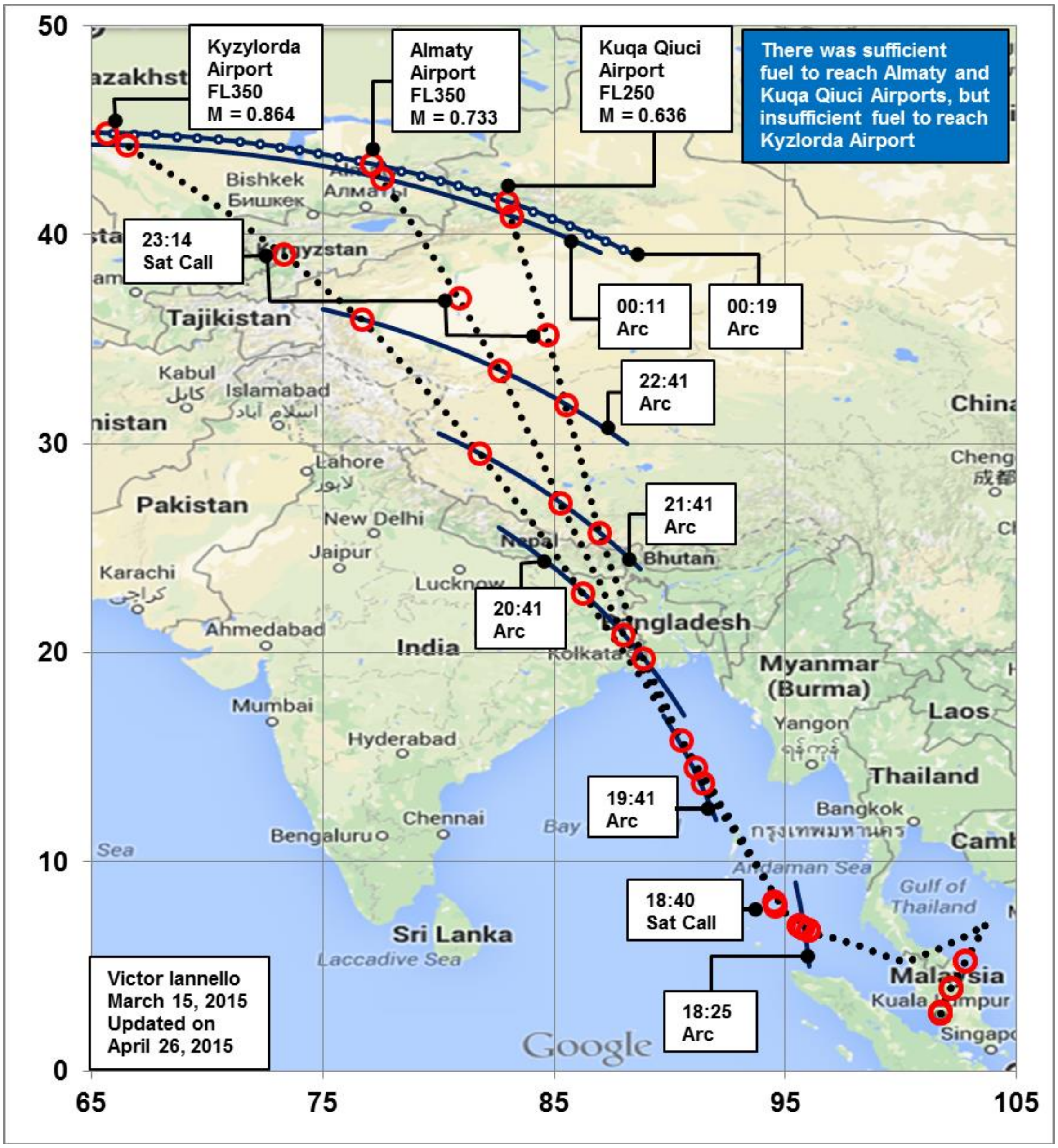

Figure 1. Flight paths to northern airports.

There remains the possibility that MH370 did indeed fly to the SIO and due to the enormity of the range of possible end points, the wreckage of the plane has not yet been found. I do not discount this possibility, and I still have hope that the search in the SIO will be successful. However, with the lack of success to date, I believe it is important to study other possible scenarios, especially since an investigation of some of these scenarios could be conducted for a fraction of the time and cost of the underwater search in the SIO.

If we allow for the possibility that the BFO data is wrong, either because it has been corrupted or because we are improperly interpreting it, then it is possible to reconstruct paths to the north that match the BTO data. In general, if we assume a particular flight speed, then for each assumed flight speed, there are a pair of paths that can be reconstructed that match the BTO data. One of these paths is towards to the north and the other is towards the south. Here I am considering only the northern paths. As no wreckage from the plane has been found in countries situated to the north of Malaysia, I am particularly interested in assessing the possibility that MH370 followed a northern path and successfully landed at an airport.

In related work, I have studied how the BFO data that would be produced if MH370 had followed a northern path may imitate the BFO signature of a southern path. I have already hinted how this may have occurred. A more detailed explanation will be presented soon.

Path Reconstruction Techniques

The methodology to reconstruct northern paths is similar to what has been presented by others, including the published work of Inmarsat's Chris Ashton and the IG's Richard Godfrey . I assume first that the primary radar data as presented in the Australian Transportation and Safety Bureau (ATSB) report is correct, and from that, the final radar position is pegged at 6.5485N, 96.3472E at a time of 18:22:17 UTC. After that time, I assume the plane continues on airway N571 on a track of 296T deg and at a ground speed of about 495 kn until it changes course at 18:34 UTC.

There are measured values of BTO at the time of each handshake between the satellite and aircraft, and these values are used to determine the range between the satellite and the aircraft. The locus of points corresponding to a particular value of BTO form an arc on the surface of the earth, and paths can be reconstructed that cross these arcs at the appropriate time by matching the satellite-aircraft range. (The exact position of the arc depends on the altitude of the aircraft. At higher altitudes, the arc is located further from the subsatellite position.) The satellite position is modeled using the PAR5_parameterization of Henrik Rydberg, which agrees well with the position and velocity vectors presented by Ashton. The earth is modeled as an oblate spheroid using WGS84.

I included meteorological data in the analysis in order to properly model the effect of temperature and wind on ground speed and fuel consumption. As some of the paths studied have considerable headwinds at the cruise altitude, wind is an important effect. The meteorological data for March 8, 2014 at 00:00 UTC was extracted from the GDAS database by Barry Martin. Data is available for atmospheric levels of 250 hPa and 350 hPa, corresponding to pressure altitudes of about 34,000 ft and 26,700 ft, respectively. The data has a spatial resolution of 1 deg in latitude and longitude.I assume that MH370 changed its trajectory at 18:34 UTC by introducing a step change in Mach number and altitude, and I assume the plane continues at this Mach number until 00:11 UTC. Between 00:11 and 00:19, the Mach number is reduced in order to reach the last arc at 00:19 at the appropriate time. Turns are allowed only at the time of a handshake, i.e., as the plane crosses an arc, and great circle (geodesic) paths are followed between handshakes. Although it would be unlikely that MH370 turned exactly at the times of handshakes, this simplification was used in light of the limited data set that is available. With this simplification, for a given Mach number, there is a unique northern path that exactly matches the BTO data.

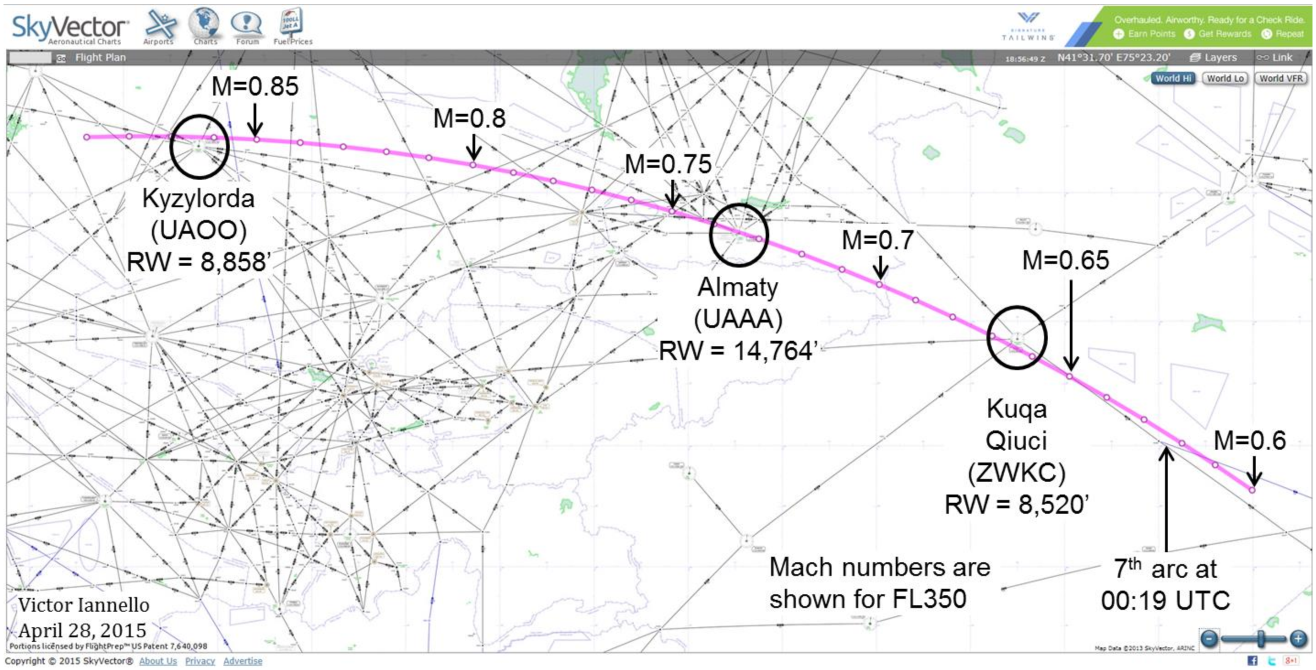

Figure 2. Airports close to the 7th arc.

The paths were reconstructed by forward integrating using Euler's method with a time step of 1 minute. During each time step, the ground speed and track angle were held constant. A finer time step of 1 second was used for the time period between 18:22 and 18:28 to find a path that matches the BTO, BFO, and radar data in this interval. The path involves a "lateral offset" maneuver to the right of airway N571 that would require active intervention of the pilot. I won't discuss more about this here as the details don't change the general observations regarding northern paths.

End Points Near Airports

The first step was to determine which airports are close to the 7th arc and therefore would merit closer examination as a potential landing site for MH370. A series of paths were reconstructed for constant Mach numbers between 0.6 and 0.89, corresponding to a realistic range of air speeds at an altitude of 35,000 ft. The end points for these paths were then plotted using SkyVector and airports within 10 km (5.4 nm) where identified.

The results are shown in Figure 2. There are three airports that met these criteria: Kyzylorda (M=0.863) and Almaty (M=0.734) in Kazakhstan, and Kuqa Qiuci (M=0.664) in Xinjiang, China, and all have runway lengths greater than 8,000 ft. The next step was to determine the feasibility of MH370 landing at one of these airports by analyzing the fuel requirements.

Fuel Flow Model

The calculation of the fuel consumed between 18:24 and 00:19 requires detailed knowledge of the performance of 9M-MRO, which is a B777-200ER equipped with two Trent 892 engines. In general, for level flight, the fuel rate is a function of the aircraft weight, Mach number, altitude, and outside air temperature (OAT). As the Mach number is defined relative to the wind, the calculation of the ground speed also needs to include the effect of winds, i.e., tailwinds increase the ground speed and headwinds and crosswinds reduce it. (The reduction in ground speed due to a headwind is much more significant than a crosswind of the same speed, although both effects were included.) As high altitude winds are very strong for the northern paths studied, this is an important effect.

To model the fuel consumed along the northern paths, I needed to model the fuel flow as a function of the weight, altitude, Mach number, and air temperature. The detailed performance specifications of a Boeing aircraft are contained in the Performance Engineer's Manual (PEM), but this was not available. If the PEM had been available for 9M-MRO, I could have calculated the fuel consumption from "first principles". Instead, a fuel consumption model was developed based on two tables from a portion of the Quick Reference Handbook (QRH) that was supplied to me on a confidential basis. For this work, the two important tables from the QRH are:

- Long Range Cruise (LRC). An aircraft following an LRC speed profile will be flying at a speed 2%-4% higher than Maximum Range Cruise (MRC) with a penalty of 1% on range, i.e., fuel efficiency. In the LRC table, fuel flow and air speed (Mach number) are provided as a function of weight and altitude.
- Holding (flaps up). An aircraft flying at Holding speed will be maximizing its endurance by minimizing the fuel flow. As is the case for the LRC table, the fuel flow and air speed are provided as a function of weight and altitude. The Holding speed is in general significantly less than the LRC speed, and the fuel flow is at its minimum for a given weight and altitude.

In general, an aircraft will not be flying in accordance with either of these criteria, so instead I used the data in these tables to develop a generalized fuel model that could be extrapolated to other conditions.

There was one other important assumption regarding the performance of the engine that was required: the ratio of fuel flow to thrust is approximately constant when corrected for air temperature. The relationship can be expressed as:

$$FF = TSFC^{*}D \left\{\left(\frac{T_s}{T_{ref}}\right)(1 + 0.2M^2)\right\}^{0.6} \qquad (1)$$

where FF is the fuel flow in units of (lb_m/hr), $TSFC^*$ is the corrected thrust specific fuel consumption (assumed to be constant) in units of (lb_m/hr-lb_f), D is the drag in units of (lb_f), which is assumed to be equal to the engine thrust, T_s is the static temperature in units of (K), T_{ref} = 288 K, and M is the Mach number.

In order to calculate the fuel flow, it is necessary to calculate the drag for a given set of conditions. Typically, the relationship between the lift coefficient C_l and drag coefficient Cd is presented as a "drag-polar plot" in the PEM. Lacking the PEM, I reverse-engineered this relationship using Eq 1 with the assumption that to first-order, Cd is only a function of C_l and M (neglecting the effect of Reynolds number), i.e.,

$$C_d = C_d(C_l, M) \qquad (2)$$

I then found an empirical relationship for C_d that produced an adequate match between the predicted fuel flow and the fuel flow values in the tables from the QRH.

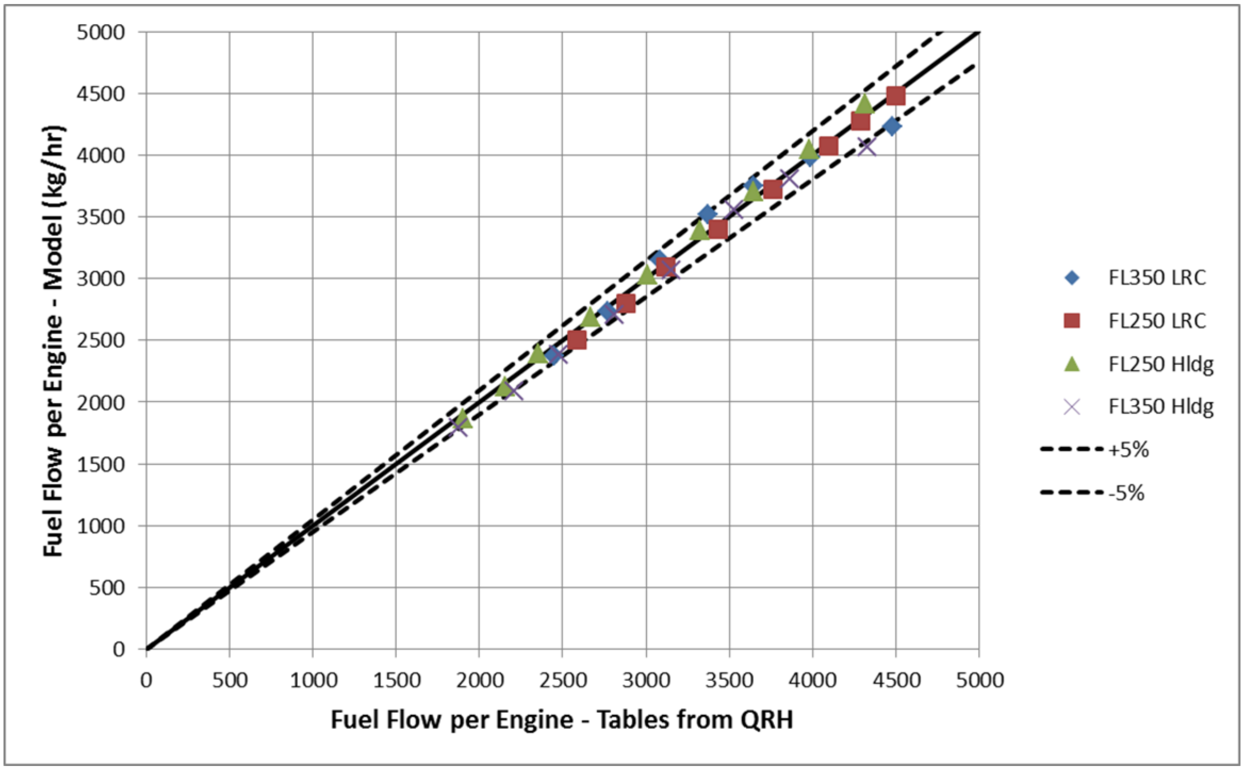

Figure 3. Predicted and tabular values of fuel flow at selected conditions.

Figure 3 shows the relationship between the predicted fuel flows and the values listed in the table for LRC and Holding conditions at FL350 and FL250. The RMS error is 3.2%. Another factor is the Performance Degradation Allowance (PDA) of the engine, which might increase fuel consumption by another 2%. Including uncertainty due to PDA, the model predictions are assumed to have error bounds of -3.8% / +3.2%

<u>Fuel Consumption for Paths to Airports</u>

Armed with a model for fuel consumption, I studied whether the model would predict whether there was adequate fuel to reach the three airports previously identified as possible landing sites for MH370. For Kyzylorda and Almaty, I assumed the flight between 18:34 and 00:19 was at 35,000 ft. For Kuqa Qiuci, I assumed the flight was at 25,000 ft as the Mach number at 35,000 ft (0.664) was below the speed for Holding and the resulting fuel consumption was high. The results are listed in the following table.

Table 1. Fuel Consumption Results

End Pt	Lat	Long	Altitude	Mach No	Average Headwind	Peak Headwind	Remaining Fuel	Remaining Fuel
	(deg)	(deg)	(ft)	(-)	(kn)	(kn)	(kg)	(%)
Kyzylorda	44.7062	65.5917	35,000	0.864	22.5	43.0	-7,503	-15.3
Almaty	43.3553	77.0447	35,000	0.735	10	22.9	3,837	7.8
Kuqa Qiuci	41.6767	82.8718	25,000	0.636	3.5	16.4	2,004	4.1

For the path to Kyzylorda at 35,000 ft, the required speed is M=0.864 and the average headwind was 23 kn at FL350 with a peak headwind of 43 kn. The fuel flow model predicts that an additional 7,503 kg of fuel would be required, or about 15.3% of the initial fuel load of 49,100 kg. This is well beyond the expected error margin of the fuel model prediction. It is therefore considered unlikely that there was sufficient fuel to reach Kyzylorda Airport.

Jeff Wise has proposed a scenario in which MH370 passed Kyzylorda and landed on a runway at Yubileyniy, which is 237 km (128 nm) beyond Kyzylorda Airport. I don't see a way that this could have occurred unless the fuel load at takeoff was significantly different than contained in the ACARS data stream.

For the path to Almaty Airport at 35,000 ft, the required speed is M=0.735 and the average headwind is 10 kn, with a peak of 23 kn. The predicted fuel remaining at Almaty would be about 3,837 kg, or about 7.8% of the initial fuel load. Even with the uncertainties (-3.8%/+3.2%) of the fuel flow model, I predict there was sufficient fuel to reach Almaty.

For the path to Kuqa Qiuci Airport at 25,000 ft, the required speed is M=0.636 and the average headwind is 4 kn with a peak of 16 kn. The predicted fuel remaining at Kuqa Qiuci is 2,004 kg, or about 4.1% of the initial fuel load. Considering the uncertainties of the fuel flow model (-3.8%/+3.2%), it is possible that MH370 was able to reach this airport, although the fuel margin is significantly less than for Almaty.

Some Additional Comments

The three flights studied all cross into the Xinjiang province of China. The path to Kyzylorda skirts the border of China, but the paths to Almaty and Kuqa Qiuci represent significant incursions into Chinese airspace. Any theory developed around these flight paths would need to explain why China did not act to stop this incursion.

In addition to the civil runway at Almaty Airport, there is Boraldai Airport (UAAR), formerly Burundai Airport, located about 11 km (6 nm) to the west from Almaty, as shown in Figure 4. It is privately-owned by Altair Air and is the base of operations for Burundaiavia, which supplies helicopter services for civilian, transport, and military uses. The airport is primarily used for light fixed-wing aircraft and helicopters and has a runway with a length of 4,790 ft. Although this is relatively short for a B777, it is would be sufficient length to land a B777 that had little remaining fuel. A landing at this airport might raise less suspicion than at Almaty.

Conclusion

In this work, I studied potential flight paths of MH370 that terminate to the north of Malaysia. The studied was performed to assess the possibility of a successful landing in the event that the BFO data from MH370 is either corrupted or has been misinterpreted. I used the BTO data to identify the paths to the north that end at airports along the 7th arc at 00:19 UTC with the requirement that the BTO data is matched at all other handshake times. Three airports were identified that are located within the error bounds of the 7th arc. Of the three, there appears have been insufficient fuel to reach Kyzylorda Airport. On the other hand, there appears have been sufficient fuel to reach Almaty and Kuqa Qiuci Airports, although there would have been significantly less fuel margin to reach Kuqa Qiuci. Near to Almaty is a smaller airport named Boraldai that is also viable for landing. It is very unlikely that MH370 reached the runway at Yubileyniy.

Figure 4. Boraldai Airport is close to Almaty Airport.