Assignment 5: Air Transportation Systems Analysis

Solution Instructor: Trani

Problem 1

For the new generation long-range transport aircraft provided in the class web site (http://128.173.204.63/courses/cee5614/cee5614_pub/boeing787_class.m) to answer the following questions.

a) Use the **unrestrictedClimbAnalysis.m Matlab script** to estimate the mass of the aircraft at the Top of Climb (TOC) point. The aircraft takeoff weight is 225,000 kg. with OEW of 117,700 kg., 71,300 kg. of fuel and 36,000 kg of payload (passengers and belly cargo). The pilot climbs to 35,000 feet restricted by Air Traffic Control. Use the default climb speed profile provided in the aircraft data file. Use ISA atmospheric conditions in your calculations. The departure airport is located at sea level conditions.

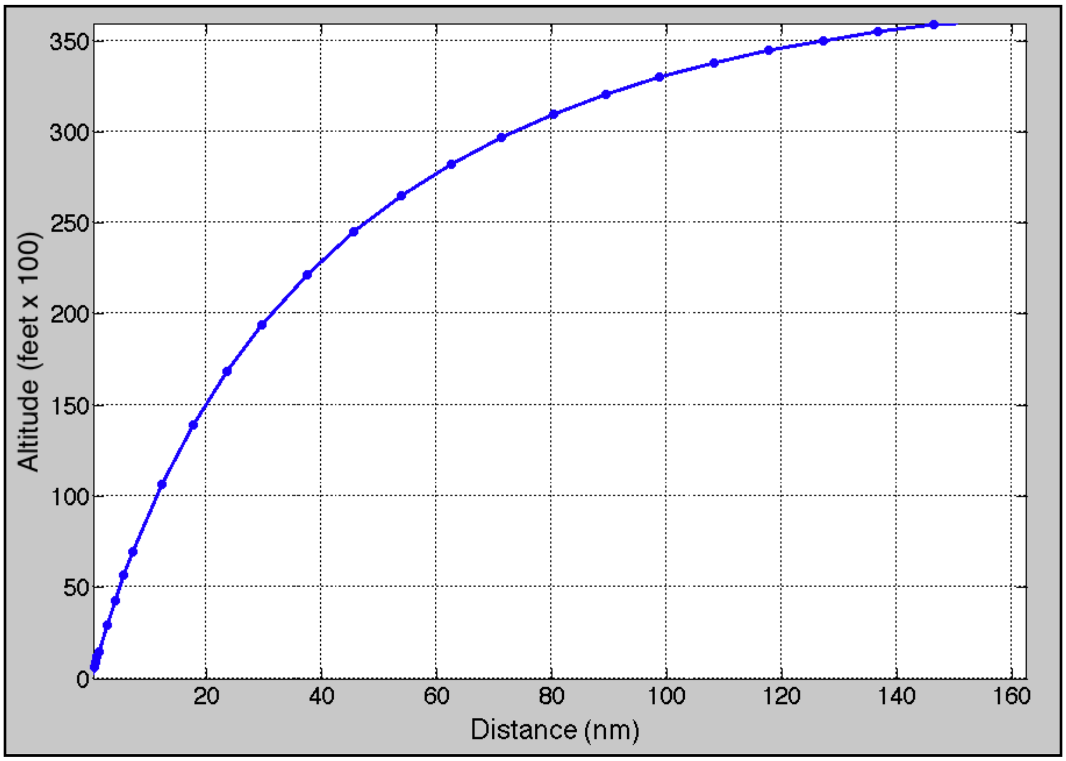

Figure 1. Climb Analysis. Twin-engine Transport Aircraft. Mass = 225,000 kg (Takeoff). 127 nm to Climb to 35,000 feet. ***4,067 kg of Fuel*** *Used in the Climb Profile to 35,000 feet. Mass at TOC = 220,933 kg.*

b) Use the **unrestrictedDescendAnalysis.m Matlab script** to estimate the fuel used from the Top of Descent (TOD) point (at 35,000 feet) to the destination airport. The destination airport is located at sea level conditions (assume ISA conditions in the decent as well). In this calculation assume the mass at the TOD point is 158,000 kg. This provides a 4,000 kg. of fuel reserve allowance at the end of the long flight.

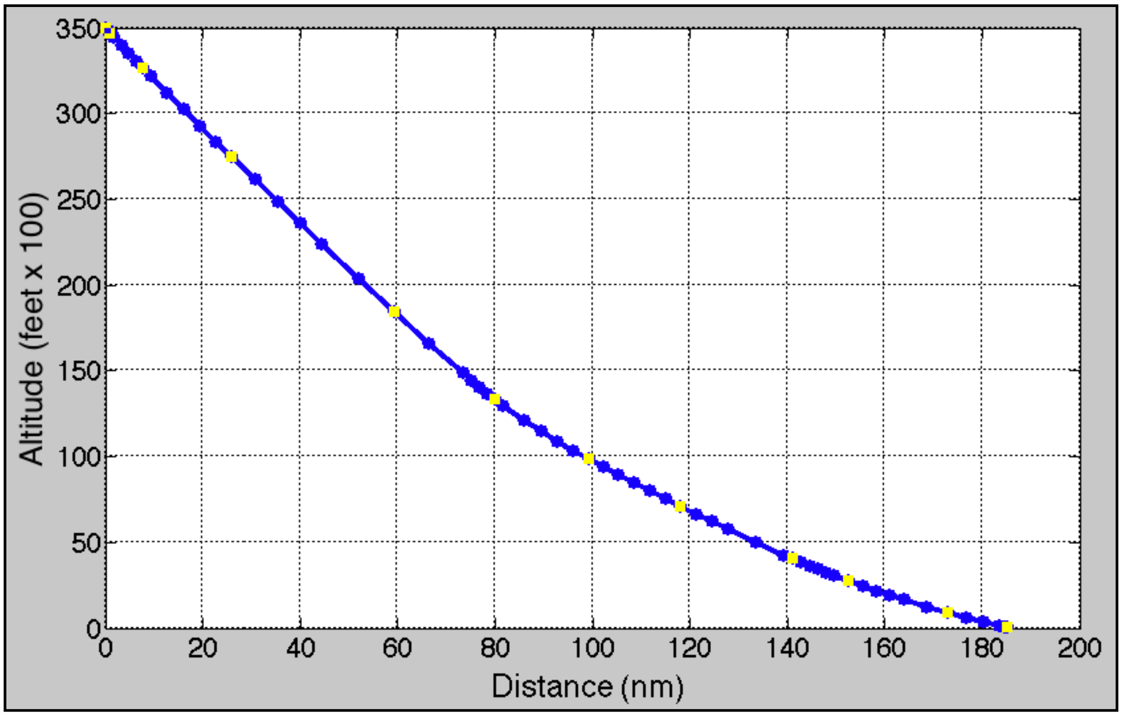

Figure 2. Descent Profile for Large Twin-Engine Transport Aircraft. ***185 nm used*** *in the Descent Profile.*

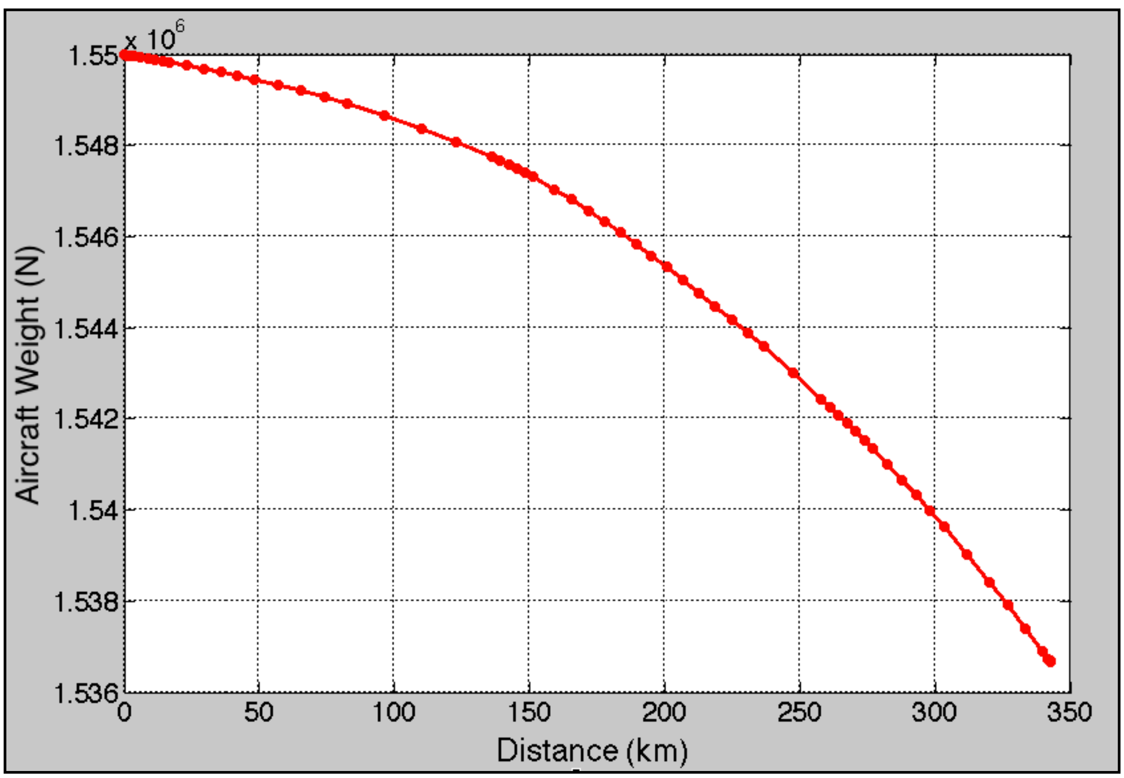

Figure 3. Descent Profile from 35,000 feet. 1,374 kg of Fuel Used in the Descent Profile.

c) Using the Breguet range equation, find the still-air (no wind) range of the aircraft with the parameters provided in parts (a) and (b) with the aircraft flying at 36,000 feet and Mach 0.82. To calculate the range parameter use the mass of the aircraft at a mid-point between TOC and TOD.

At the TOC point:

Flying at 36,000 feet and ISA conditions, Mach 0.82 equates to 241.9 m/s and 312.6 knots IAS. Density at 36,000 ft is 0.3653 kg/cu.m.

$$C_d = 0.0274$$
$$C_l = 0.5269$$
$$D = 112{,}740N$$
$$L / D = 19.22$$

Using the aircraft L/D ratio at the TOC point, the Range equations is:

$$R = \frac{V}{TSFC}\left(\frac{L}{D}\right)\ln\left(\frac{W_i}{W_f}\right)$$
$$R = \frac{241.9\text{m/s}}{1.53e-4\ \text{N/s/N}}(19.22)\ln\left(\frac{220993*g\ \text{N}}{158000*g\ \text{N}}\right)$$
$$R = 1.0196e7\ \text{m}$$
$$R = 10{,}196\ \text{km}$$
$$R = 5{,}506\ \text{nm}$$

This calculation is pessimistic because the aircraft L/D ratio is higher than 19.22 during the cruise profile. Use the mid point weight to estimate the value of L/D.

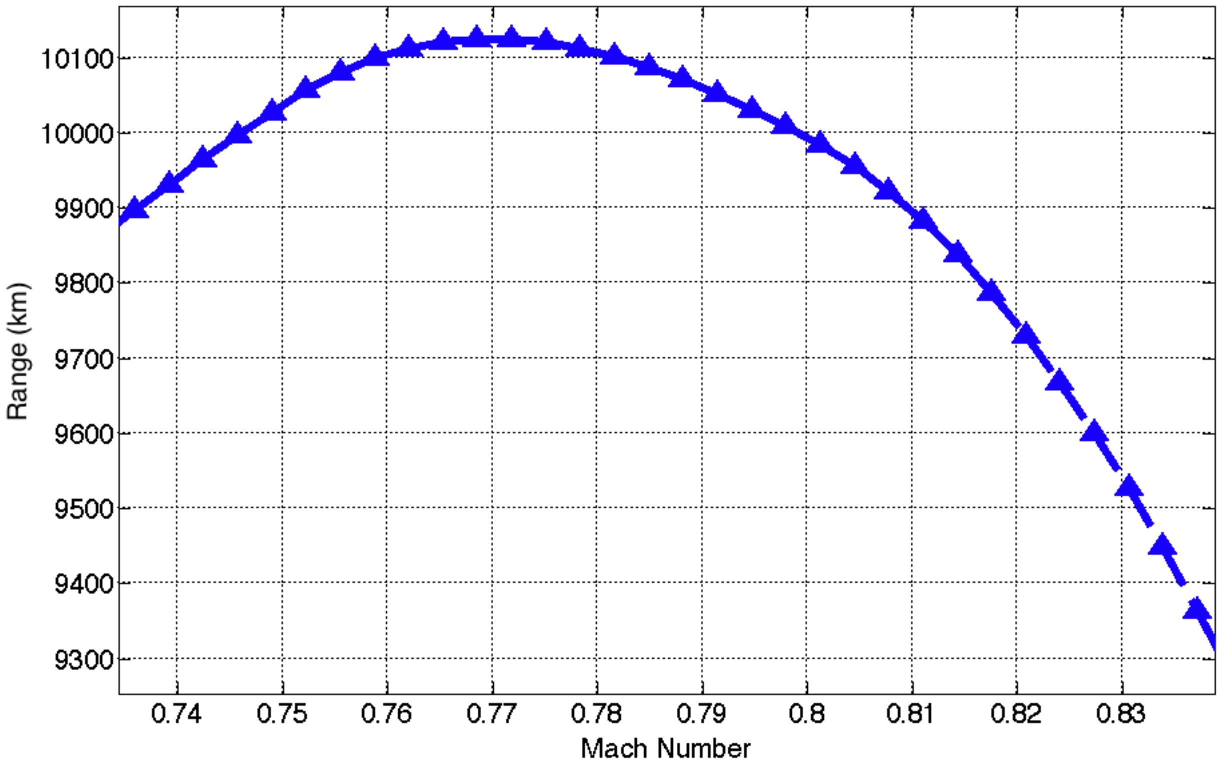

Figure 4. Range Parameters for Lang-Range Transport. Mass at TOCX = 220,993 kg. Mass at TOD = 158,000 kg.

d) Verify that the best speed for maximum range is Mach 0.81 while the aircraft cruises at 12,000 meters (39,000 feet).

To verify this part we can make a plot of the range parameter vs. Mach number and also for multiple altitudes. The plot shown in Figure 5 demonstrates that this aircraft maximizes its range when flown at Mach 0.81 and 12,000 meters.

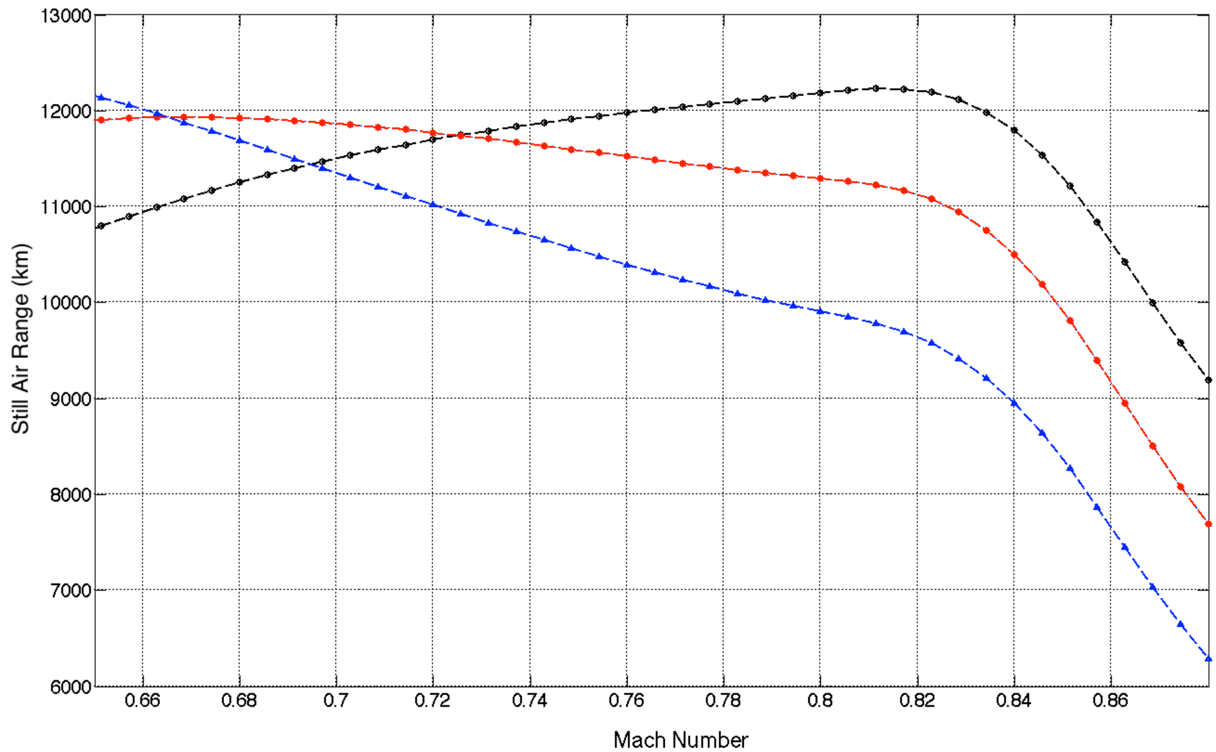

Figure 5. Still-Air Range for Three Altitudes and various Mach Numbers. Black line = 12,000 meter cruise, red line = 10,000 meter cruise and Blue line = 8,000 meter cruise. At Mach 0.81 and 12,000 meters the range is maximum.

Problem 2

An airline wants to fly the route CLT-FRA with a new advanced twin engine aircraft (http://128.173.204.63/courses/cee5614/cee5614_pub/boeing787_class.m). The route of this flight is one of the many routes optimized daily for North Atlantic operations using the North Atlantic Organized Track System - NAT OTS (see Figure 1). Read about the NAT at: **http://en.wikipedia.org/wiki/North_Atlantic_Tracks**. On the day of the flight there are 6 tracks designated by letters from U to Z as shown in Figure 1. You can check the daily tracks at: http://www.turbulenceforecast.com/atlantic_eastbound_tracks.php.

The flight plan for this aircraft indicates a takeoff weight of 217,700 kg. with OEW of 117,700 kg., 60,000 kg. of fuel and 40,000 kg of payload (passengers and belly cargo). The aircraft is expected to climb to FL 360 directly after departing CLT and fly the first leg (CLT to NAT Track W) at Mach 0.82 (assume ISA conditions). The aircraft reaches the entry point of the North Atlantic Organized Track System (NAT OTS) near St. Pierre, Canada (see Figure 1). Just before entering the NAT the pilot requests FL 380 and Mach 0.83 for the North Atlantic leg crossing. Canadian controllers accept the request for both speed and cruise altitude. The final leg of the flight (NAT TRack W to FRA) is also expected to be flown at 38,000 feet as shown in Figure 1.

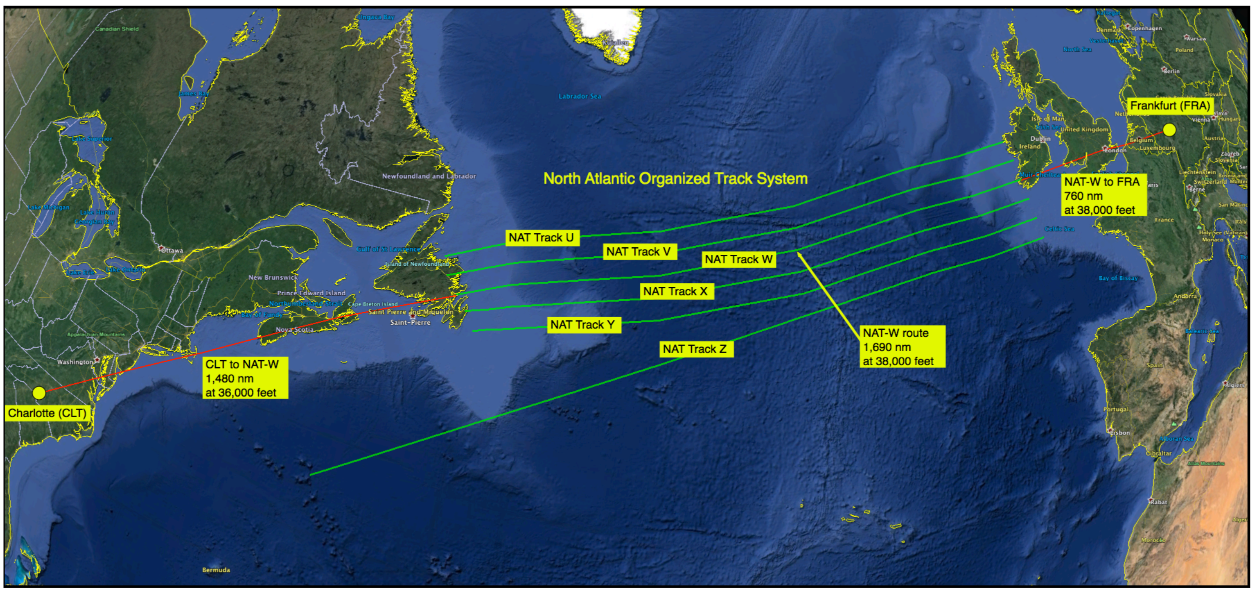

Figure 2.1. CLT-FRA Flight Using the Organized North Atlantic System (OTS).

a) Calculate the total fuel used in the flight given the parameters shown in Figure 1. In your calculations make sure to also include the fuel consumed in the climb phase from FL 360 to 380 before the aircraft enters the NAT OTS system. Assume the pilot performs the climb at Mach 0.82 and uses maximum continuous thrust.

For the cruise portion of the flight, approximate the fuel burn using the mid-point mass of every leg flown. Recall that fuel consumption in cruise is the product of drag and TFSC as shown below.

Solution: The total distance to be traveled from CLT to FRA is: 1480+1690+760 = 3,930 nautical miles.

Climb Profile:

For the climb profile we use DTW = 217,700 kg.

Climb Fuel (kg) 5653.0627

Climb Time (minutes) 34.2945

Climb Distance (nm) 243.0136

Cruise Profile to NAT:

Cruise distance at 36,000 feet is 1237 nm

Starting mass = 217,700 - 5,653 Kg

Cruise Fuel (kg) 15716.7784

Cruise Time (minutes) 157.7859

Cruise Distance (nm) 1237

Climb Profile from 36,000 feet to 38,000 feet

At Mach 0.82 the aircraft does not have a good rate of climb capability to climb to 38,000 feet. The procedure to climb to 38,000 feet requires slowing down a bit to perhaps Mach 0.79 and then climbing to 38,000 ft. Assume climb is done at Mach 0.79 (V = 233 m/s or 300 knots IAS). The plot in Figure 2.2 illustrates a climb at Mach 0.79 from 36,000 to 38,000 feet starting at a mass of 196,330 kg.

Mass at NAT point = 217700-5653-15717 = 196,330 kg.

Fuel to Climb = 196,330 - 195,780 = 546 kg.

Distance in climb (36-38K) = 39 nm

Mass at new TOC inside NAT = 195,780 kg.

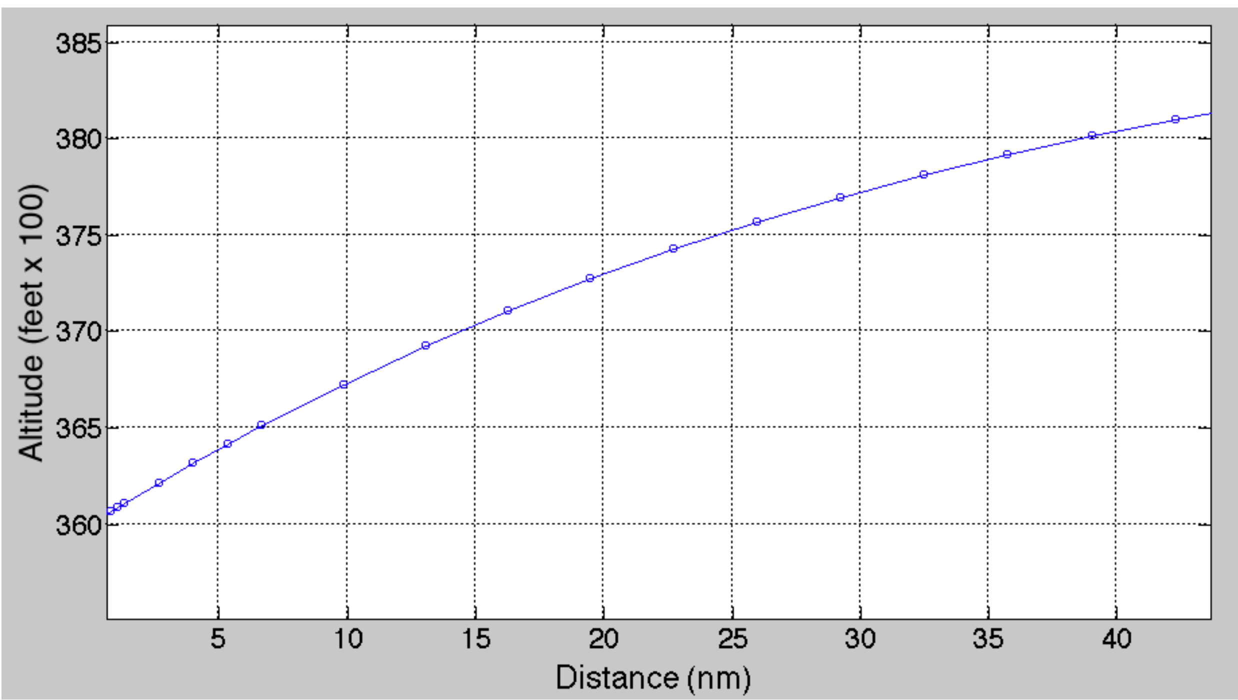

Figure 2.2 Climb form 36000 to 38000 feet at Mach 0.79 (300 knots IAS). The Climb Requires 39 nm and uses 546 kg. of fuel.

Cruise Profile Inside NAT:

Cruise distance at 38,000 feet is (1,690 - 39) = 1,651 nm

Mach speed = 0.83

Starting mass = 195,780 Kg

Cruise Fuel (kg) 19445.1247

Cruise Time (minutes) 208.0604

Cruise Distance (nm) 1651

Ending Mass = 195,780 - 19445 = 176,335 kg.

Cruise Profile from NAT to TOD point:

Cruise distance at 38,000 feet is (760 - Descent distance) ~ 570 nm

I estimated a typical descent distance of 190 nm using the unrestricted descent profile and 165,000 kg as the mass at the TOD point.

Mach speed = 0.83

Starting mass = 176,335 kg.

Cruise Fuel (kg) 6413.586

Cruise Time (minutes) 71.8319

Cruise Distance (nm) 570

Descent Profile:

Descent distance from 38,000 feet is 190 nm

Speed profile in the aircraft file provided.

Starting mass at TOD = 176,335 - 6,414 = 169,922 kg.

Descent Fuel (kg) 1,305

Descent Distance (nm) 190

Table 2.1 Summary of Fuel Used in Flight.

Phase of Flight	Fuel Used (kg)	Remarks
Climb to 36,000 ft	5,653	
Cruise to NAT	15,717	at 36,000 feet and Mach 0.82
Climb to 38,000 ft	546	from 36-38 kft
Cruise inside NAT	19,445	at 38,000 ft and Mach 0.83
Cruise from NAT to TOD	6,414	Mach 0.83 and 38 kft.
Descent	1,305	from 38000 feet
Total	**49,080**	

b) Based on the calculations performed, what is the fuel reserved carried? (fuel left after the flight is completed).

The flight carries plenty of extra fuel (more than 10 metric tons).

c) Calculate the fuel penalty to the airline if the aircraft receives an ATC clearance to fly the NAT OTS system at 36,000 feet instead (assume FL 360 for the NAT to FRA leg).

Using 3930 nm at 36,000 feet the following mission parameters are obtained:

Mission Fuel (kg) 49540.8952

Travel Time (minutes) 517.7856

Total Distance (nm) 3930

Average Speed (knots) 455.4009

Climb Fuel (kg) 5653.0627

Climb Time (minutes) 34.2945

Climb Distance (nm) 243.0136

Cruise Fuel (kg) 42356.4232

Cruise Time (minutes) 445.046

Cruise Distance (nm) 3489.0428

Descent Fuel (kg) 1531.4092

Descent Time (minutes) 38.4451

Descent Distance (nm) 197.9436

The additional fuel used flying at 36,000 feet is 461 kg. Note that the original flight was also doing Mach 0.83 in cruise inside the NAT up to the TOD point. Assuming no difference in wind conditions, the higher speed (5.7 knots difference) would have saved 3.41 minutes of travel time.

d) Calculate the additional cost to the airline per flight if the lower altitude is used. The fuel price today in large volumes is $3.15 per gallon of Jet-A fuel. Comment if the cost differential would be significant if the airline makes 600 crossings per year in that route.

1 gallon = 6.7 lb. of jet-A fuel or 3.045 kg of jet-A fuel.

The airline saves 276,600 kg. (90,837 gallons) of fuel per year. This would translate into $286,140 in savings per aircraft.

e) What is the minimum longitudinal separation today in the OTS for aircraft with ADS-B and Datalink equipped aircraft?

10 minutes for all aircraft. 5 minutes in-trail if the aircraft are equipped with ADS-C and CPDLC datalink.