CEE 5614

Analysis of Air Transportation Systems
Extended-Range Twin-Engine Operational Performance Standards (ETOPS)

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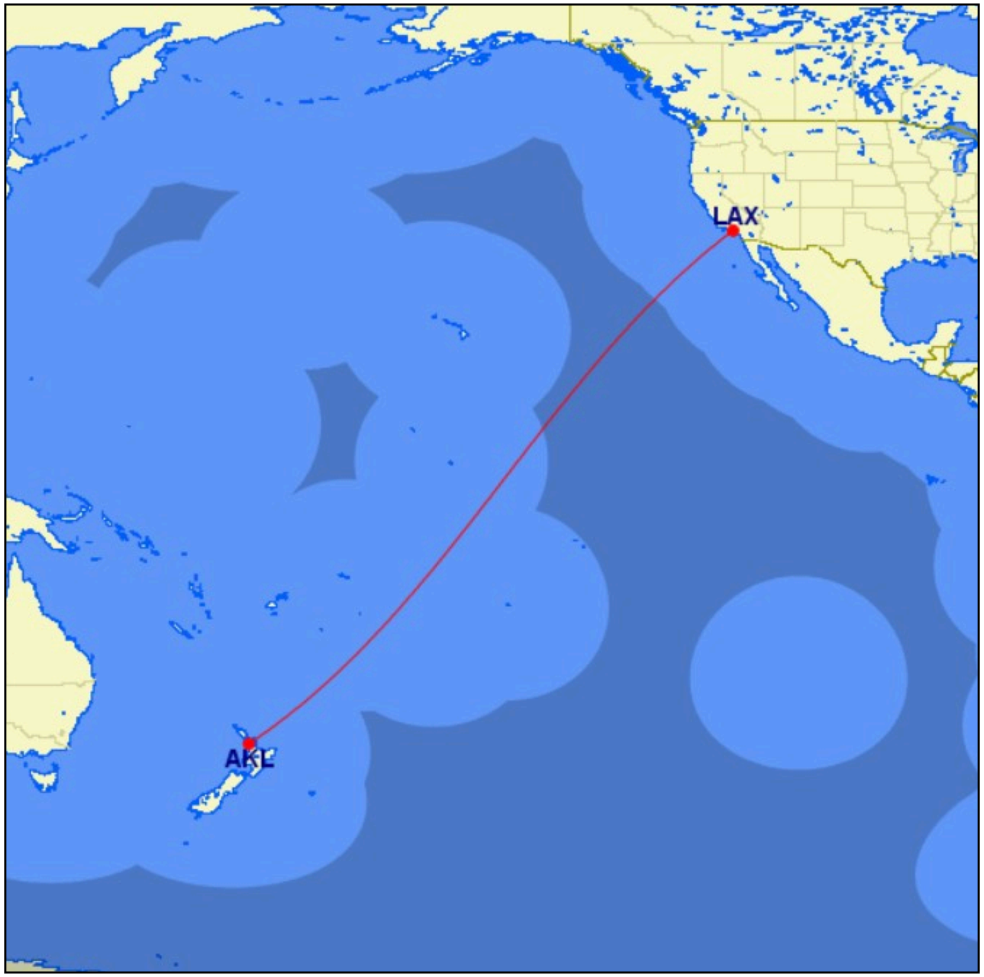
Oceanic Operations with Twin-Engine Aircraft

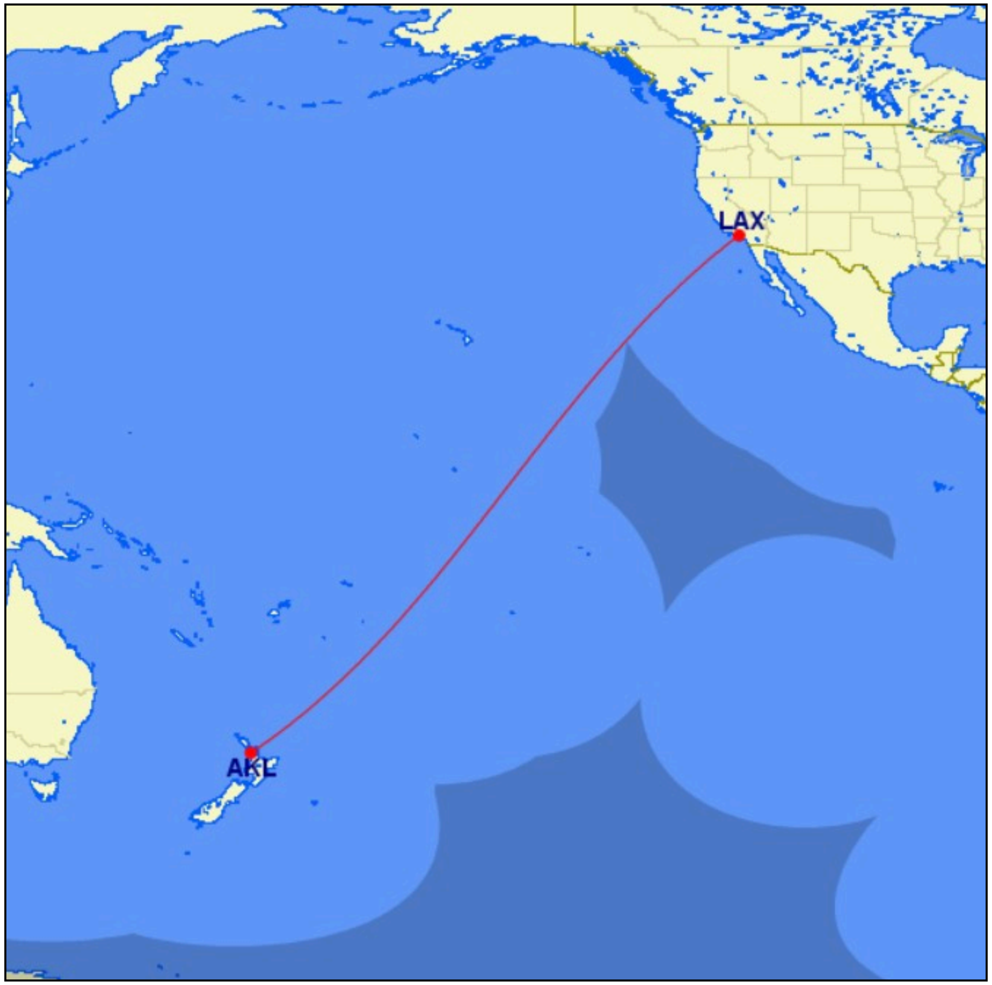
- Today's twin engine aircraft are certified to operate over the water and far away from diversion airports
- The critical conditions are:
  - In-flight Engine Shutdown - operating at one-engine speed for a designated period of time
  - Failure of the pressurization system that would require a descent to 10,000 feet* for the remaining of the flight
- For more information consult 14 CFR Appendix P to Part 121, Requirements for ETOPS and Polar Operations

* 10,000 feet is the maximum altitude allowed without pressurization and oxygen

Oceanic Operations with Twin-Engine Aircraft (Auckland-Los Angeles)



ETOPS 120 Minutes (400 knots)



ETOPS 180 Minutes (400 knots)

Source: Great Circle Mapper (http://www.gcmap.com)

ETOPS 180 Cannot Support the Auckland-Santiago (Chile) Route

ETOPS 180 Minutes (400 knots)

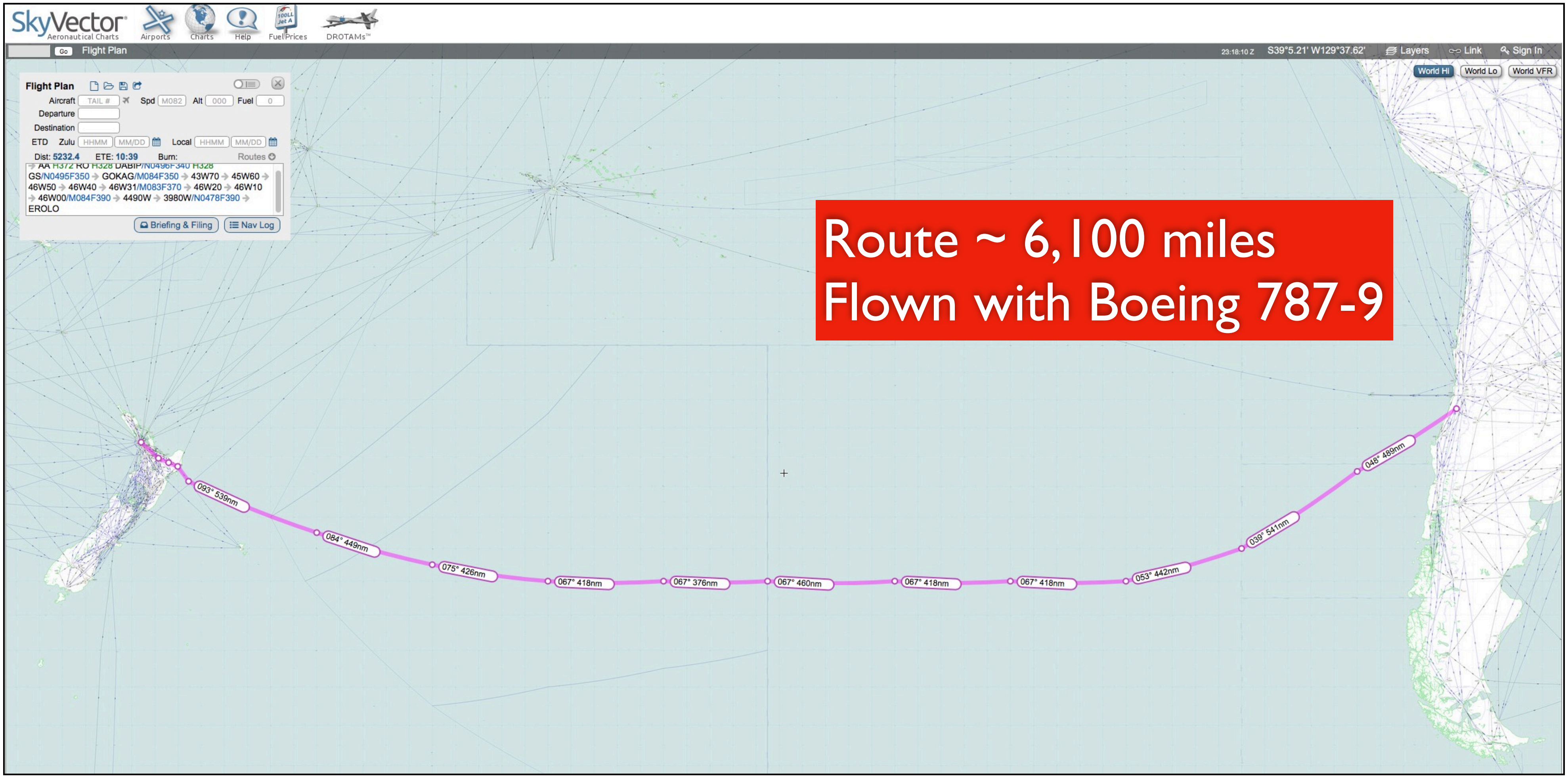
Source: Great Circle Mapper (http://www.gcmap.com)

ETOPS 330 Supports the Auckland-Santiago (Chile) Route

ETOPS 330 Minutes (400 knots)

Source: Great Circle Mapper (http://www.gcmap.com)

Typical Flight Plan Between Auckland-Santiago (Chile) - LAN Chile # 800



Source: Great Circle Mapper (http://www.gcmap.com)

Historical Operations with Twin Engine Aircraft

Aircraft	ETOPS (min)	Year
Airbus A300	90*	1978
Boeing 767	120	1985
Boeing 777	180 330	1988 2011
Airbus A330	240	2009
Boeing 787	330	2014
Airbus A350	370	2014

* ETOPS designation rules started in 1985

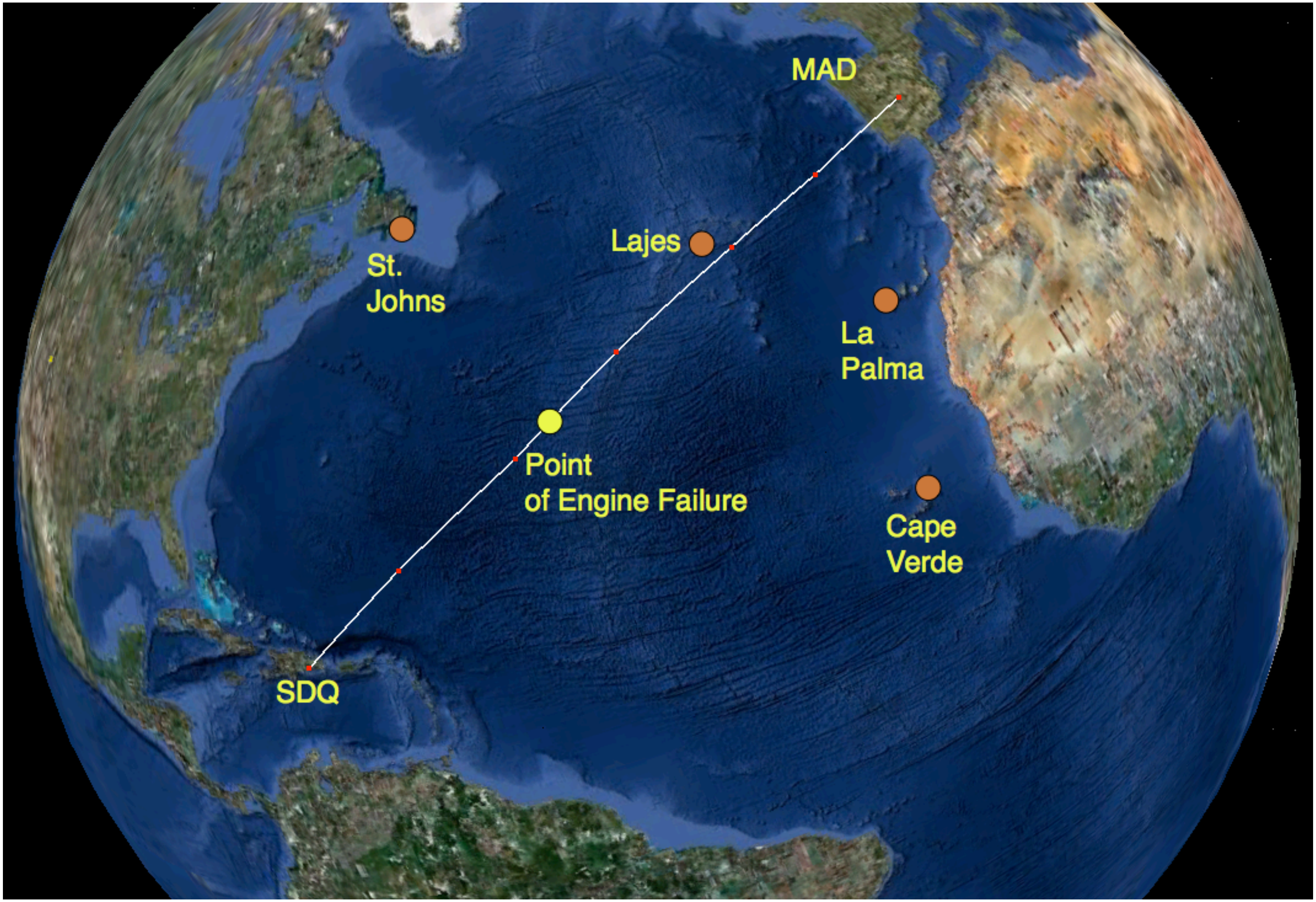
Narrow body aircraft (Boeing 757, 737, Airbus A320) operate Hawaii-West Coast routes under ETOPS 180 minutes

Case Study
Atlantic Flight
Santo Domingo-Madrid

Problem Description

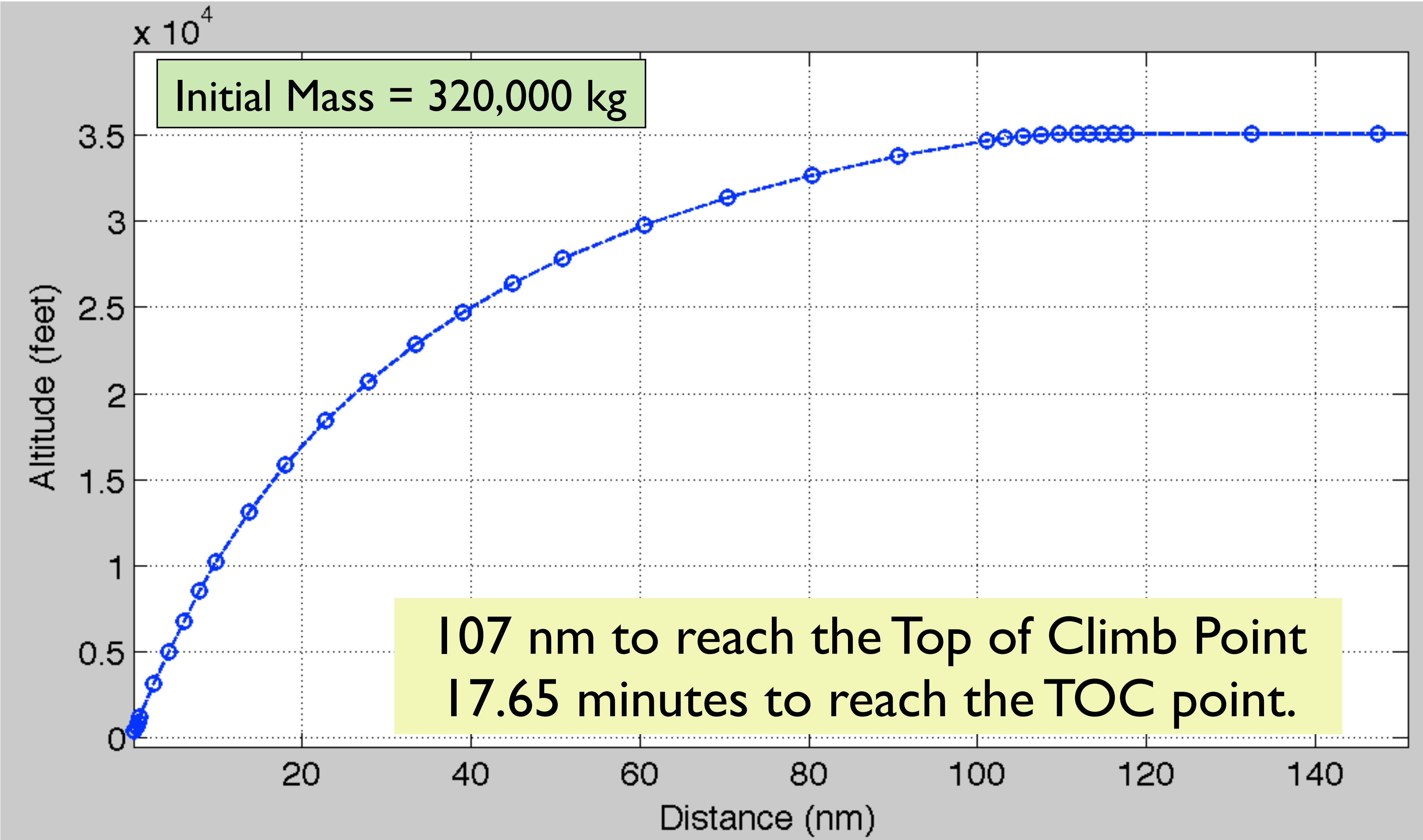
- Use the large twin-engine transport aircraft performance file provided in the Matlab files for CEE 5614 (http://128.173.204.63/courses/cee5614/matlab_files_cee5614.html to answer the following questions.
- The aircraft is cruising at FL 350 and Mach 0.82 over the Atlantic Ocean enroute from Santo Domingo (SDQ), Dominican Republic to Madrid (Spain) as shown in Figure 1. The aircraft has a mass of 320,000 kg at the departure airport (SDQ). The takeoff mass is comprised of the following:
    - Operating empty mass = 145,000 kg
    - Fuel weight onboard= 115,000 kg
    - Payload = 60,000 kg (300 passengers + 30,000 kg of belly cargo in LD3 containers)
- The pilot files a flight plan and requests Flight Level 350 for the cruise portion the flight
- The aircraft flies to a waypoint position located 1,700 nm from SDQ (see Figure 1) when an engine failure is detected by the crew.
- The crew initiates a gradual descent at 290 knots IAS and declares an emergency with Oceanic ATC) and diverts to the best alternate airport. The distances from the point of engine failure to all alternate airports filed in the flight plan are shown in Table 2. Assume ISA conditions in the analysis.

ETOPS Flight (SDQ-LEMD)



Source: Google Earth

Calculation of Climb Profile (Using Matlab Code)



Fuel Burn to the Point of Engine Failure

$$\frac{dR}{dt} = V$$

$$T = D = \frac{1}{2}\rho V^2 S C_d$$

$$\frac{dW}{dt} - TSFC(D) = -TSFC(\frac{1}{2}\rho V^2 S C_d)$$

The system of two simultaneous equations can be solved using Matlab. Note that during the cruise phase, the speed of the aircraft does not change.

The aircraft cruises at Mach 0.82 at 35,000 feet. Assuming ISA conditions, the speed of sound (a) at 10,671 meters is 295 m/s. The true airspeed is:

$$V_{tas} = 295 m/s (0.82) = 241.9\ m/s$$

Fuel Burn at TOC Point

$$W_{TOC} = W_{takeoff} - FW_{climb}$$

$$W_{TOC} = (320{,}000\ kg)(9.81\ m/s^2) - (6{,}405 kg)((9.81\ m/s^2)$$

$$W_{TOC} = 3{,}076{,}400 N = 313{,}595 kg$$

The drag at cruise at the Top of Climb point would be:

$$V_{tas} = 241.9\ m/s$$

$$C_l = 0.6412\ (dim)$$

$$C_d = C_{do} + C_{di} = 0.0189 + 0.0175 = 0.0364\ (dim)$$

$$D = 178{,}300\ N$$

Fuel Burn at TOC Point

The fuel consumption at the TOC point is then,

$$\frac{dW}{dt} = -TSFC(D) = -TSFC(T) = -(1.6e-4\ \mathrm{N/N/s}) * (178300\ \mathrm{N})$$

$$\frac{dW}{dt} = -28.53\ \mathrm{N/s}$$

The aircraft takes 12,196 seconds (3.39 hours) to travel 1,593 nm (2,950.2 km) to the point of engine failure. In the process the aircraft burns 347,930 N of fuel at 28.53 N/s

This translates into 35,467 kg of fuel consumed

Mass at TOC Point

The final mass at the point of engine failure is estimated to be:

$$W_{failure} = W_{TOC} - FW_{cruise}$$

$$W_{failure} = (313,595\,kg)(9.81\,m/s^2) - (347,930\,N)$$

$$W_{TOC} = 2,728,400\,N = 278,130\,kg$$

Note that this calculations are pessimistic because the aircraft burn fuel is assumed to be constant while flying from the TOC point to the point of the engine failure

As the aircraft consumes fuel, the fuel burn will decrease

Mass at TOC Point (Using Mid Mass)

If we use the mid-point weight of the aircraft between TOC and point of engine failure,

$$W_{mid-point} = \frac{1}{2}\left(W_{TOC} + W_{failure}\right)$$

$$W_{mid-point} = \frac{1}{2}(313{,}595\,kg + 278{,}130\,kg)(9.81\,m/s^2)$$

$$W_{mi-point} = 2{,}902{,}400\,N = 295{,}860\,kg$$

The drag for the mid-point is:

$$V_{tas} = 241.9\,m/s$$

$$C_l = 0.5929\ (dim)$$

$$C_d = C_{do} + C_{di} = 0.0339\ (dim)$$

$$D = 165{,}850\ N$$

Mass at TOC Point (Using Mid Mass)

$$\frac{dW}{dt} = -TSFC(D) = -TSFC(T) = -(1.6e-4\ N/N/s)*(165850\ N)$$

$$\frac{dW}{dt} = -25.54 N/s$$

$$W_{failure} = W_{TOC} - FW_{cruise}$$

$$W_{failure} = (313,595 kg)(9.81\ m/s^2) - (323,630 N)$$

$$W_{failure} = 2,764,900 N = 281,840\ kg$$

Note that both solutions differ by about 3 metric tons. Either solution is only an approximation but acceptable for our analysis.

Find a Diversion to Alternate

- Need to evaluate a suitable speed and altitude to do the diversion to an alternate
- Need to consider one-engine operational conditions
- Need to factor winds to estimate ground speed and thus calculate diversion times

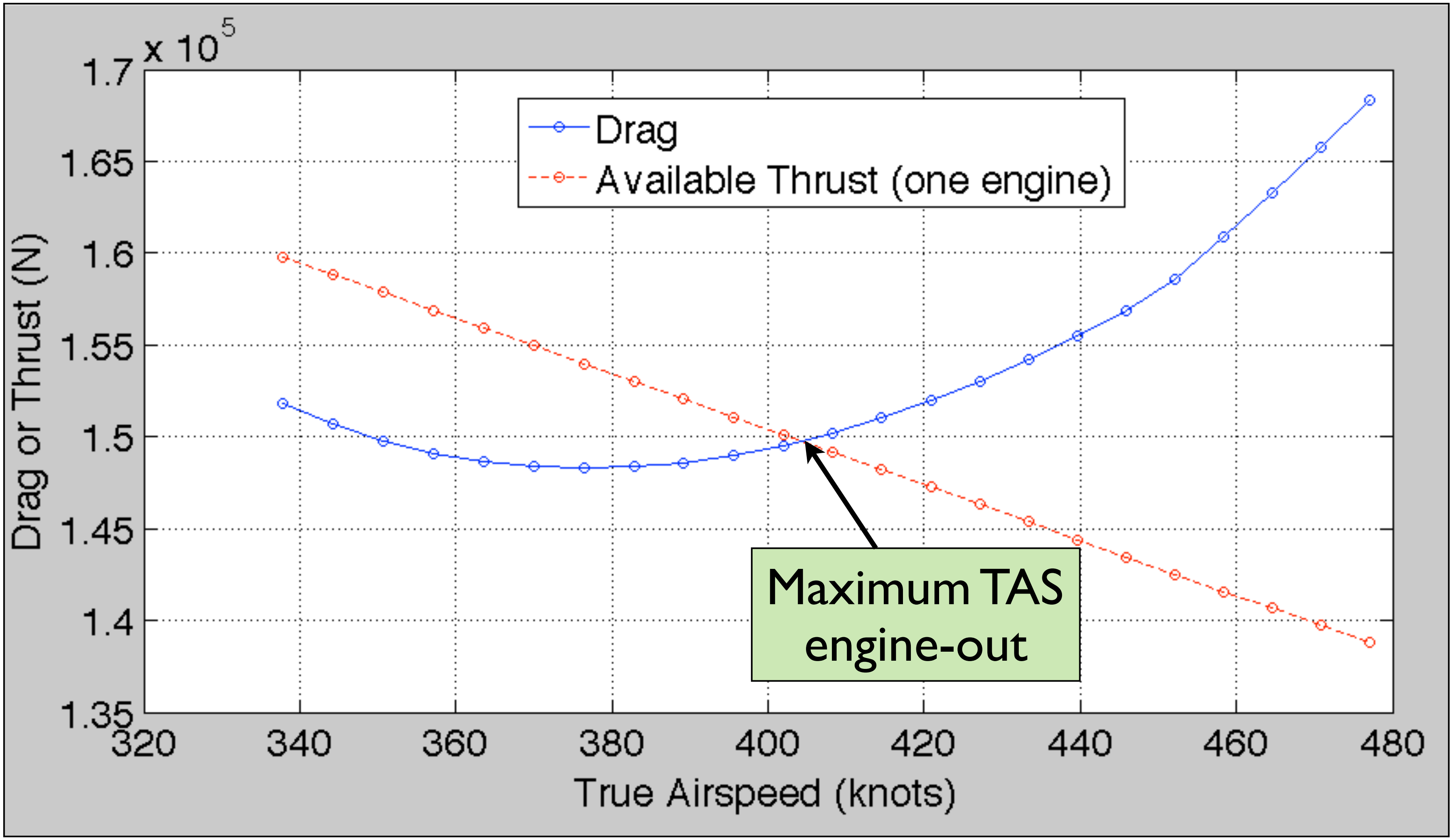
Procedure in Selecting Diversion Speed and Altitude

- Use the **drag03.m function** to calculate drag at altitude
- The corresponding values of optimal speeds (i.e., lowest drag) are found in Table 1
- Note that the minimum fuel burn condition is found at the minimum drag point
- Note that in Figure 4 we illustrate the concept of excess thrust for maneuvering
- Recall that if the aircraft is to perform a turn at the one-engine altitude, a small excess thrust would be required

Procedure in Selecting Diversion Speed and Altitude

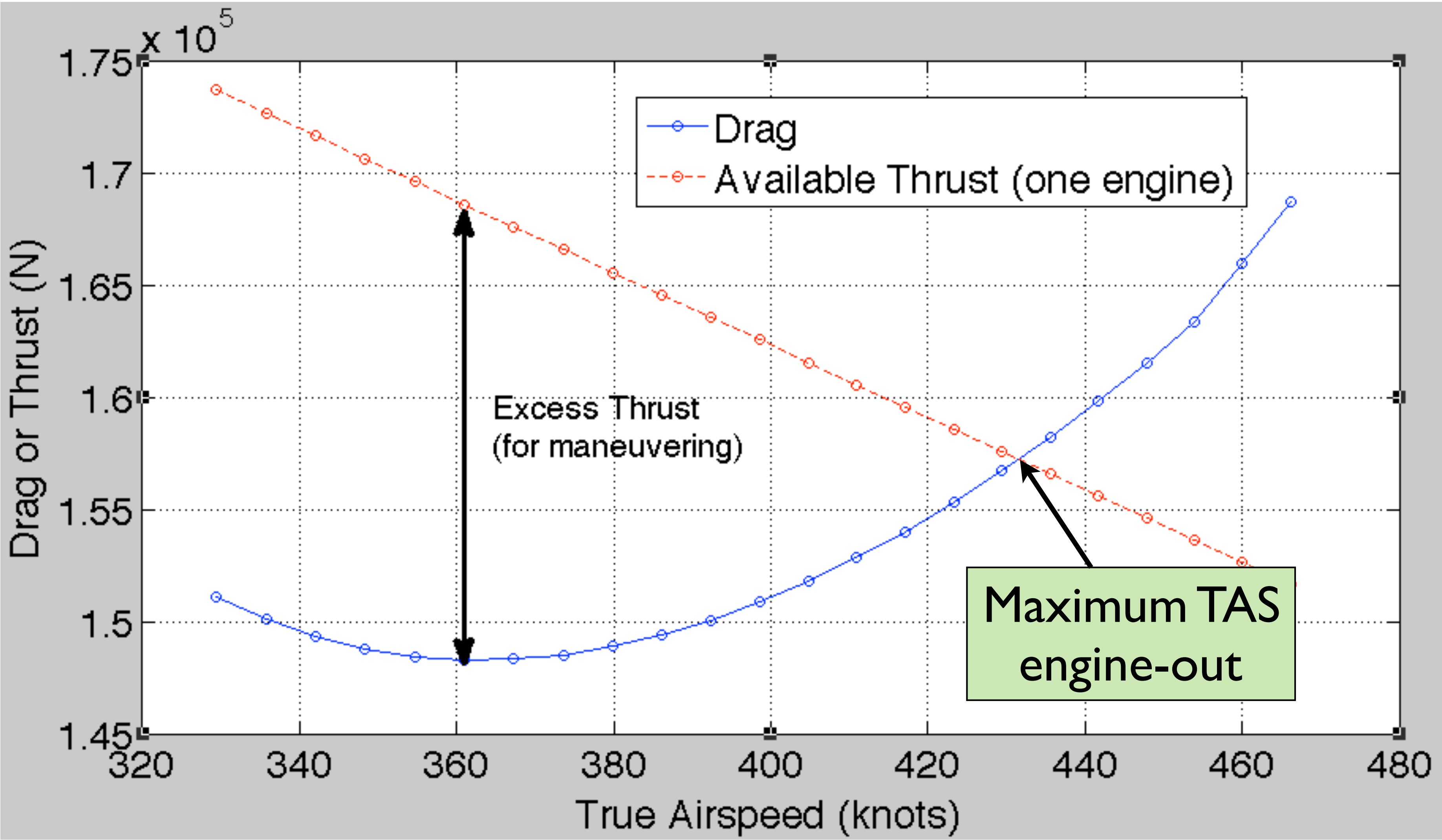
- For this example I use 24,000 feet as the one-engine cruise altitude
- 364 knots true airspeed to fly to the alternate
- This requires an indicated airspeed of 277 knots (at 24,000 feet)
- Note that for all three altitudes, the drag is approximately the same for the optimal speeds found

Finding a Diversion Speed



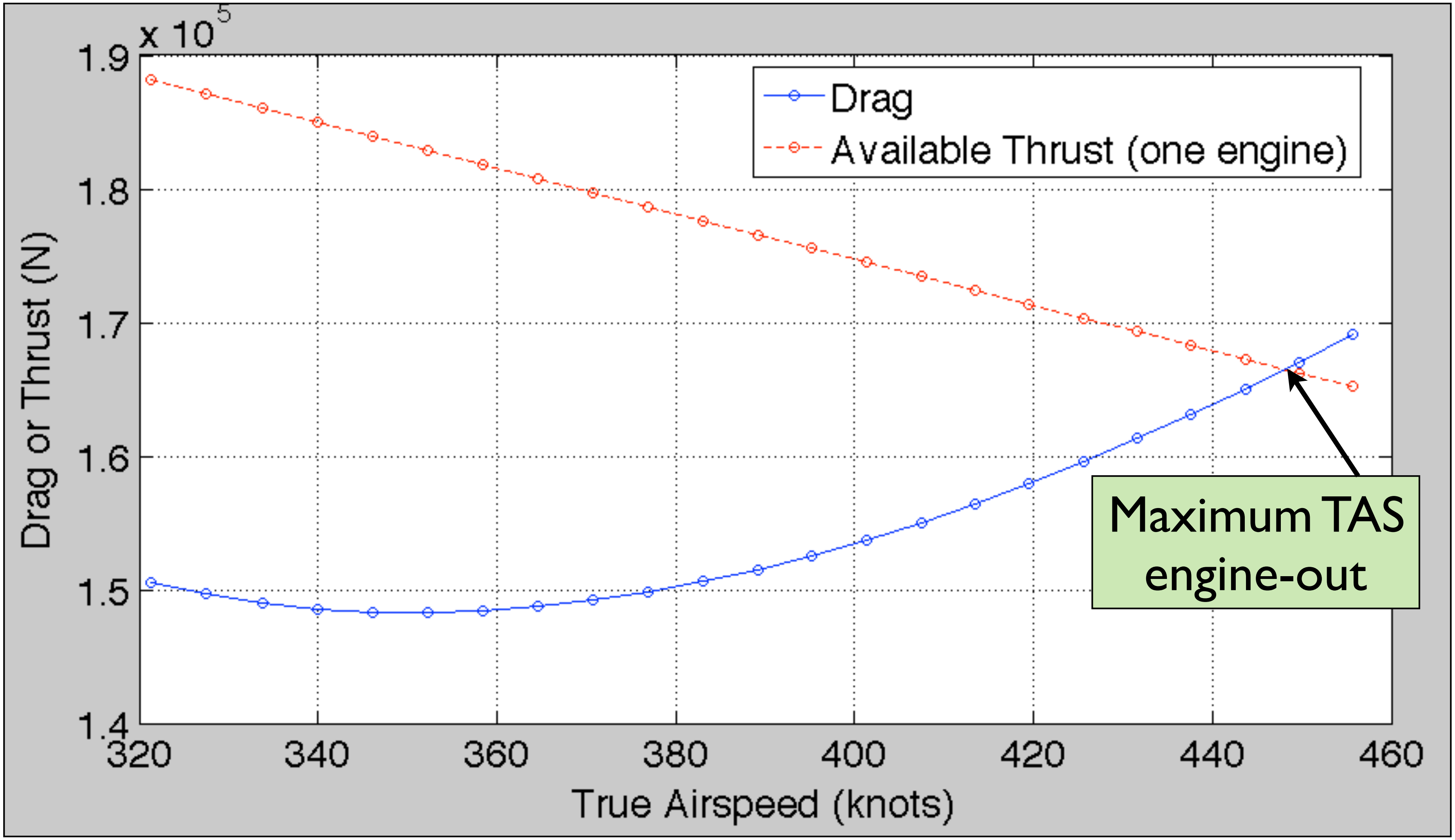
Drag and Thrust Available at h = 26,000 feet and mass = 280,800 kg.

Finding a Diversion Speed



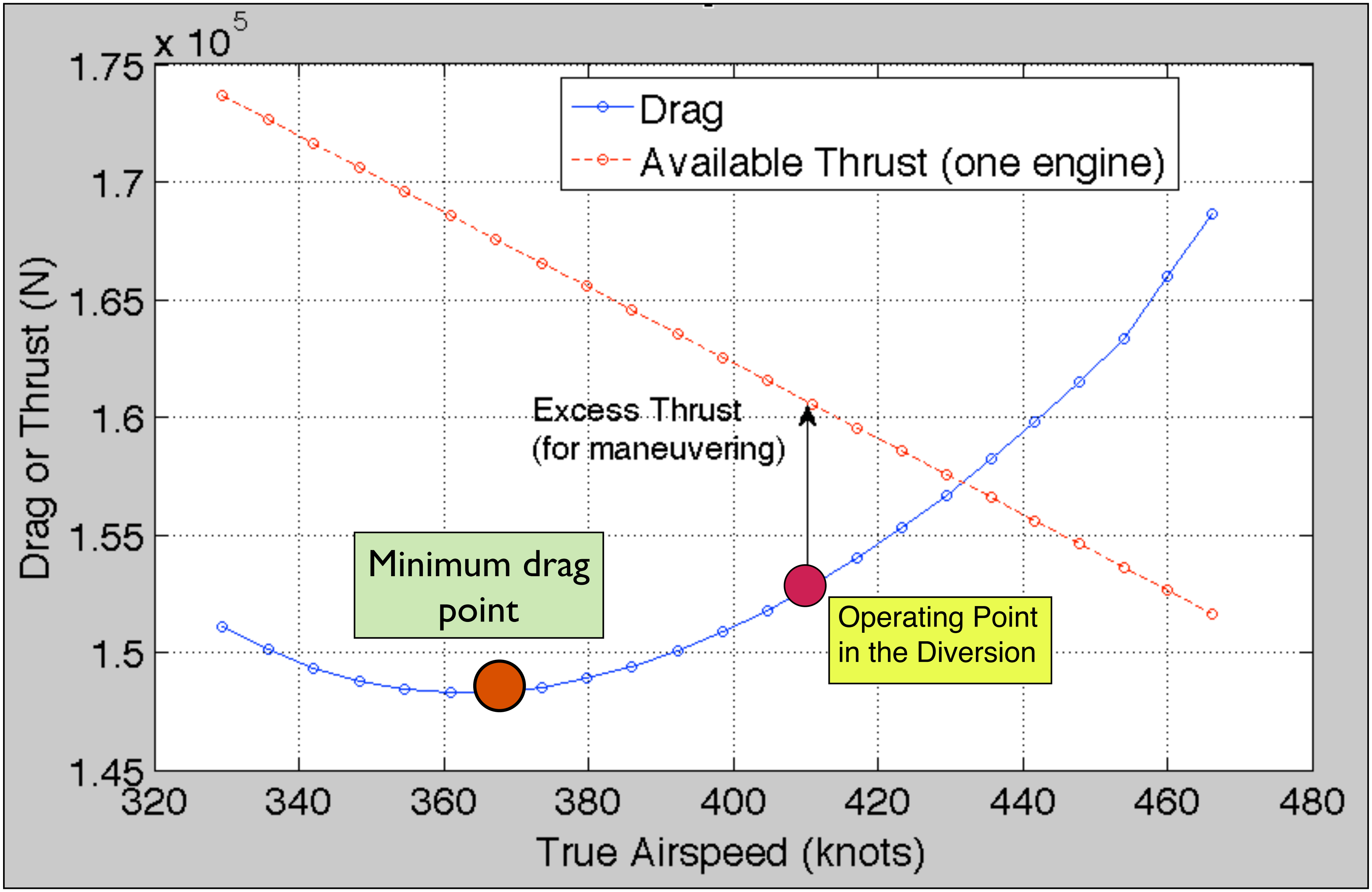
Drag and Thrust Available at h = 24,000 feet and mass = 280,500 kg.

Finding a Diversion Speed



Drag and Thrust Available at h = 22,000 feet and mass = 280,500 kg.

Descent from FL 350 to 240 (Selected Diversion Altitude)



Finding a Diversion Speed

Table 1. Possible Cruise Flight Level Alternatives and Fuel Consumptions.

Cruise Flight Level (x 100 ft) (one engine)	Drag (N)	Fuel Burn (kg/min)	Optimum True Airspeed (Knots)
260	148,300	145.1	375
240	148,250	145.1	364
220	148,240	145.1	352

Calculating the Distance To Descend from FL 350 to 240

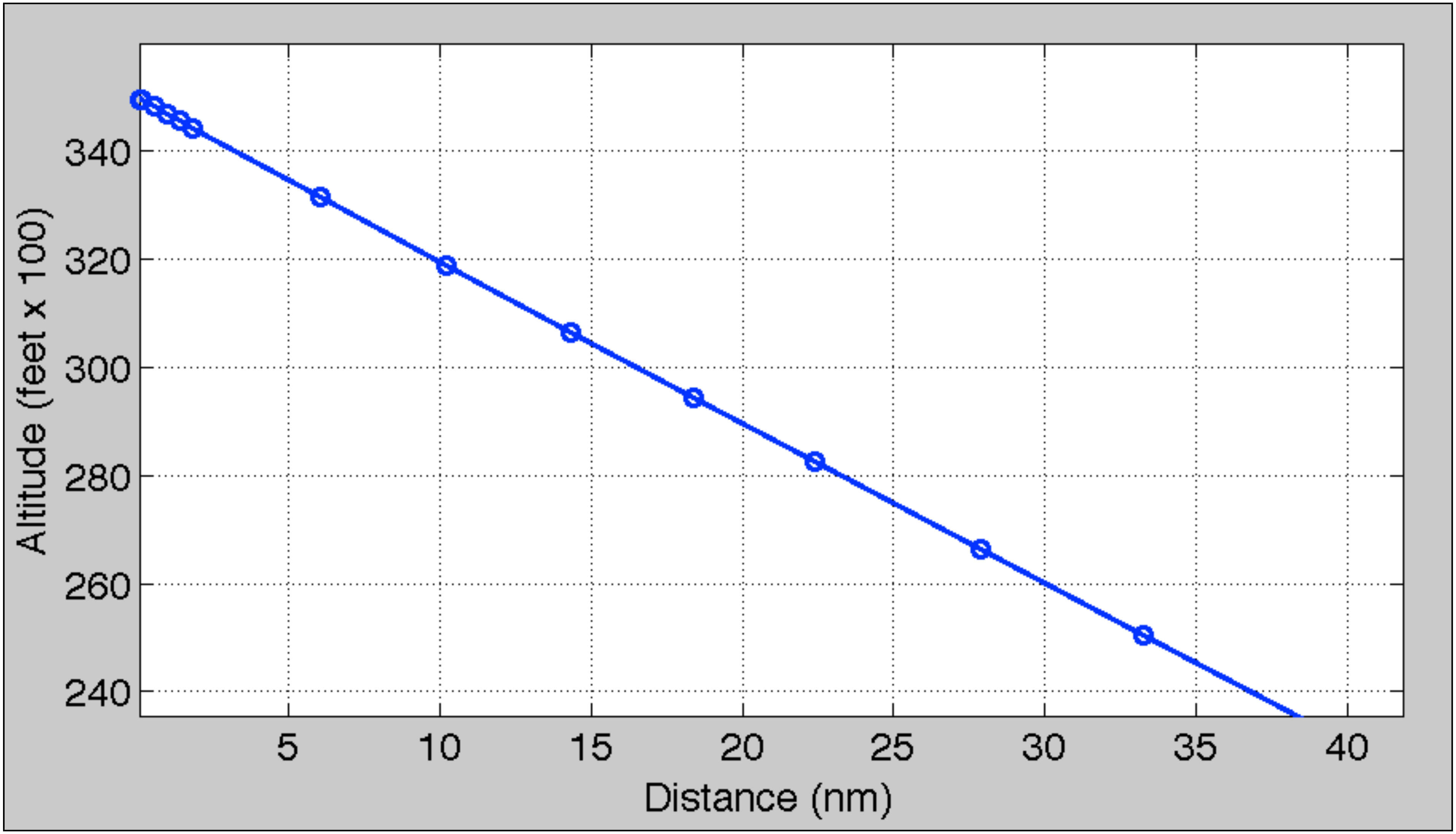
- Using the UnrestrictedDescentProfile.m program calculate the the descent from FL 350 to FL 240
- Figure 6 illustrates the details of the descent profile
- The aircraft covers 37 nm in the descent maneuver.
- The descent takes 328 seconds (5 minutes and 28 seconds) and consumes 75.5 kg of fuel
- I assumed 10% residual thrust in the descent on the remaining engine

Weight at 24,000 feet is

$$W_{24kft} = W_{failure} - FW_{descent} = (280{,}580 \text{ kg - } 76 \text{ kg})(9.81 \text{ m/s}^2)$$

$$W_{24kft} = 280{,}504 \text{ kg} = 2{,}751{,}700 \text{ N}$$

Descent Profile form FL 350 to 240



Finding a Diversion Time (considering wind)

Table 2. Diversion Alternatives. Using Minimum Fuel consumption Optimal Speed at 24,000 feet. Allows for excess thrust for maneuvering.

Airport	Distance from Start of One-engine Cruise to Airport (nm)	Average Wind to Destination (knots)	True Airspeed (knots)	Ground Speed (knots)	Estimated Diversion Time (min)	Legal?
St Johns (Canada)	1,245 - 37 = 1208	0	364	364	3.32	No
Lajes (Azores)	**1,280 - 37 = 1243**	**+ 40**	**364**	**404**	**3.08**	**No**
La Palma (Canary Islands)	1,560 - 37 = 1469	+ 55	364	419	3.51	No
Cabral (Cape Verde)	1,760 - 37 = 1723	-20	364	344	5.01	No

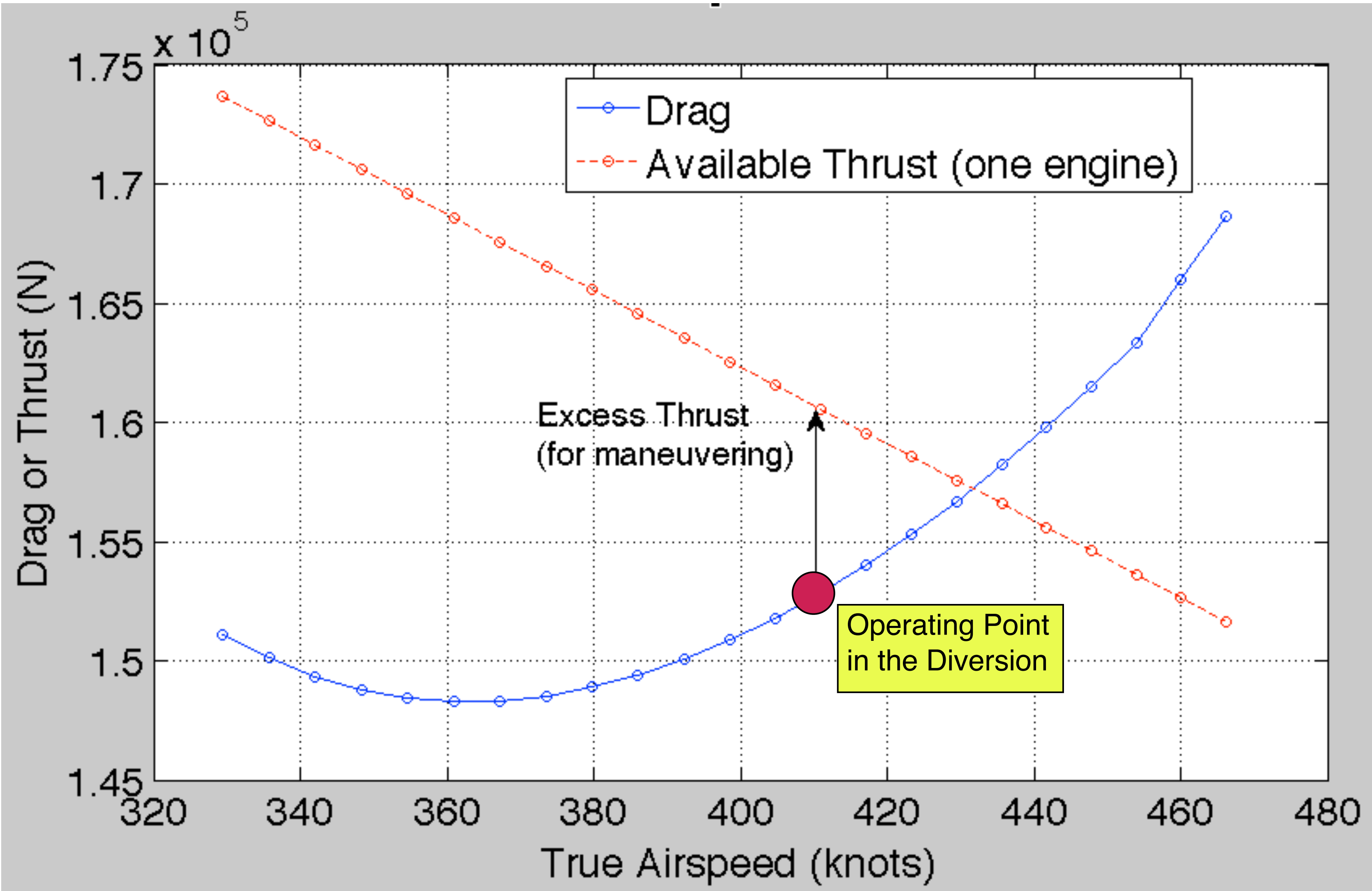
Analysis of Table 2

- The remaining distance to the alternate is reduced accordingly
- Check that the diversion times are within the required 3 hours (assumed 180 minute ETOPS rule)
- Use the head/tailwind components to estimate the travel times.
- Table 2 contains approximate diversion times flown at the optimal (i.e., more fuel efficient speeds)
- Since diversion times exceed the 3 hour requirement we need to shorten the diversion to stay within the 3 hour diversion limit at single-engine speed

Adjusting the Diversion Speed to Achieve a 180 minute Diversion

- It is obvious that Lajes is the best alternative from all alternatives presented
- To fly the 1,243 nm to Lajes within the 3 hour limit we need an equivalent GROUND speed of at least 450 knots if we account for the reductions of speed on the final descent
- Since the aircraft is expected to have a 40 knot tailwind in the trip to Lajes, this implies the aircraft needs a 410 knot true airspeed to achieve 450 knot ground speed with 40 knots of tailwind.

Adjusted Diversion Speed to meet 180 minute Diversion Rule



Drag and Fuel Flow in Diversion

- The flight profile is flown with 152,550 Newtons of drag at the starting point of the 24,000 feet.
- This is also the thrust required by the remaining engine at 410 knots TAS (True Mach Number 0.67 at 24000 feet)
- The aircraft consumes 149.3 kg/minute of fuel at that speed (24.42 N/s)
- Contrast the diversion Mach number (0.67) with the original cruise Mach number (0.82)

Diversion Calculations

- A 2.56-hour diversion at 24,000 feet to reach the TOD point (not accounting for a 19 minute descent) would consume 22,514 kg of fuel from the starting point of the single-engine cruise point to the TOD (conservative estimate) before descent

- The first estimate of aircraft weight at the Top of Descent point (WTOD) would be:

$$W_{TOD} = W_{i-cruise} - FW_{cruise}$$

$$W_{TOD} = [(280,504 kg) - (22,514 kg)](9.81\ m/s^2)$$

$$W_{TOD} = 2,530,900 = 257,990\ kg$$

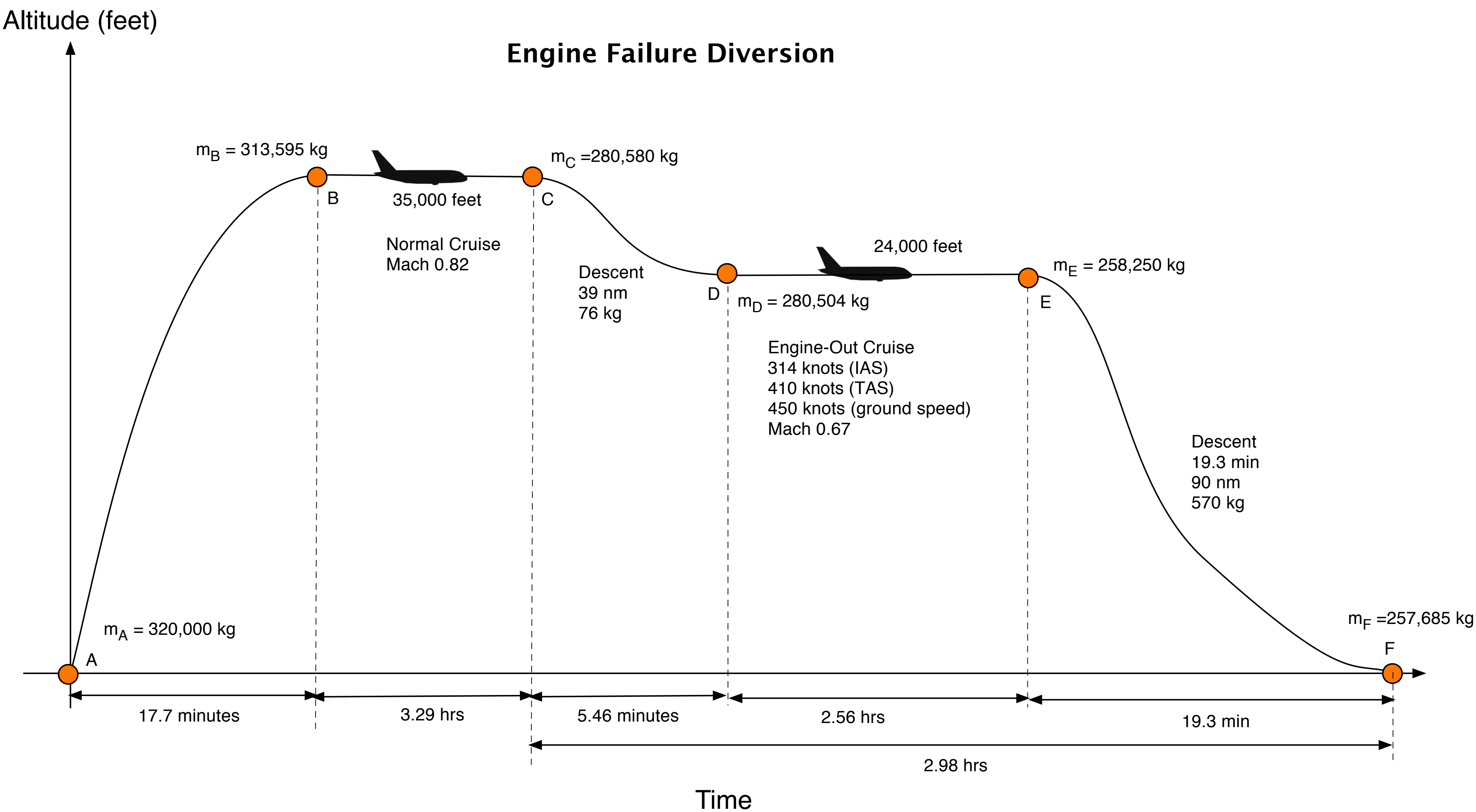
Final Calculations

- Calculate the descent profile from 24,000 feet to sea level (Lajes is located at sea level conditions)
- The aircraft covers 90 nm miles in the descent and takes 19.27 minutes (1155 seconds) to reach sea level conditions
- The aircraft burns 570 kg in the descent. This implies the aircraft mass at the end of the journey is 257,420 kg
- The total fuel consumption would be 62,580kg. The aircraft carries 115,000 kg. thus the journey and diversion legal

Final Calculations (II)

- The travel time from the engine-out cruise point to the TOD is 2.5622 hours to cover 1153 nm (1243-90) at 450 knots of ground speed
- Adding the 19.3 minutes for descent from 24,000 feet to the airport, 5.47 minutes to descend from 35,000 to 24,000 feet and 2.56 hours in cruise mode at 24,000 feet produces a total travel time of 2.98 hours to complete the diversion
- This is within the 3 hour limit expected by the regulators.
- Lajes in the Azores is the best diversion alternative

Vertical Profile of Engine Failure Diversion



Example of In-Flight Engine Shutdown

Swiss Air Boeing 777-300
Zurich-Los Angeles (February 1, 2017)

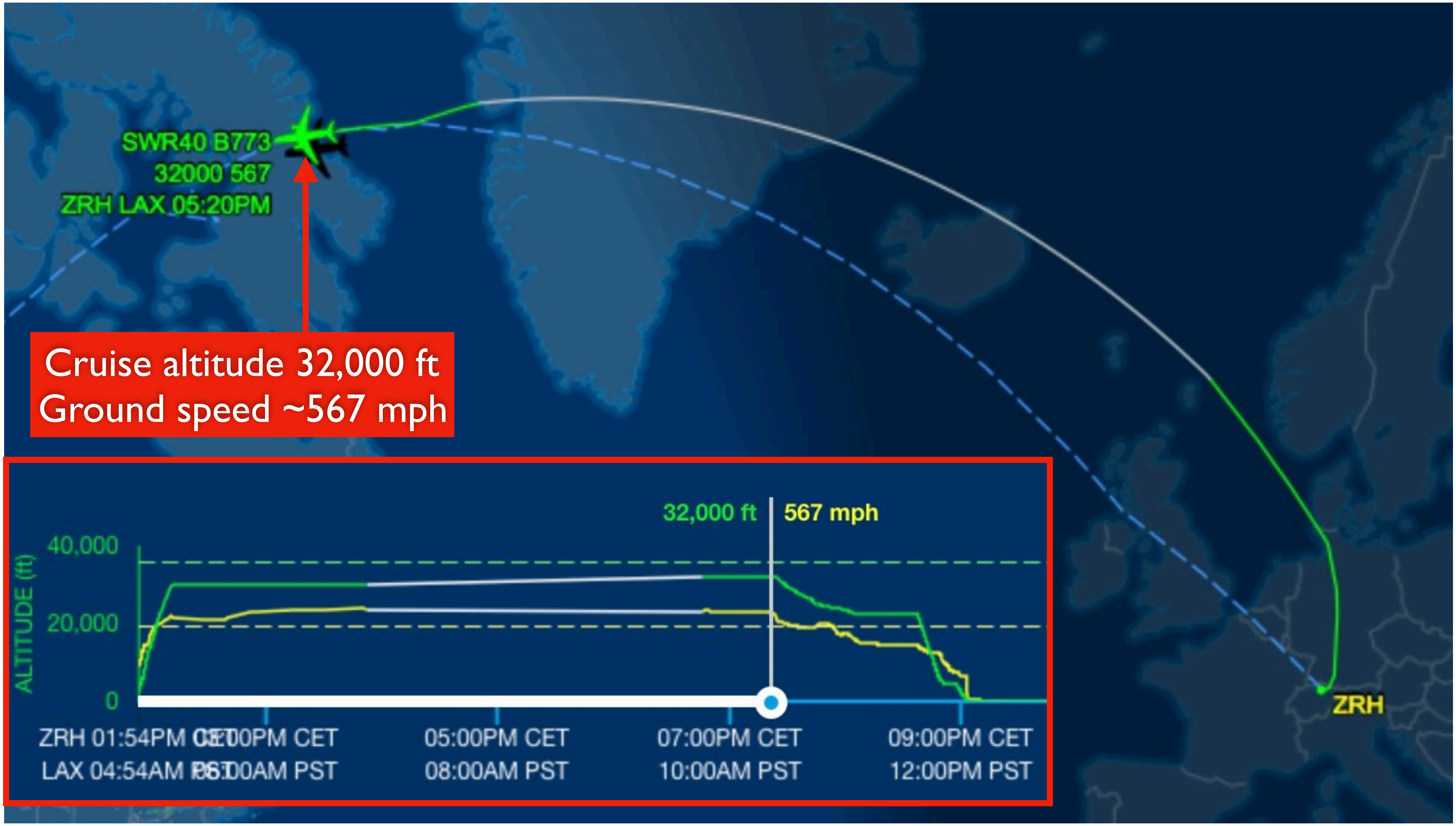
Source: Flightaware https://flightaware.com/live/flight/SWR40/history/20170201/1210Z/LSZH/KLAX

In-Flight Shutdown Event

- While flying at 32,000 feet and 290 nm from Iqaluit, Canada, the left engine shutdowns automatically *
- Crew diverts to Iqaluit, Canada (single runway is 8,605 feet)
- Aircraft drifted down to 22,600 feet after the engine shutdown
- Initial ground speed was 567 mph (476 knots estimated true airspeed - estimated)
- Single engine speed was reduced to 380 mph (370 knots true airspeed - estimated)

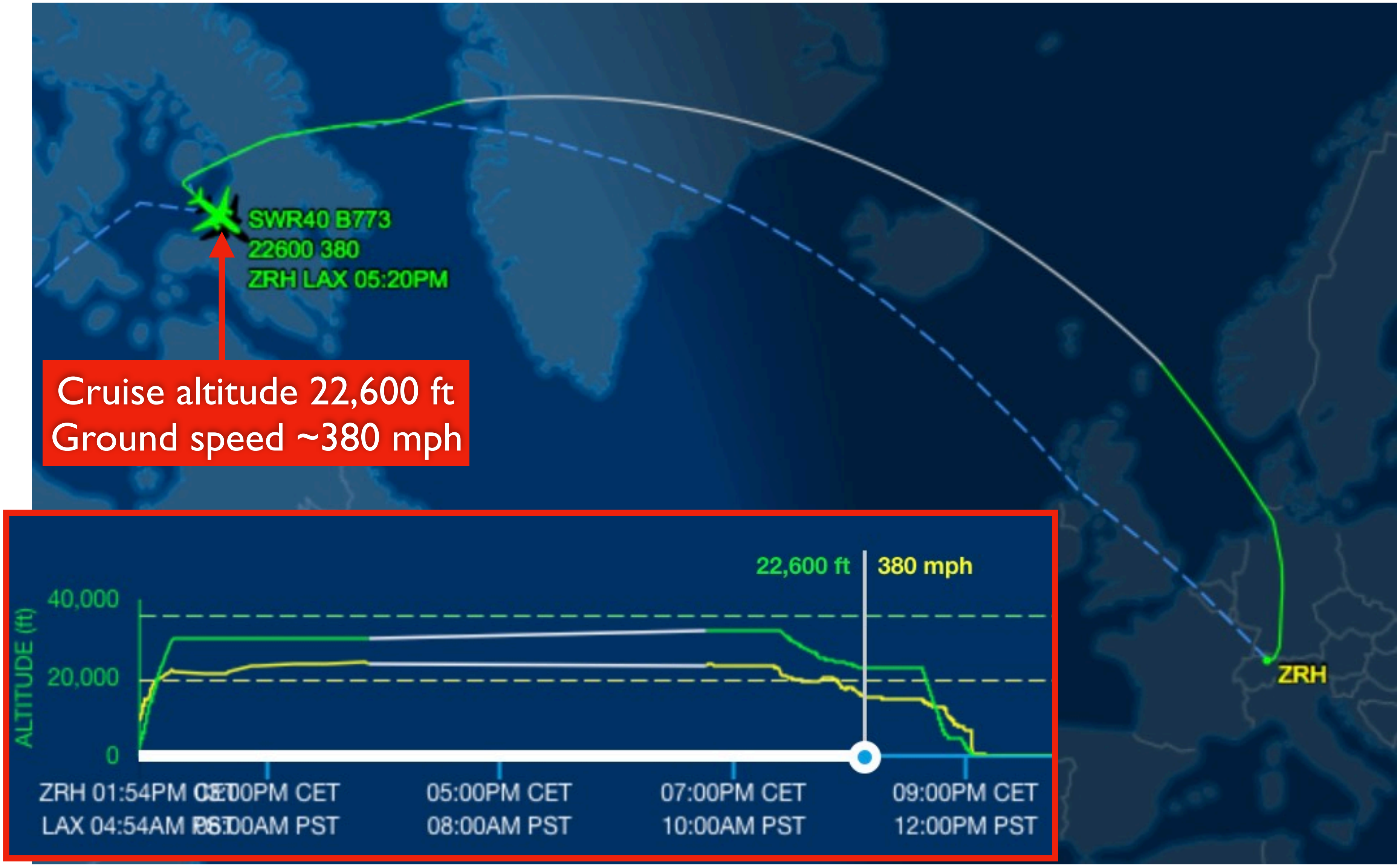
* Source: avherald.com (http://avherald.com/h?article=4a453674&opt=0)

Swiss Air Boeing 777-300 Before Engine Shutdown



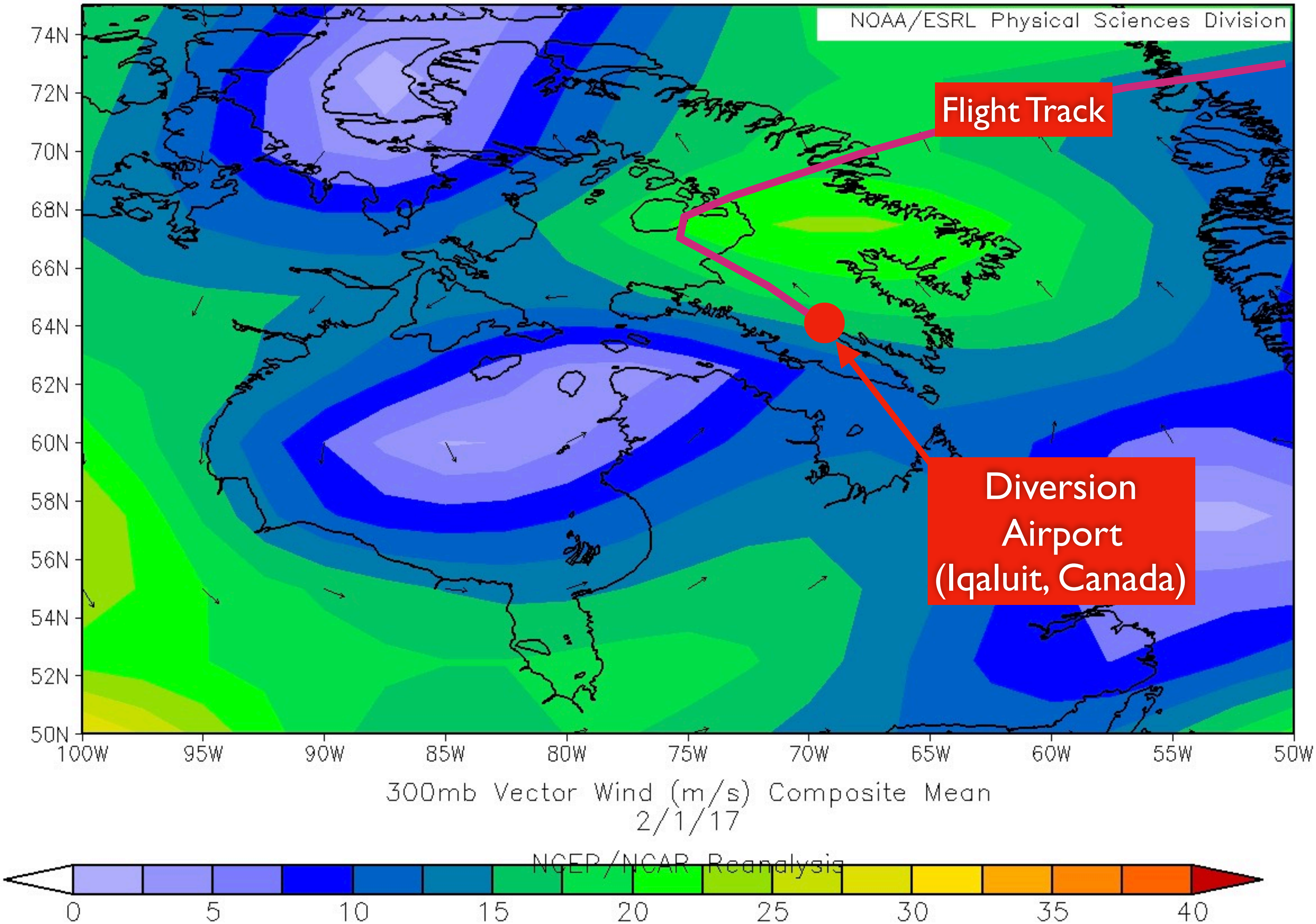
Source: Flightaware https://flightaware.com/live/flight/SWR40/history/20170201/1210Z/LSZH/KLAX

Swiss Air Boeing 777-300 After Engine Shutdown

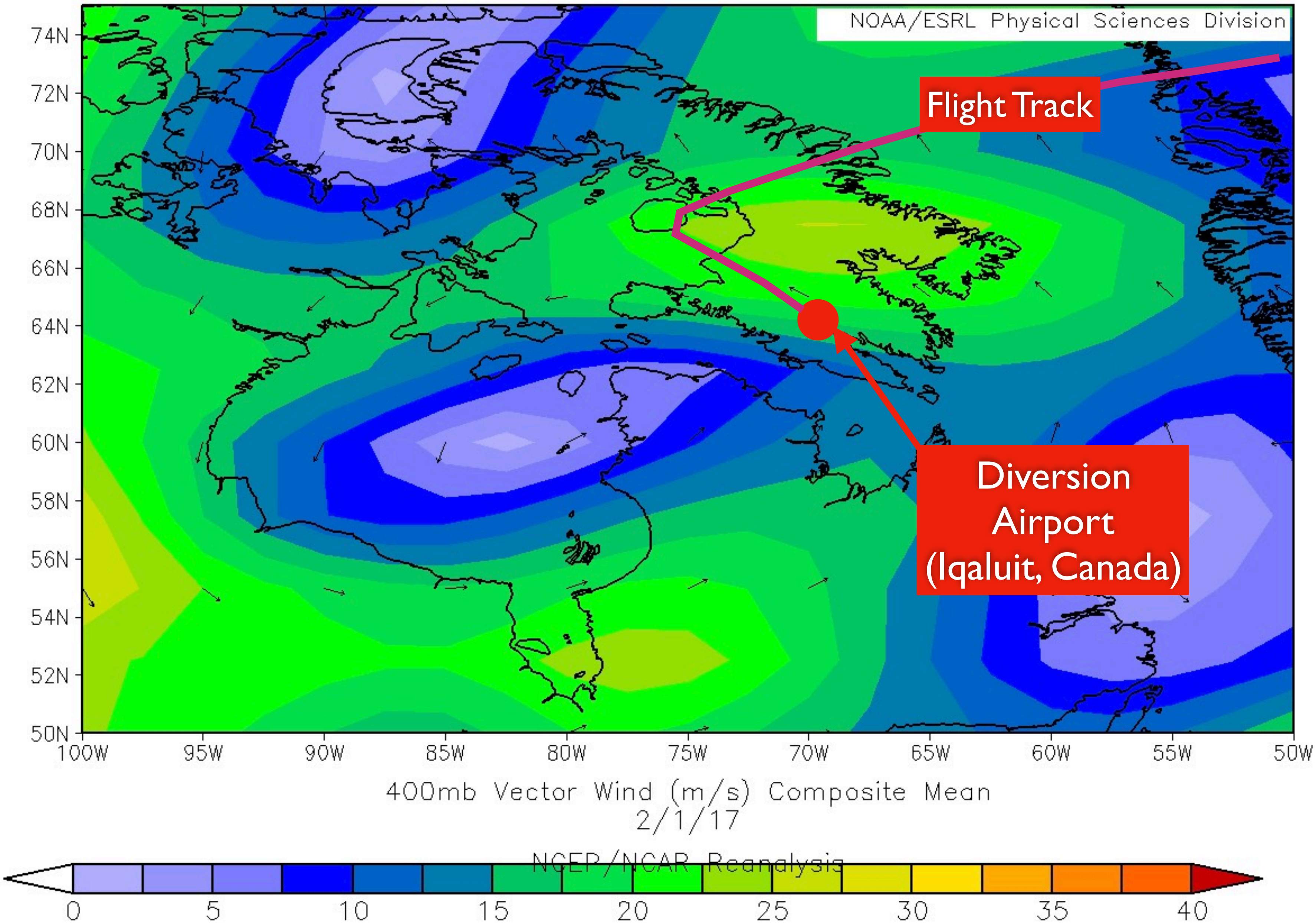


Source: Flightaware https://flightaware.com/live/flight/SWR40/history/20170201/1210Z/LSZH/KLAX

Winds on Feb/1/2017 at 30,000 feet



Winds on Feb/1/2017 at 23,500 feet



Observations

- Aircraft drifted down to **22,600** feet after the engine failure
- Aircraft encountered ~38 knot headwinds after turning Southeast to Iqaluit (370 knot true airspeed)
- The aircraft was initially flying at 476 knots (TAS)
- The aircraft lost **106 knots** at the end of the drift down maneuver down **to 22,600 feet**
- Discuss: implications of flying over high terrain