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**PRELIMINARY DEVELOPMENT AND FLIGHT TRIALS OF A
CRUISE ALTITUDE AND SPEED OPTIMIZATION DECISION
SUPPORT TOOL**

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This report is based on the Master's Thesis of Clement Li submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degree of Master of Science at the Massachusetts Institute of Technology.

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Preliminary Development and Flight Trials of a Cruise Altitude and Speed Optimization Decision Support Tool

by

Clement Li

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Abstract

A cruise altitude and speed optimization decision support tool, based on the concept of a minimum cost altitude tunnel, was developed to aid flight crew and dispatcher situational awareness and decision-making in vertical trajectory planning in order to reduce fuel and time costs. As the optimal altitude for an aircraft changes with speed, weight, outside air temperature, and winds, flight crew decision-making can benefit from the calculation and display of the relative flight costs of possible trajectories. The concept of a minimum cost tunnel is introduced, and the decision support tool is presented. Four preliminary flight trials were conducted with a Boeing 777-200 and prototype decision support tool. The preliminary flight trials suggest that the decision support tool is useful and improves situational awareness and coordination between dispatcher and flight crew. The initial flight trials also indicated that flight crews would benefit from higher quality turbulence information, including synchronization of the turbulence information available to flight crews and dispatchers. The largest fuel savings observed for a flight from the preliminary flight trials was over 3800 lbs. Additionally, the flight trials suggest that the minimum cost tunnel would even be useful as a static image included as part of the flight plan to provide situational awareness and facilitate coordination with dispatchers.

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Chapter 1

Introduction

This study investigates opportunities for improving airline flight efficiency through a cruise altitude and speed optimization decision support tool. Although significant effort has been spent on optimizing lateral routes, optimizing vertical trajectories can result in significant savings [1]. Currently, some flights spend some or all of cruise off the optimal speed and altitude. This may be due to either planned deviations or tactical adjustments made en-route, and deviations may occur for turbulence, air traffic constraints, outdated weather information, difficulties in communicating complicated trajectories, or other reasons.

Currently, flight crews are provided with limited information and guidance for flying optimal vertical trajectories. Flight plans are typically generated two to three hours before takeoff and consist of a list of lateral waypoints and a single altitude profile with winds provided at three or four altitudes. The optimal trajectory changes with the flight's weight and with the evolution of weather. While optimal trajectories often tend to increase gradually in altitude as the aircraft burns off fuel, they can also involve unexpected and sudden altitude shifts up and down when crossing into or out of jetstreams.

As a result, when off-nominal situations arise, such as encountering unexpected turbulence along the planned route, determining the optimal trajectory with respect to the new situation can be difficult for flight crews. In current practice, flight crews use general rules of thumb and the flight management computer (FMC) to calculate

estimated fuel burn and flight time. Using the FMC can impose workload demands, as manual input of each trajectory considered is required.

A decision support tool (DST) was developed to assist in increasing situational awareness and reducing costs by calculating and displaying the costs of the performance space in the form of a minimum cost tunnel, along with identifying the cost-optimal trajectory. The minimum cost tunnel provides a graphical representation of the relative costs of the altitude decision space, allowing crews to evaluate trajectory options by visual inspection. The decision support tool also incorporates higher resolution wind data and updates to forecasts as they become available over the progression of a flight.

Chapter 2

Background

Airlines seek to minimize the costs of a flight without compromising safety or passenger comfort. As aircraft typically spend the majority of their flight time and, consequently, fuel burn in cruise, the cruise phase presents an opportunity for reducing flight costs through trajectory optimization. Flight costs can be broken down into fuel burn and time-associated costs, such as crew costs and maintenance costs that generally scale with time. Trajectory planning involves determining the lateral route, altitude profile, and speed profile for a flight that minimizes the flight's total cost within constraints imposed by the airspace structure, air traffic control, and weather for the safety of the flight. Additionally, flights also take into account turbulence in order to maintain a comfortable ride quality for passengers.

2.1 Lateral Planning

Planning of lateral routes consists of finding routes that minimize flight time at a constant airspeed, given the expected winds aloft during the flight and accessible airspace. In the presence of winds, the great-circle route, which minimizes ground distance between two points, is often not the route resulting in the shortest flight time or fuel burn. Wind-optimal trajectories achieve shorter flight times while flying slightly longer ground distances by taking advantage of favorable tailwinds and minimizing the impact of headwinds. Flights must also be planned to avoid restricted

areas, such as active military operating areas, and areas of significant weather. Consideration may also be given for air traffic control considerations, such as ATC fees or routes likely to be cleared by air traffic control. Savings on the order of 1-3% can be achieved by improving lateral route planning, and there is significant ongoing effort to improve lateral trajectory planning both for the pre-flight planning phase and while en-route [3] [4].

2.2 Vertical Planning

In addition to lateral optimization which has been well studied, significant savings can also be realized through vertical optimization, where less research has been directed. Vertical planning seeks to minimize costs by determining the altitude and speed profiles based on both aircraft performance and wind conditions. As the aircraft gets lighter from burning fuel, the optimal altitude tends to increase. However, if there is a differences in the wind field at various altitudes, the optimal altitude may also shift towards stronger tailwinds or weaker headwinds when the difference in windspeed is significant enough to offset the additional fuel burn. As the wind field varies with time and lateral location, the optimal altitude will also tend to have local variations. When turbulence is expected en-route, airlines may prefer to fly vertical trajectories with higher costs in order to avoid turbulence.

A study of domestic flights in the U.S. examined potential fuel burn savings from altitude optimization [1]. The distribution of potential savings is shown in Fig. 2-1. While the average potential savings from the study was 1.75%, the distribution has a long tail with a quarter of flights showing potential savings of over 4.5%. This research focuses on vertical optimization.

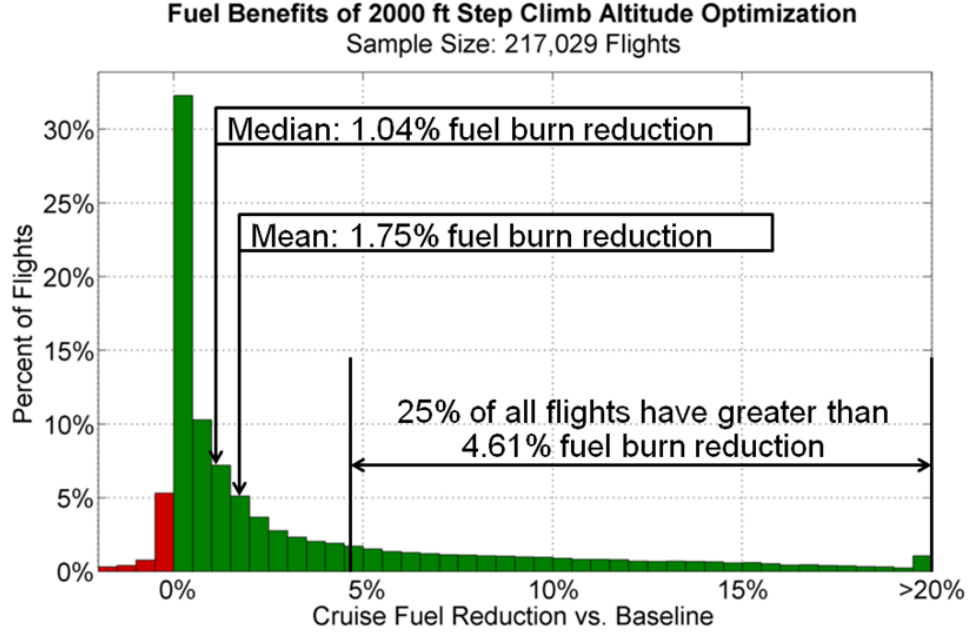


Figure 2-1: Fuel Savings from Altitude Optimization for 217,000 U.S. domestic Flights in 2012. Adapted from [1]

2.3 Cost

For this thesis, the total cost incurred for a particular trajectory or trajectory segment is defined as

$$\text{Cost} = C_F * F + C_T * T \quad (2.1)$$

where F is the amount of fuel burned, T is the flight time, C_F is the cost of fuel and C_T is the cost of time. However, since the cost of fuel and cost of time can vary, airlines use the cost index to describe the relative cost of time to cost of fuel [5]. The cost index is defined as

$$\text{Cost Index} = \frac{\text{Value of Time}}{\text{Value of Fuel}} \quad (2.2)$$

As a result, the cost of a trajectory or trajectory segment can be described as

$$\text{Cost} = C_F * F + C_F * CI * T \quad (2.3)$$

where CI is the cost index.

2.4 Fuel Burn

The fuel-optimal altitude and speed for an aircraft at any given point along its flight depend on the weight of the aircraft, winds aloft, and outside air temperature. Efficiency contours of specific ground range (SGR) for a typical transport aircraft at a given weight are shown in Fig. 2-2. SGR is a measure of the ground distance traveled per mass of fuel burned. The efficiency contours are spaced more widely near the optimal point, representing a region where the fuel burn is relatively insensitive to altitude and speed. However, as an aircraft's speed and altitude move away from that region, the fuel efficiency falls off sharply, reflected by the narrowing contours. Current airline flights typically fly faster than fuel-optimal and at altitudes that may vary from the optimal altitude.

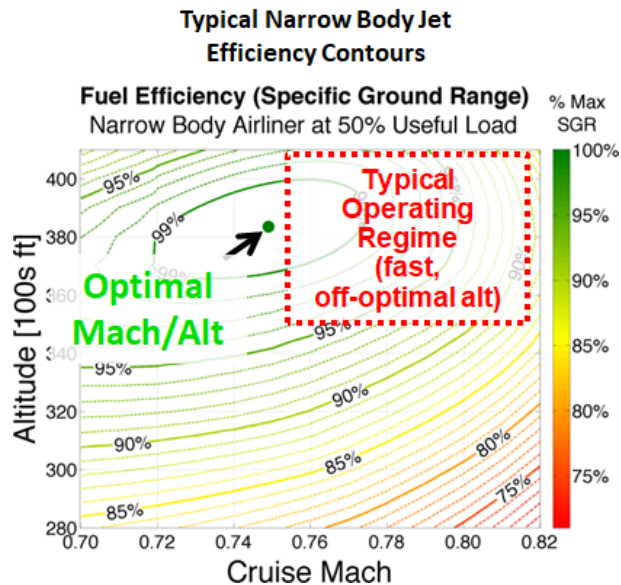


Figure 2-2: Typical Fuel Efficiency Contours. Adapted from [1].

As aircraft weight decreases due to fuel burn, the optimal altitude increases. As weight decreases, the amount of lift generated by the aircraft must also decrease to maintain steady level flight. In order to maintain the angle of attack that achieves the maximum lift-to-drag ratio, the aircraft can either slow down or climb to a higher altitude where the air density is lower. Higher speeds, within the normal operating speeds of transport aircraft, maximize the distance travelled per unit of fuel, and

therefore, the optimal altitude increases as weight decreases [6].

Accounting for winds, the fuel-optimal altitude tends to shift toward altitudes with stronger tailwinds and away from stronger headwinds. Stronger tailwinds require less energy to travel a given ground distance, since the aircraft's speed over the ground increases compared to the true airspeed, which determines fuel burn. Headwinds require additional fuel for the same distance, since the groundspeed decreases compared to the true airspeed.

In headwinds, the fuel-optimal speed increases in order to reduce the amount of time the aircraft spends in the headwind. Similarly, in tailwinds, the fuel-optimal speed decreases, as the aircraft is then able to extract greater benefit by staying in the tailwind for a longer period of time over a given distance.

2.5 Flight Time

Airlines also consider maintenance and crew costs, which increase with flight time. As a result airlines may fly faster than fuel-optimal in order to reduce time costs. In the event of delays, airlines may also be willing to burn additional fuel in order to regain schedule. Cruise speed is primarily managed through the cost index. Cost index policy differs between airlines, but generally will vary with aircraft type, current fuel and labor costs, route, and the extent a flight is early or late.

2.6 Turbulence

Passenger flights also take ride quality into consideration and may choose to fly trajectories with additional costs in order to avoid turbulence. Turbulence may cause passenger discomfort, or in severe cases, be a safety concern for passengers and crew who may be injured by being thrown against the cabin or from unsecured objects. In 2016, 44 serious injuries were reported [7]. Flights are typically planned to avoid areas of forecast or reported turbulence, and flight crews often request changes in altitude upon encountering unexpected turbulence. If unable to avoid the turbulence,

the flight crew may slow the aircraft to turbulence penetration speed and ensure that the cabin crew, passengers, and objects are secured.

Turbulence information is available in the form of forecasts and observations from pilot reports (PIREPs) or automatic aircraft reports of encountered turbulence. A common metric used for turbulence is eddy dissipation rate (EDR), an aircraft-independent quantity that is used to measure turbulence intensity. EDR describes the rate of dissipation of kinetic energy into heat [8]. EDR can be measured in situ with sensors onboard aircraft or estimated from numerical weather prediction models. Dispatchers at an airline operations center have access to forecasts and the subset of pilot reports that are publicly available, submitted internally within the airline, or from the airline’s weather service provider. Flight crews generally have access to turbulence forecasts and any additional turbulence information provided by the dispatchers. They are also able to query ATC for ride reports from flights in the vicinity.

2.7 Current Flight Planning Practice

Dispatchers, along with the captain of the flight, are responsible for preflight planning, dispatching, and monitoring of flights to ensure safety and efficiency [9]. Dispatchers are typically located at a centralized airline operations center and monitor weather conditions at the destination, alternate airports, and along the route [10]. Dispatchers use flight planning tools and past experience to plan lateral routes based on forecasts for en-route winds and weather, en-route charges such as ATC fees, as well as other requirements that may vary depending on region and route. Fuel loading is calculated based on the route, speed, winds aloft, aircraft performance, payload weight, and reserve requirements. For domestic flights, FAR part 121 specifies that flights must also include sufficient fuel to fly to an alternate airport and an additional 45 minutes [11].

The altitude profile is generated based on the estimated optimal altitude for the expected weight along the route. The start of cruise, when air traffic constraints

allow, is planned for the optimal altitude at the expected weight and time at top of climb. Step climbs along the route are planned as the optimal altitude increases along the progression of the flight. Although the optimal altitude varies continuously, step climbs are used to approximate the continuous optimal profile due to the airspace allowing flights only at specific, discrete flight levels. The cost index is determined by economic factors and schedule, with higher cost indices sometimes employed to recover from delays.

The dispatcher makes additional modifications based on his or her experience and judgment if there are anticipated issues such as with air traffic control or weather at the destination. For example, dispatchers may load additional fuel if convective weather is expected around the destination airport in case of the need to hold over the destination or modify the lateral trajectory en-route for weather avoidance.

The briefing package, including the flight plan and other relevant flight information such as significant weather charts and NOTAM briefings, is sent to the flight crew approximately two hours prior to departure.

The captain reviews the briefing package, flight plan, and other relevant information before either signing off on the flight plan or discussing any issues with the dispatcher. The captain may, for example, request additional discretionary fuel based on his or her experience. The dispatcher and captain reach consensus on the flight plan, and the flight is released. The dispatcher files the flight plan with air traffic control, which may clear the flight for the proposed route or amend the routing that is cleared and delivered to the flight crew. The dispatcher may also revise the flight plan if weather conditions change, significant delays are incurred, or the expected takeoff weight of the aircraft changes significantly.

The flight plan is provided to the flight crew as a point-to-point list of lateral waypoints with a corresponding, recommended altitude, as shown in Fig. 2-3. The leftmost column lists waypoint names. Moving to the right, the next column lists the planned altitude in 1000s of ft. Also listed are latitude, longitude, planned Mach, winds, and expected segment fuel burn.

Once en-route, the dispatcher continues to monitor the progress of the flight and

VERTI		N45.25	W074.84	800	046°	551	-02
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AGLUK		N46.21	W073.37	800	054°	551	+00
AGLUK	35	3080	0:15	2231	061°	461	002 121
BAREE		N48.15	W069.30	800	068°	562	+07
BAREE	35	2879	0:37	5202	071°	465	007 107
TUDEP		N51.17	W053.23	800	066°	551	-00
TUDEP	35	2229	1:47	14552	065°	461	029 093
N52W050		N52.00	W050.00	800	086°	552	-01
5250N	35	2098	2:01	16363	082°	460	031 095
N52W040		N52.00	W040.00	800	077°	579	-03
5240N	35	1727	2:41	21392	076°	459	019 126
N53W030		N53.00	W030.00	800	076°	565	-08
5330N	35	1355	3:19	26094	083°	456	107 124
N54W020		N54.00	W020.00	800	088°	534	+13
5420N	35	994	3:59	30912	093°	469	120 084

Figure 2-3: Typical flight plan showing waypoint names, latitude, longitude, planned Mach, winds, expected segment fuel burn, and other information

conditions along the route. The flight crew is able to request desired altitude changes from ATC, which can grant or deny the request depending on airspace availability. ATC may also amend route clearances to avoid traffic or weather and to provide more direct routing when feasible. Significant deviations from the flight plan, generally 4,000 ft or 100 NM laterally, require coordination with the dispatcher that is following the flight.

If the planned vertical trajectory cannot be followed, or conditions change, the flight crew may need to consider alternatives. The flight plan, however, does not provide suggestions or costs for alternate trajectories. If turbulence is encountered on the planned altitude, the flight plan does not indicate whether climbing or descending is the lower cost option. Pilots may rely on experience or rules of thumb. Estimates for the fuel burn and flight time can be calculated by the FMC. However, the FMC is not designed for exploration, requiring manual entry of each trajectory, which results in workload imposed on the flight crew. The limited guidance provided by the flight plan, particularly for replanning trajectories, suggests that improved decision support in the cockpit may provide increased situational awareness and potential cost reduction.

2.8 Altitude Tunnel

In his work on altitude and speed optimization, Jensen developed the concept of a fuel efficiency tunnel [1], illustrated in Fig. 2-4, which shows a visual depiction of the additional fuel burn penalty relative to the fuel burn of the optimal trajectory for various altitudes in cruise along the progression of a flight. The colors correspond to varying rates of fuel burn, with cooler colors represent less fuel burn, while the warmer colors indicate increased fuel burn. The optimal altitude trajectory occurs in the center of the dark blue region.

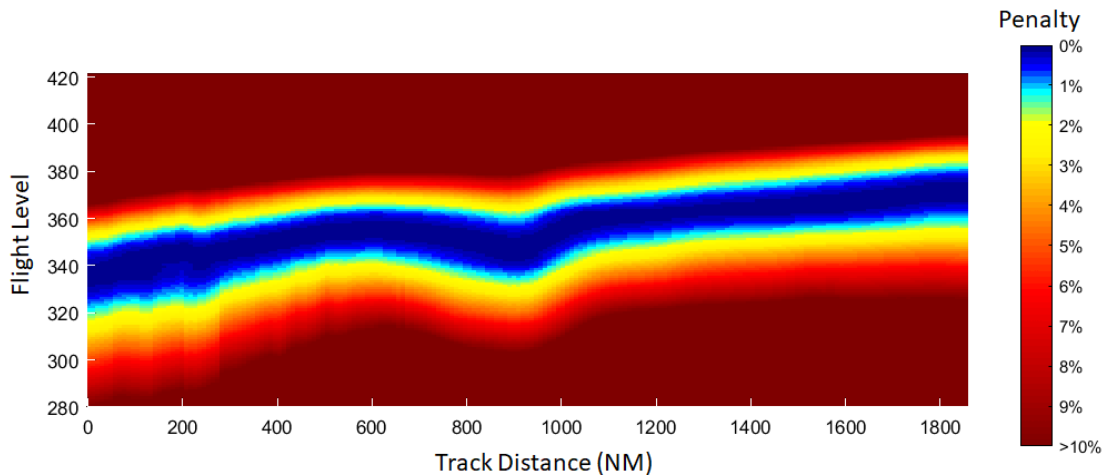


Figure 2-4: Minimum cost tunnel showing relative penalty costs at various altitudes along the cruise track. Cooler colors indicate lower penalty costs (e.g. blue represents altitudes with less than 1% penalty cost). Adapted from [1]

Although the optimal altitude is constantly varying across a flight, the performance curves of the aircraft near the optimal point are relatively flat in altitude and speed, such that there exists a range of altitudes near the optimal for which the increase in costs is comparatively small. As the flight moves away from the center of this region near the minimum cost trajectory, the costs begin to increase more sharply. As a result, there is a range of altitudes, in this case approximately 3000 ft, at each point along the track for which the additional fuel burn penalty is within only one or two percent additional cost. Beyond this range, the fuel burn begins to increase at a higher rate. The altitude range varies by aircraft type, and a list of aircraft and their

corresponding altitude ranges can be found in [1].

Figs. 2-5 through 2-7 presents a set of example cases. Fig. 2-5 shows a typical fuel efficiency tunnel shape where the optimal altitude profile generally follows the expected cruise-climb as the aircraft weight decreases over time. However, due to changes in winds aloft, the tunnel does not always follow this general shape. Fig. 2-6 is a case where the altitude tunnel decreases in altitude due to a vertical wind gradient favoring lower altitudes that becomes stronger as the flight progresses. If there is a change in the altitude gradient of a strong headwind or tailwind due to flying into a jetstream or a heading change, there can be a sudden shift in the tunnel altitude that may not be expected. Fig. 2-7 shows an example of a sudden drop in the altitude tunnel approximately a quarter of the way along the track.

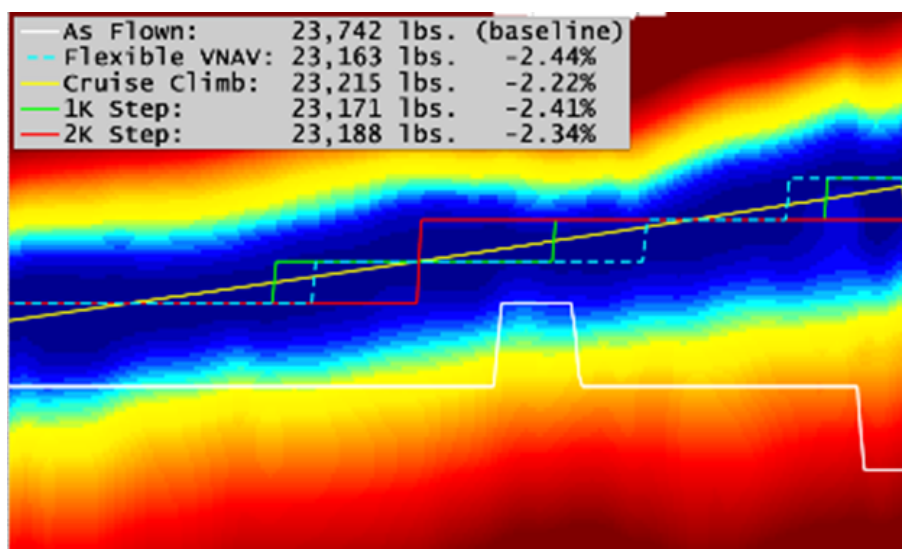


Figure 2-5: Example fuel efficiency tunnel showing a typical case where the tunnel approximately follows a cruise-climb. Adapted from [2]

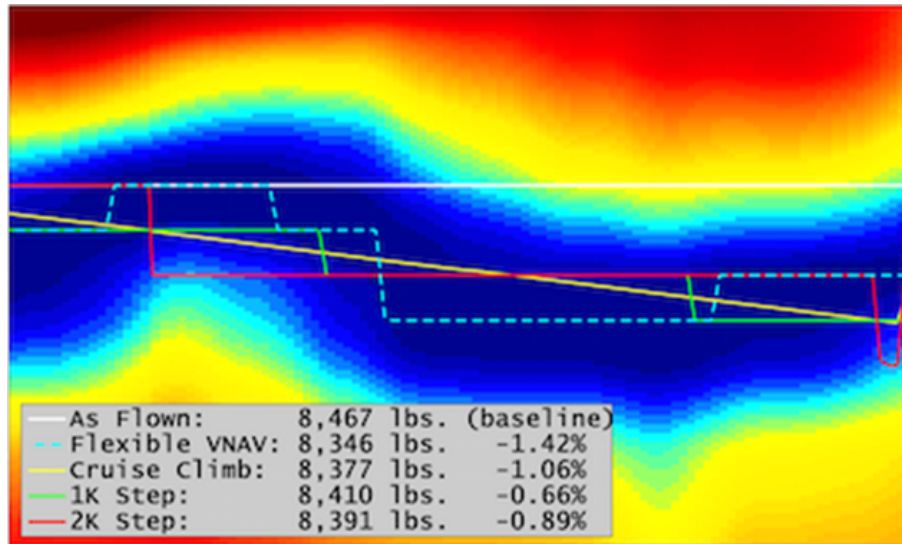


Figure 2-6: Example fuel efficiency tunnel showing a descending tunnel due to favorable winds at lower altitudes. Adapted from [2]

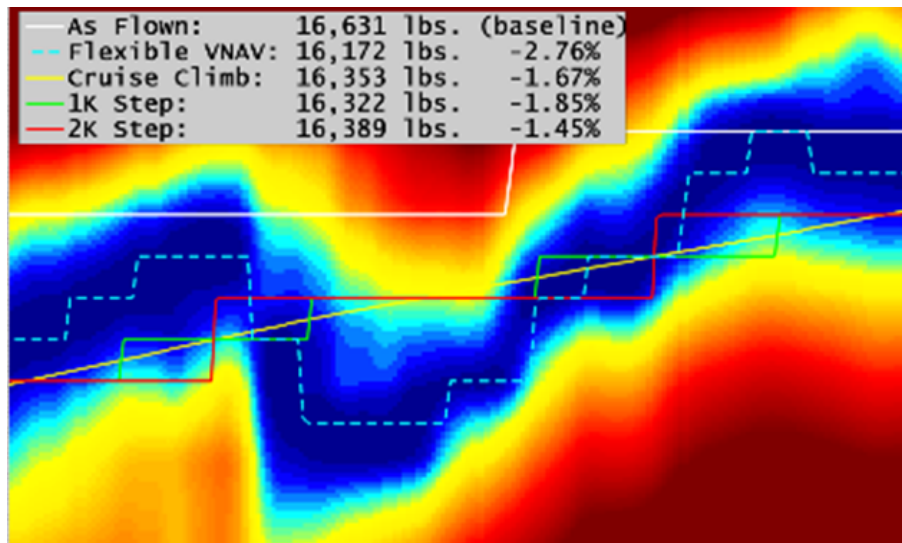


Figure 2-7: Example fuel efficiency tunnel showing sudden altitude shifts due to flight crossing into and out of jetstreams. Adapted from [2]

The altitude tunnel is expanded to include time costs and explained in this thesis as a method to improve flight crew situational awareness by communicating the context of the relative costs of various altitude options.

Chapter 3

Cost Minimization Approach

3.1 Optimization and Cost Calculation Process

The optimal vertical trajectory and off-optimal penalties for a flight are calculated for a given lateral trajectory using a discretized approach with an aircraft performance model, gridded weather forecasts, and an initial baseline altitude and speed profile based on the approach in [1]. The initial profiles are either specified or a default profile is assumed as the optimal altitude and speed based on the aircraft and atmospheric conditions at the start of cruise. The cost index is either specified, or a default is assumed of zero.

To determine the optimal vertical trajectory and off-optimal penalties, the lateral trajectory is discretized into segments, and the expected weight of the aircraft along the lateral route is first calculated. A cost matrix is generated for a set of possible altitudes and speeds at each segment along the lateral route, and the optimal trajectory is selected. Finally, the performance of the selected trajectory is calculated for fuel burn and time estimates.

3.1.1 Step 1: Initial Performance Estimate

The performance of the flight along the baseline trajectory is first calculated in order to estimate the expected weight of the aircraft and time along the entire trajectory

for use in later optimization. This requires a lateral route, initial weight estimate at the start of cruise, and initial baseline vertical trajectory.

As a simplification for computational efficiency, the expected weight and time is calculated from a single baseline vertical trajectory and used later for determining performance at all altitudes and speeds for each point along the track. As there is limited variation in aircraft weight along the route for different vertical paths in the vicinity of the typical cruise regime, it is not necessary to recalculate and store the weight and time for every possible trajectory combination. This results in minimal effects on estimated performance, but large computational savings that allow for real-time, in-flight optimization. An initial baseline vertical trajectory that is in the vicinity of the typical cruise regime is used to obtain reasonable weight estimates. The initial baseline vertical trajectory can be specified, or a default trajectory will be used. The default trajectory is assumed as the optimal altitude and speed based on the aircraft and atmospheric conditions at the start of cruise.

The lateral route is discretized into segments on the order of 15 NM. The performance of the aircraft is evaluated at the midpoint of each segment using the aircraft performance model, beginning with the first segment and continuing sequentially through the other segments. The aircraft weight, altitude and Mach number from the baseline altitude and speed profiles, and outside atmospheric conditions are used to calculate the drag on the aircraft. The drag is balanced by the thrust when in steady level flight, which is then used to calculate the fuel flow rate in terms of specific air range (SAR). SAR is a measure of the distance travelled through the air per mass of fuel burned and does not account for winds. The SGR is then calculated from the SAR and groundspeed, determined by adjusting the true airspeed of the aircraft with the wind vector.

$$\text{SGR} = \text{SAR} * \text{GS}/\text{TAS} \quad (3.1)$$

where GS is groundspeed and TAS is true airspeed.

If the aircraft is climbing or descending, a fuel burn correction is applied based on the climb or descent angle that scales the SGR by the increased or decreased thrust

required to balance either the positive or negative contribution of weight

$$SGR_{Climb/Descent} = SGR * \frac{Thrust}{Thrust + Weight * \sin(\theta)} \quad (3.2)$$

where θ is the flight path angle. The flight path angle was set as a constant angle of 1.25 degrees based on the typical climb performance of a Boeing 777 at altitude.

The midpoint SGR is applied to the entire segment by dividing the segment distance by the midpoint SGR to calculate the fuel burn across that entire segment. The SGR of that segment is also used to estimate the weight at the midpoint of the next segment, and then the performance evaluation process is reiterated for the next segment.

Flight time for each segment is calculated by determining the airspeed based on Mach number and temperature. The airspeed is then corrected with wind for groundspeed. The segment length is divided by groundspeed for flight time.

Step 1 is illustrated in Fig. 3-1.

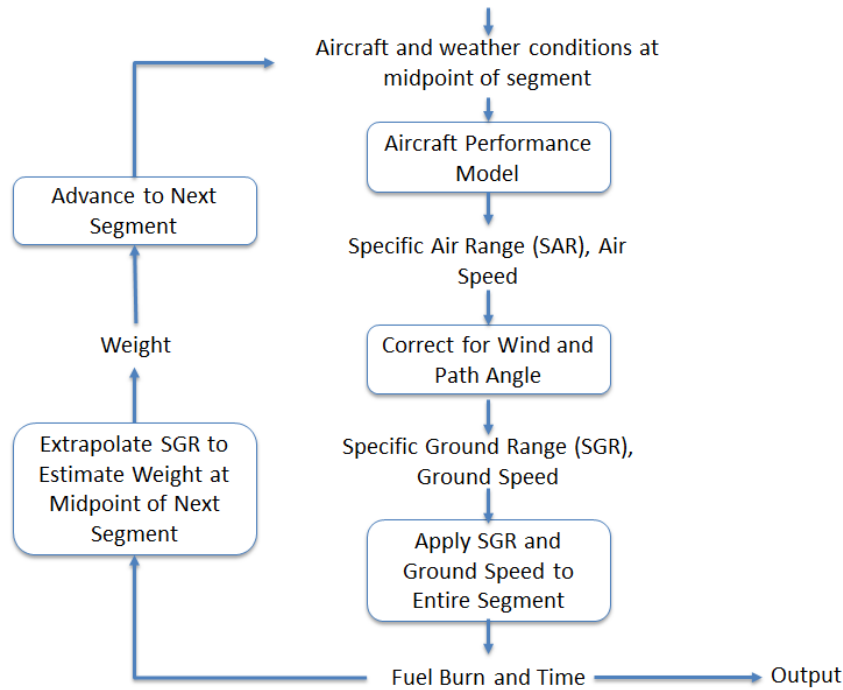


Figure 3-1: Performance estimation process iterated for each lateral segment along the track

3.1.2 Step 2: Cost Matrix Generation and Optimization

With the expected weight and time already calculated for each segment using the baseline trajectory, the relative costs of various altitude and speed options are determined. Altitudes are evaluated from FL280 up to the maximum operating altitude of the aircraft in increments of 100 ft. Performance for both allowable flight levels (e.g. FL330, FL350, etc. for eastbound flights) and altitudes in between allowable flight levels (FL331, FL332, etc.) are computed. Unallowable flight levels are used for altitude tunnel generation. Speeds are evaluated between Mach 0.70 and the max operating Mach number of the aircraft in increments of .01. The SGR and ground-speed are calculated for a set of possible altitudes, speeds, or combination of both at each segment. Similar to Step 1, the SAR is calculated using the aircraft weight and atmospheric conditions using the aircraft performance model at each of the altitude and speed conditions. The SAR is corrected for winds to obtain SGR. For all conditions, the aircraft is assumed to be in steady level flight, so no path angle correction is necessary.

For computational efficiency, a single weight at each point along the track, estimated from Step 1, is used for performance estimation at all altitudes and speeds, as the impact on performance estimates from vertical trajectory path-dependence are second order effects.

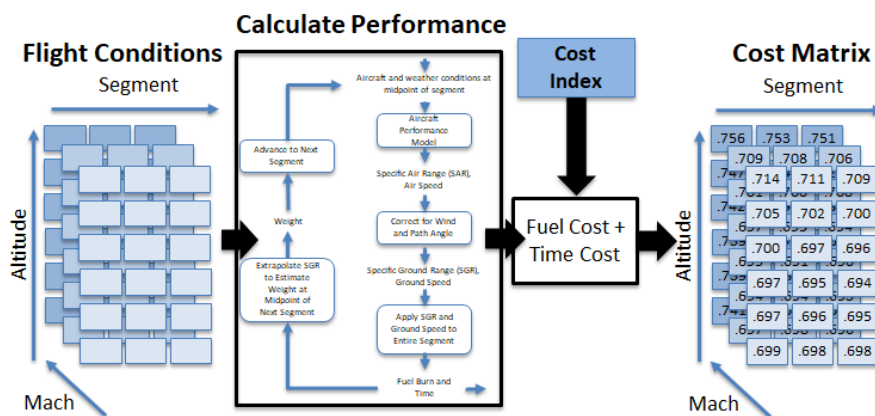


Figure 3-2: Cost minimization process calculates performance for a set of possible flight conditions and produces a cost matrix

The cost of each altitude and speed option at every segment is calculated by adding the time cost, weighted by the cost index, to the fuel burn, resulting in a cost matrix. The minimum cost path through the cost matrix is then determined.

Altitude changes are constrained by the aircraft climb rate. From segment to segment, the aircraft can stay at the current altitude or change to reachable altitudes. The time required for acceleration to a different speed is assumed to be short compared to the segment time, so all speeds are reachable at any segment.

The minimum cost trajectory is determined from the cost matrix by first filtering for the minimum cost speed at all altitudes and segments and then performing a Dijkstra's shortest path search on the remaining cost matrix. As all speeds are reachable at any given point, the optimal speed selected at any altitude will always be the minimum cost speed for that altitude and segment, regardless of previous history. This reduces the matrix that is searched from three dimensions down to only the altitude and segment dimensions.

A directed graph is then created with each node representing an allowable altitude (e.g. odd flight levels for eastbound flights) at each segment. The nodes are connected directionally from the preceding segment only to nodes in the immediately following segment. Nodes are connected between altitudes at the same flight level and adjacent allowable flight levels within the climb rate constraint. A starting node is added before the first segment, and all altitudes of the first segment are connected to the starting node. Similarly, an end node is placed after the last segment, which is connected to all altitudes in the last segment.

Dijkstra's shortest path algorithm is then used on the set of costs at each altitude to find the optimal vertical trajectory from the starting node to the end node. Since the minimum cost speed for each altitude and segment has already been identified, the selected altitude at each segment will also identify the optimal speed for that segment. No climb or descent costs are included in the optimization under the assumption that the climb and descent costs would be outweighed by steady level flight costs since relatively little time would be spent in climb or descent. To minimize excessive climbs or descents, a constraint is applied that requires a minimum time or distance between

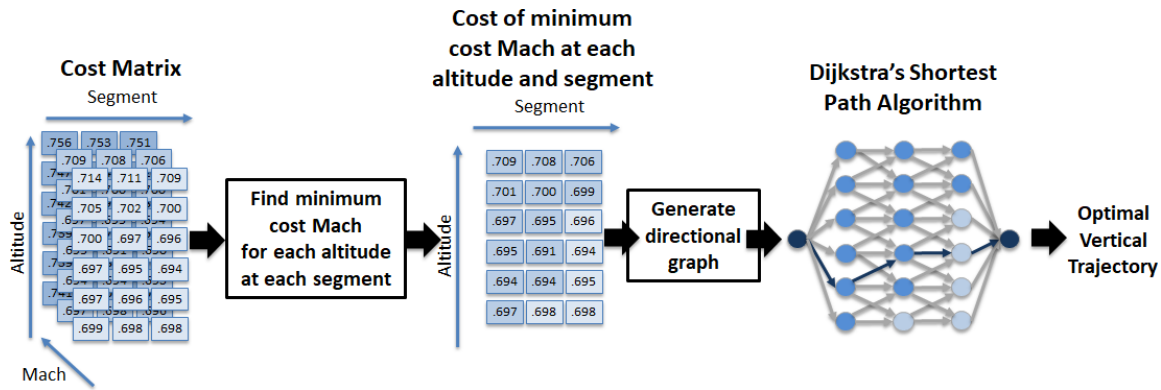


Figure 3-3: Cost minimization process then determines the minimum cost trajectory by first identifying the cost of the minimal cost speed for each altitude at each segment, generating a directed graph, and then applying Dijkstra's shortest path algorithm

altitude changes. The default minimum distance was set at 150 NM for this thesis.

The altitude tunnel can then be generated from the cost matrix and the optimal trajectory. At each segment, the costs of all altitudes are normalized by the minimum cost altitude from the optimal trajectory, and the additional penalty cost of each altitude is calculated. The speed used at each segment is the minimum cost speed that was selected at each altitude and each segment from the optimization process. The relative penalty cost of each altitude option compared to the minimum cost option is then used to generate the altitude tunnel.

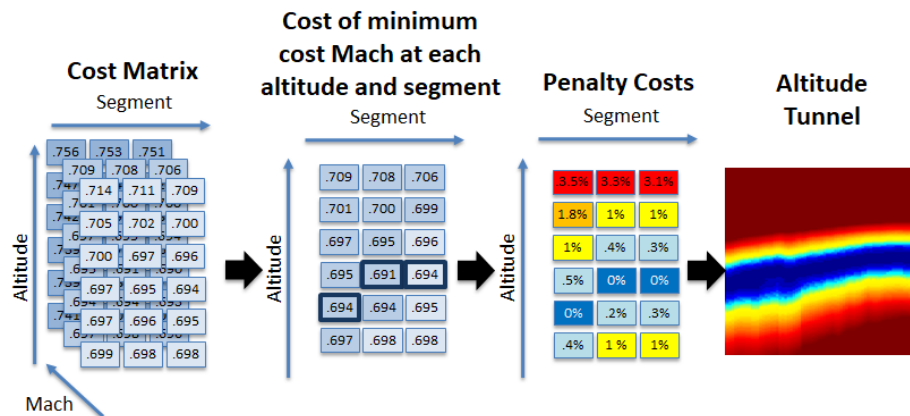


Figure 3-4: Altitude tunnel is generated using the altitude costs for each segment at the minimum cost Mach number for each altitude and each segment from the optimization. The penalty costs are calculated from the optimal trajectory cost and displayed as an altitude tunnel

3.1.3 Step 3: Final Performance Estimate

Fuel burn and flight time estimates are then calculated for the optimal trajectory, segment by segment. The aircraft weight and time at each segment is updated based on the optimal altitude profile, optimal speed profile, and atmospheric conditions. The aircraft performance model and atmospheric conditions are used to calculate SGR and flight time. Although climb and descent costs were not considered during the optimization process, they are included in the performance calculations by correcting fuel burn for path angle. For comparison of fuel burn and flight time with a baseline vertical trajectory, a climb or descent is added, if necessary, to the last segments at the end of cruise of the optimized trajectory so that both the baseline and optimized trajectories have the same altitude difference between start of cruise and end of cruise. This eliminates any geopotential energy differences of the aircraft so that fuel burn comparisons can be made between the two trajectories.

3.2 Aircraft Performance Model

The aircraft performance model used for this research was the Base of Aircraft Data (BADA) version 4. BADA4 utilizes a kinetic approach that models the aircraft as a point mass. Lift, drag, and fuel flow are modelled using polynomial expressions with aircraft-specific coefficients that account for aircraft and atmospheric conditions. BADA4 requires inputs of aircraft type, weight, speed, altitude, and outside air temperature [12].

The coefficients used by BADA4 were identified based on a set of reference performance data [13], and the specificity of the BADA4 models therefore are dependent on the quantity and range of data used in BADA4 development. BADA4 distinguishes down to variants of aircraft types (Boeing 777-200 vs. Boeing 777-300), but does not provide models for different engines (e.g. 777-300 with GE90 vs. 777-300 with PW4000 engines). It also does not capture variation between individual aircraft of the same type and variant. Individual aircraft show variations in drag and fuel flow for the same flight conditions that come from slight differences between aircraft, such

as aerodynamic rigging or engine wear. Other aircraft performance models can also be used, if available.

3.3 Weather Model

Atmospheric conditions used in performance estimation are based on forecasts from numerical weather prediction models. Gridded wind and temperature forecasts are needed that span the duration of the flight.

For flights within the continental U.S., the source used for wind and temperature data is the Rapid Refresh (RAP) product from the National Centers for Environmental Prediction (NCEP). The RAP model provides forecasts on a 13 km by 13 km grid over the continental U.S. The RAP analysis is run once each hour, outputting forecasts at intervals of every hour. For flights occurring outside of the continental U.S., the Global Forecast System (GFS) is used, which provides 0.25 or 0.5 degree grids globally with analysis cycles of every six hours and forecast intervals of every three hours.

These forecasts are limited to a number of gridded points in space and for specific forecast times, usually on the order of 5-30 NM and in intervals of 1-6 hours. As finer resolution is needed for finding the atmospheric conditions at the midpoint of each segment at the corresponding time, the gridded forecasts are interpolated spatially and temporally. Spatial interpolation is first done separately on both the forecast immediately preceding each segment time and the forecast immediately following using Delaunay triangulation and linearly interpolating in space. Then the atmospheric conditions at that point in space for the forecasts preceding and following the time of interest are linearly interpolated in time.

Chapter 4

Cruise Altitude and Speed Optimization Decision Support Tool

4.1 Minimum Cost Tunnel

In order to implement the altitude tunnel as part of a decision support tool, the colors of the altitude tunnel were modified to adhere to flight deck conventions. For example, in the original tunnel used for analysis, red indicated altitudes with low fuel efficiency. However, on the flight deck, red is reserved for warnings. The tunnel visualization was therefore simplified and is represented through penalty contours, as shown in Fig. 4-1. At altitudes within the thinner set of lines, the flight will incur an additional penalty of up to 1% of the minimum fuel burn trajectory. Within the thicker set of lines, the flight will incur an additional fuel burn penalty within 2% of the minimum burn trajectory. As the original tunnel only accounts for fuel burn, the fuel efficiency tunnel concept was expanded to a minimum cost tunnel in order to include time costs. In the case where the cost index is set to zero, the minimum cost tunnel represents a fuel efficiency tunnel, as the value of time is set to zero.

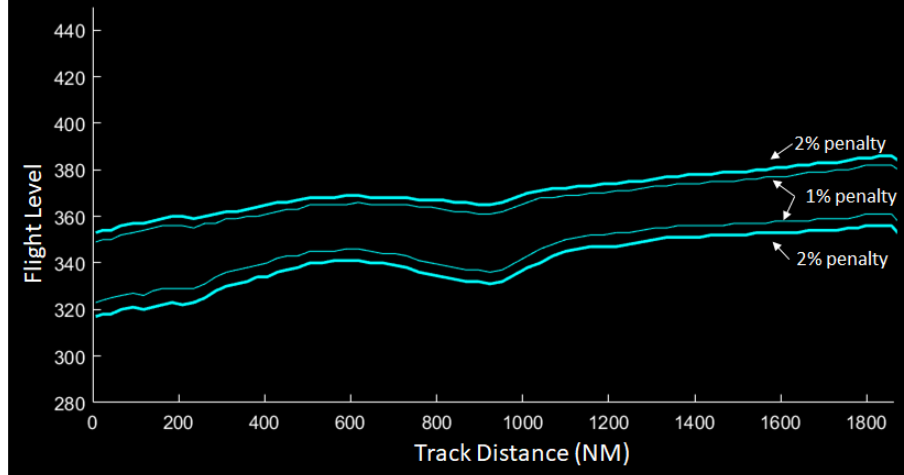


Figure 4-1: Simplified minimum cost tunnel with 1% and 2% penalty boundaries shown

4.2 Decision Support Tool

A cruise altitude and speed optimization (CASO) decision support tool, based on the minimum cost tunnel, was developed to support enhanced vertical situational awareness and decision-making for flight crews and dispatchers, building on the initial efforts of Tran et al. [2]. As inputs, the tool receives the flight plan, wind and temperature forecasts, the cost index, and the aircraft's current weight, position, and altitude. The tool then optimizes the vertical trajectory, generates the minimum cost tunnel, and calculates performance estimates, displaying these to the user. The tool is provided in the cockpit for the flight crew, while the dispatcher has a version of the tool for flight planning. During the flight, the dispatcher's tool is also able to show the crew's display, providing a common reference in discussing trajectory options, in order to facilitate coordination between crew and dispatcher.

4.3 User Interface

4.3.1 Minimum Cost Tunnel

The user interface, shown in Fig. 4-2, provides a graphical display to support altitude selection. Trajectory cost information is depicted by the minimum cost tunnel,

demarcated by the 1% and 2% marginal cost contours. The 1% contours provide a region within which the flight crew attempts to stay. A good approximation to the optimal profile can be found by following the center of the tunnel. Having the 2% contours, in addition to the 1% contour, provides a sense of the cost gradient, showing a relatively faster increase in marginal costs outside of the 1% region compared to the center of the tunnel. Flight levels are indicated on the vertical axis. Track distance along the route is displayed on the horizontal axis below the tunnel, and waypoint names are displayed above the tunnel at the corresponding location along the flight's track distance. Waypoints and track distance provide points of reference for the tunnel and trajectory options. The CASO-optimized trajectory and the current planned trajectory are overlaid on the tunnel, allowing for visual comparison with respect to the minimum cost tunnel. A performance limit for max altitude is also shown, in this case placed at the highest altitude where a climb rate of 300 ft/min is achievable. The performance ceiling overlaid on the tunnel delineates the feasible altitude options with respect to the tunnel and clearly indicates where the aircraft should not be flown in order to avoid compromising maneuver margins. Ownship position is depicted by a white outline of a triangle.

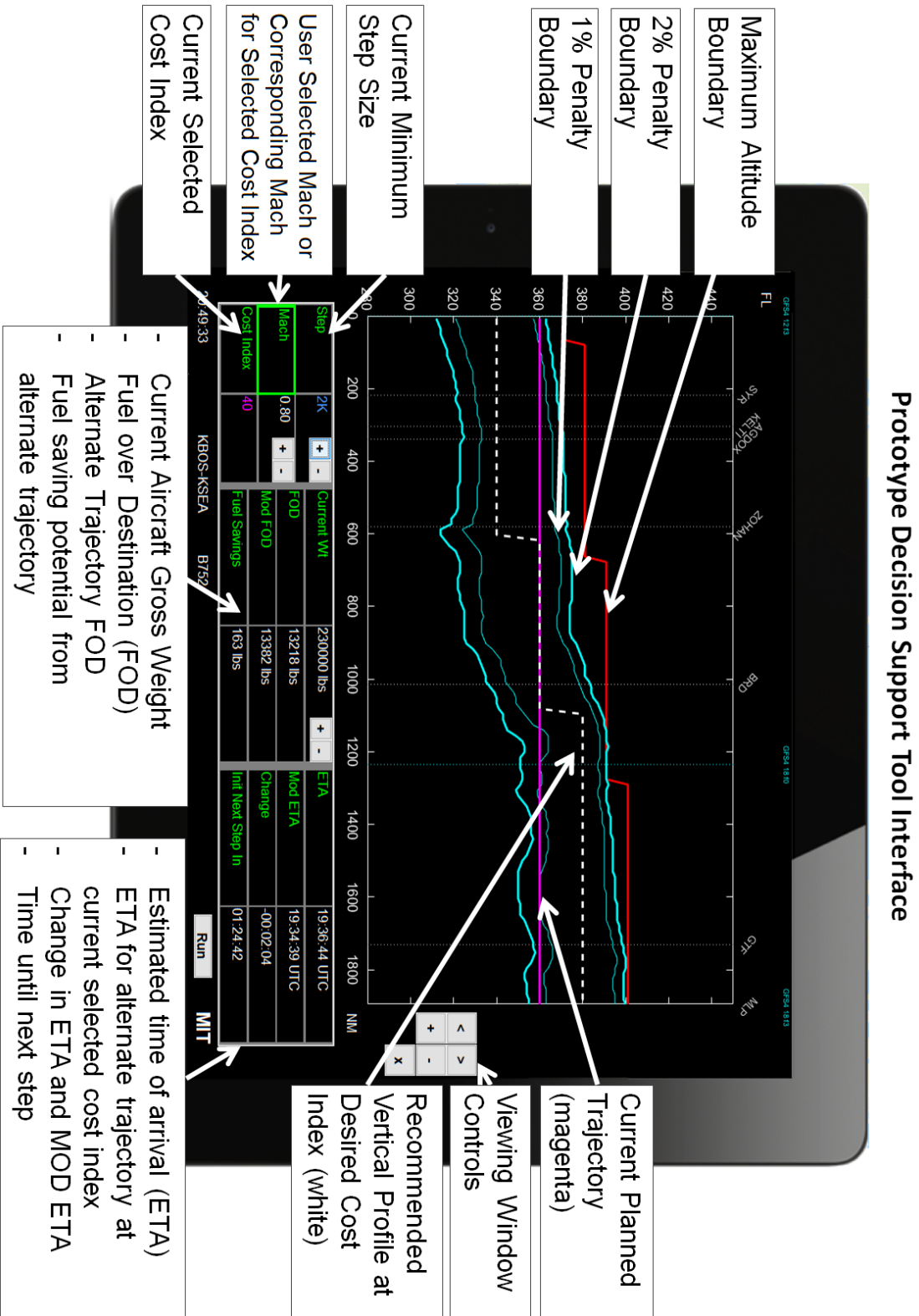


Figure 4-2: DST interface displaying minimum cost tunnel

The altitude tunnel was simplified to conform to flight deck color conventions, with the cost contours drawn in cyan, which is normally used for communicating information. Red is reserved for warnings, and as a result, is used to mark the altitude limit. When depicting lateral routes, magenta is used to depict the FMS programmed trajectory and is used in this case to denote the planned vertical trajectory.

The tunnel depiction provides a method for simple visual evaluation of the decision space, compared to the limited winds aloft information currently provided to the flight crew, consisting of wind vectors at three or four altitudes at each waypoint. As wind patterns can result in complex optimal trajectories, dispatchers have indicated a desire for an effective method of communicating the rationale behind complex vertical trajectories to flight crews. The tunnel is also intended to provide context for optimal trajectories and visually indicates altitudes where the combined effects of winds and aircraft performance are more favorable.

The analysis and forecast times for each weather forecast used in the optimization are displayed above the waypoints. This details which forecasts were used at each location along the flight and provides a sense for how current or dated the forecasts are.

The viewing window can be set to show the entire cruise phase, or zoomed in to focus on the immediate area. When zoomed in, the viewing window can track the ownship position, with the tunnel scrolling by as the flight progresses, reflecting the perspective of the aircraft. When zoomed out to show the entire cruise phase, the ownship marker moves against the stationary tunnel.

4.3.2 User Controls

At the bottom of the interface, the user is able to modify the cost index or select a specific Mach number to govern speed, rather than using the cost index. When a specific Mach number is selected, the cost index is still used for generating the minimum cost tunnel. This may be useful, for example, when air traffic control assigns a Mach number while flying in the North Atlantic Organized Track System to maintain procedural separation outside of radar coverage. [14].

Similarly, the minimum step constraint for altitude changes can be specified. In general, aircraft are separated into even and odd flight levels (e.g. FL320 vs. FL330) based on the aircraft direction. Flights with magnetic heading between 0 and 179 degrees are assigned odd flight levels, while aircraft flying 180 to 359 degrees are assigned even flight levels, resulting in intervals of 2,000 ft between possible flight levels for an aircraft in most cases. However, there are exceptions, such as one-directional tracks where flight levels may be assigned in 1,000 ft increments.

The lateral route can be modified by manually entering the new set of waypoints, or by downloading an updated flight plan. As flights will occasionally be given significant lateral reroutes, particularly when weather is a factor, the lateral trajectory can be modified in flight.

The user is also able to specify a custom vertical trajectory, either by drawing on a touchscreen or by manual entry of waypoint locations and flight levels, for the DST to calculate performance predictions. This allows the user to directly specify preferences and to quantitatively compare specific trajectories that the user has in mind.

The tool may also support the user specification of areas for the trajectory optimizer to avoid, such as areas of known turbulence, or a required time of arrival by which the recommended trajectory will be constrained during optimization. If a flight is delayed and trying to arrive by a specific landing time, the user may constrain the optimizer to arrive by that specified time. Similarly, if a flight is early, the user may constrain the optimizer to arrive at the desired time, particularly if there may be penalties associated with early arrivals. In some cases, noise restrictions at certain airports preclude landing before a specific time, or otherwise enforce a penalty or quota [15]. Flights may be forced to fly a holding pattern if they arrive early. By reducing speed or through judicious altitude selection, some fuel savings may be gained, in addition to arriving at the desired time.

Aircraft parameters and performance estimates are also located at the bottom panel. The current aircraft weight is displayed. Expected fuel on board at end of cruise for the current planned trajectory is shown alongside the expected fuel on

board at the end of cruise for the optimized or user-modified trajectory, and the fuel savings of the optimized or user-modified trajectory over the planned trajectory is highlighted as a separately displayed value to clearly present the potential benefit. The estimated time of arrival at the end of cruise is also shown for both the planned trajectory and the optimal or user-modified trajectory, with the difference in cruise time also displayed separately. Additionally, the time until next altitude change for the recommended trajectory is displayed to provide the crew with awareness of the timeframe in which action is suggested.

4.3.3 Additional Information

Additional relevant information, such as turbulence information, can be displayed alongside the altitude tunnel. One possible implementation is shown in Fig. 4-3, where turbulence forecasts are displayed in the background of the altitude tunnel as a heat map of EDR. The color scale for the EDR heat map is shown to the right side of the display. The EDR forecast displayed is from the Graphical Turbulence Guidance (GTG) product, which provides a gridded forecast with 13 x 13 km resolution in the continental U.S. up to 18 hours ahead. As the GTG is a forecast, there is uncertainty present and would benefit from being supplemented with information about actual conditions. Actual observations from PIREPs can also be displayed, which provide a picture of observed conditions at the time of the report. PIREPs, however, provide information on specific points in space and time and are limited to the trajectories of flights in the air. Forecasts and PIREPs are thus able to complement each other.

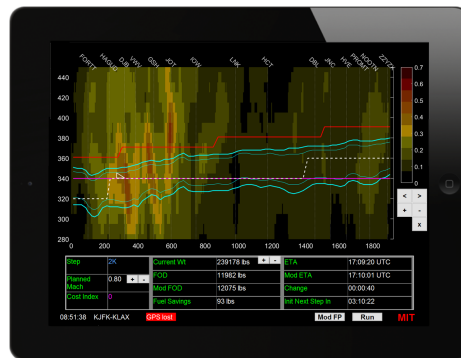


Figure 4-3: DST interface displaying EDR as example turbulence information

Placing the turbulence and fuel efficiency information on the same display facilitates simultaneous consideration of both factors while making altitude decisions. In current operations, turbulence information is provided on a chart or display separate from efficiency or cost information, requiring switching attention between different charts or documents to evaluate both.

The DST is designed to accept other sources and forms of turbulence information, as well as other types of information.

4.4 DST Information Flow Architecture

The decision support tool is designed to be displayed in the cockpit on electronic flight bags (EFBs) or flight displays for the flight crew, and on the ground for the dispatcher. The computational processes can be run on the EFB or computer onboard the aircraft, or on a computer on the ground with the outputs uplinked to the aircraft.

Fig. 4-4 shows the information flow for the case where computations are run on onboard the aircraft. The DST receives aircraft state information (e.g. current lateral position, altitude, and weight) from the aircraft databus. Wind, temperature, and turbulence information is obtained through an air-to-ground datalink, such as the inflight Wi-Fi linked to onboard passenger entertainment systems. There is a trend towards increasing equipage, reliability, and bandwidth of inflight Wi-Fi capabilities in airlines, with major carriers equipping most if not all of their fleets. Newer systems have demonstrated download speeds of up to 15 Mbps. Once the most recent forecasts are available, the forecasts will automatically download and be stored in a database to ensure the latest available information is being used. By downloading automatically to an internal database, the DST is also able to recalculate trajectories with those forecasts even if the flight's internet connection is lost.

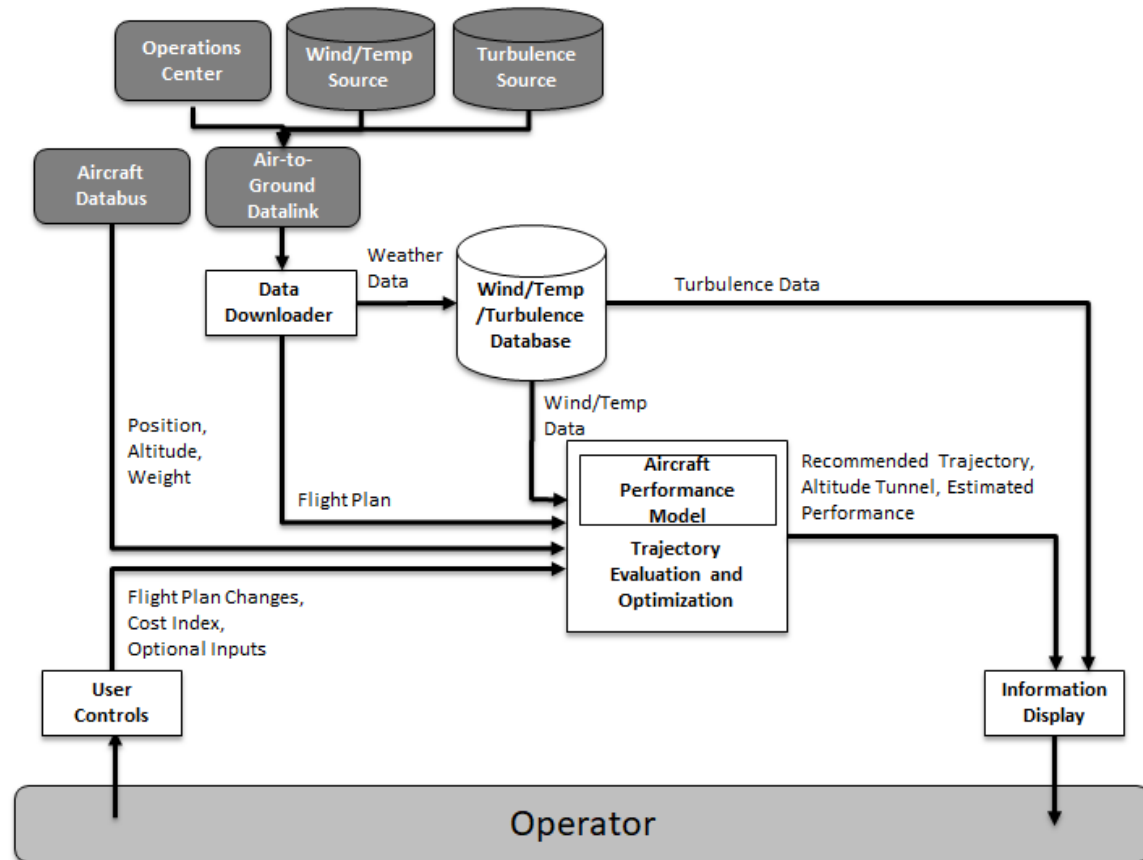


Figure 4-4: Information Flow Architecture

To reduce the bandwidth required, relevant geographic subgrids of the weather forecasts can be downloaded. Geographical and temporal margin in the subgrids and forecasts can be included to handle potential reroutes or delays without requiring redownloading. Within the continental U.S., the Graphical Turbulence Guidance 3.0 product is available for turbulence forecasts of eddy dissipation rate.

The DST would obtain all aircraft state data directly from the aircraft databus. This reduces workload for the flight crew and minimizes the chance for errors to be inputted by the flight crew. Similarly, flight plans can be directly sent to the DST. However, manual entry or modification of flight plans is also permitted, allowing flight crews to make changes if given a reroute. Crew inputs are received from the user interface.

Performance evaluation and trajectory optimization is done on the tablet or computer processor, and the altitude tunnel and turbulence information are displayed on

the user interface. The CASO tool is able to utilize different aircraft performance models, as well as different weather models.

The DST can also be run while the aircraft is on the ground either on the EFB for the flight crew's use prior to departure or at a dispatcher workstation. Weather data is received through a regular internet connection, and aircraft position, altitude, and weight are entered manually or pipelined from aircraft reports to the dispatcher workstation.

4.5 Prototype DST

A prototype of the decision support tool was developed that was independent of aircraft systems for testing purposes, as shown in Fig. 4-5. The stand-alone device did not require any access to the aircraft databus. Instead of receiving position and altitude from the aircraft databus, position and altitude come from either an external GPS receiver or from manual input. Similarly, the initial weight is entered manually and estimated automatically based on predicted fuel burn as the flight progresses with the option for manual reentry, rather than from the aircraft databus. Weather information is received using the inflight Wi-Fi from the passenger entertainment system. A website was also set up for the dispatcher to view the display from the DST for coordination between flight crews and dispatchers. GPS functional testing and weather download tests were conducted in the cabin of a number of commercial flights, including a B738 and A321.

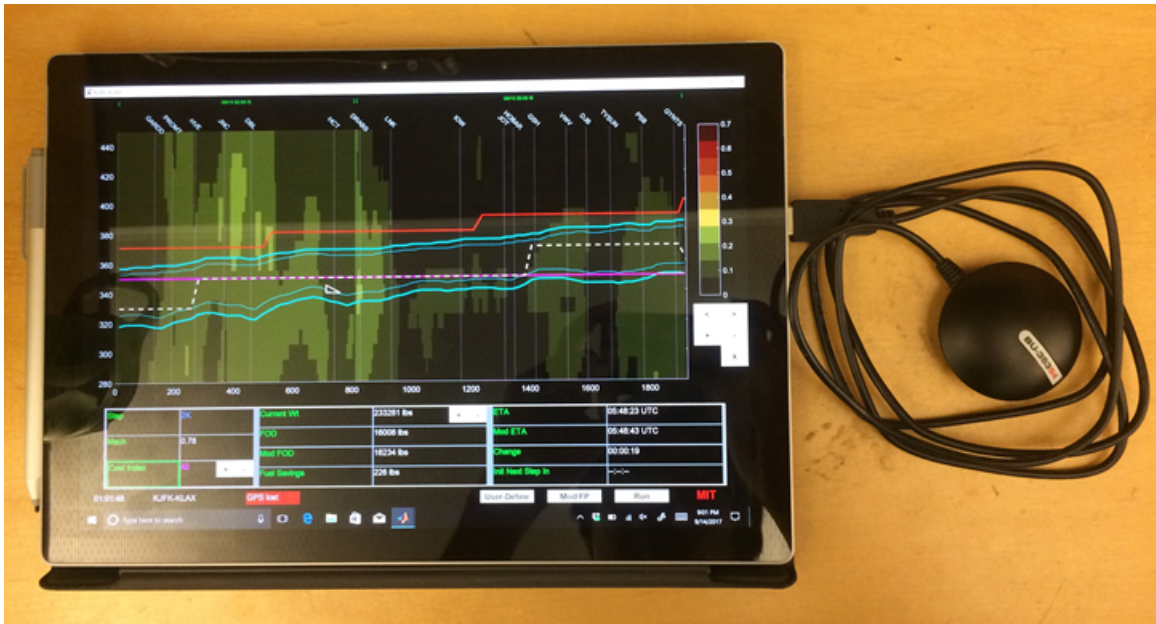


Figure 4-5: DST prototype with external GPS receiver

Chapter 5

Preliminary Flight Trials Set-Up

Preliminary flight trials were conducted on a Boeing 777-200 in collaboration with a major carrier for initial evaluation of the DST. Four initial trial flights were conducted in April and May 2018.

CASO guidance from the DST was provided to the crew before departure and updated en-route whenever the flight plan was modified, weather forecasts were updated, or a position report was received. The flight crew consulted the DST output and attempted to follow the CASO guidance when possible. Fuel burn and flight time was recorded onboard the aircraft and then compared with the flight planned fuel burn and flight time. After the flight, debrief discussions were held with the flight crew regarding decisions made and feedback on the DST.

5.1 Decision Support Tool Set-Up

The preliminary flights occurred while work was ongoing to gain jumpseat access. As a result, the DST was run on a computer on the ground, and the output was sent to the flight crew and dispatcher for the preliminary flights. The setup for the preliminary flight trials is shown in Fig. 5-1. The flight crew and dispatcher for each flight were briefed on the CASO DST prior to the flight. The flight plan, including expected aircraft weight at start of cruise, was received after being created by the dispatcher and entered into the DST, which optimized the vertical trajectory and

generated the minimum cost tunnel. An image of the output was provided through the website to the dispatcher and flight crew, while they were still on the ground. If desired, the flight crew or dispatcher could ask questions concerning the DST prior to departure. If a weather update or aircraft weight revision occurred, the DST would be rerun, and the output provided to the dispatcher and crew. As the majority of all four flights was outside of GTG coverage, and the airline's commercial turbulence forecast products were not available in usable formats, no turbulence forecasts were displayed for these four initial flights. The GFS was used for all wind and temperature forecasts.

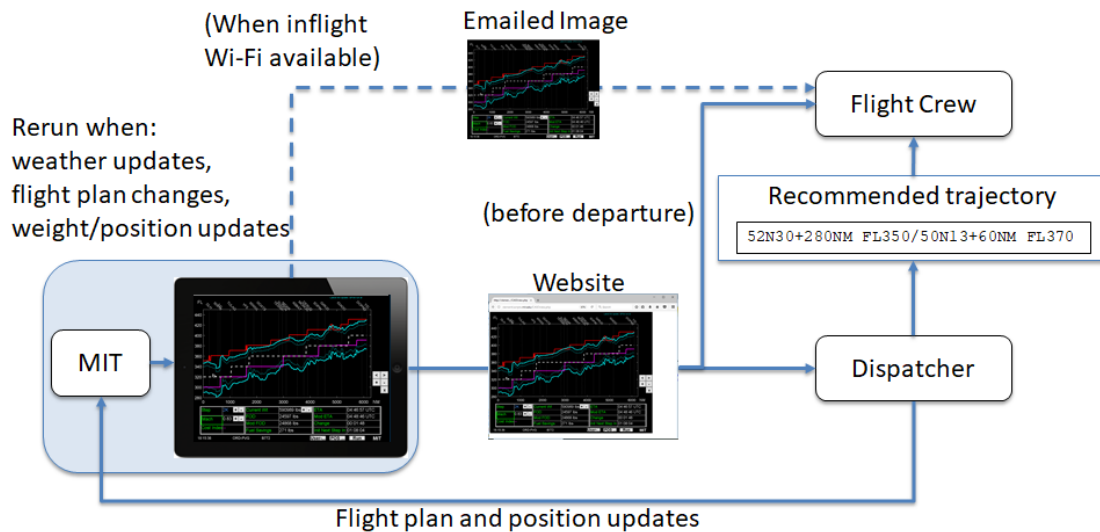


Figure 5-1: Preliminary flight trial setup. DST was operated on the ground with images sent to flight crew via website and inflight Wi-Fi. When inflight Wi-Fi in-operative, recommended trajectory sent via ACARS. Dispatcher viewed DST display through website.

5.2 In-Flight

In flight, updates to the DST output were sent to the flight crew. If inflight Wi-Fi was available, images of the entire output were sent to the crew. When inflight Wi-Fi was not operational, only updates to the recommended trajectory were sent as text via ACARS. Because of the uncertainty associated with delays, taxi times,

and departure routes, the aircraft weight and cruise start time were updated in the DST from the first available position report after reaching cruise. Afterwards, the DST was updated each time new weather forecasts were made available and when weight and time updates were received at reporting points along the flight. Position reports were requested from the dispatcher following the flight, who provided the reports whenever workload permitted. Fuel-on-board values and flight time were also recorded at reporting points for analyzing the flight's fuel burn. Fig. 5-2 is an image of the DST information being displayed in the cockpit.



Figure 5-2: DST information displayed on the flight deck

5.3 Post-Flight

After the flight, follow up questions were asked regarding decisions made and the rationale behind them. Events along the flight, such as reroutes, were clarified, and

barriers to following the CASO guidance that were encountered were identified. Feedback was collected from the crew and dispatcher after the flights regarding the tool and its usefulness. The recorded fuel burn and flight time from the as-flown trajectory was compared with the flight planned trajectory’s fuel burn and flight time.

5.4 Flight Trials

The four initial trial flights were conducted in April and May 2018, flying from Los Angeles (LAX) to Honolulu (HNL), from HNL to San Francisco (SFO), from Chicago (ORD) to Shanghai (PVG), and from PVG to ORD, as shown in Fig. 5-3.

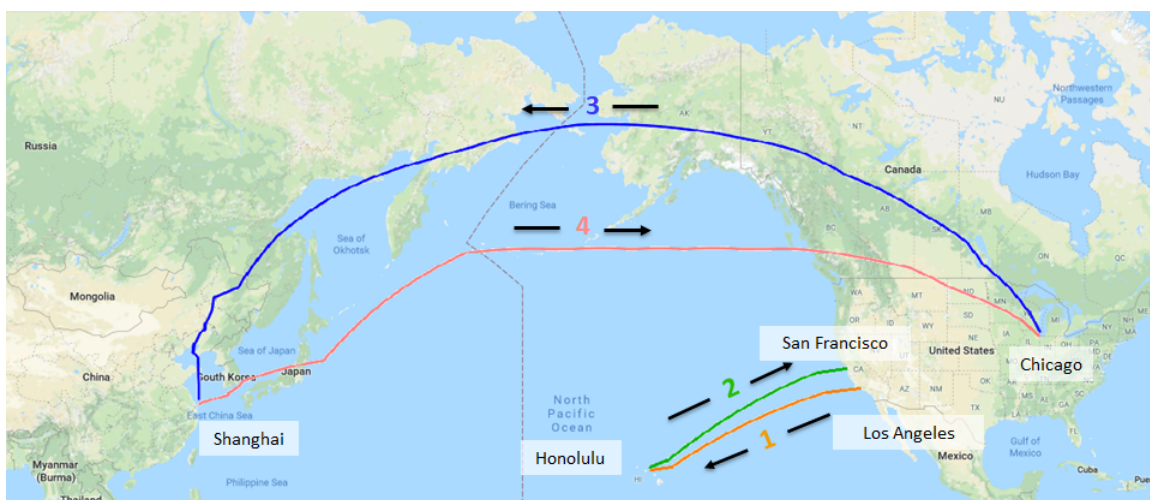


Figure 5-3: Lateral routes for preliminary flight trials

Chapter 6

Preliminary Flight Trials Results

6.1 Flight 1: LAX-HNL

For Flight 1, the generated fuel optimal tunnel and recommended trajectory were displayed to the dispatcher and the crew prior to departure. After takeoff, the crew received text updates from the dispatcher through ACARS regarding any changes to the recommended trajectory, but did not view the cost tunnel image directly. The flight plan was created three hours prior to departure. The DST display generated from the flight plan and 0600Z weather forecasts is shown in Fig. 6-1 with a fuel optimal tunnel displayed. The flight plan specified the cost index for the flight as 35 in units of 100lbs/hr. As cruise occurred in the one-directional Pacific tracks to Hawaii, the tool was set to allow for 1000 ft climbs. The flight planned trajectory (magenta line) was at FL360 for all of cruise, while the DST trajectory (white dash line) recommended a step up from FL360 to FL370 approximately 750 NM into cruise with an expected 200 lbs of fuel savings and flight time increase of two minutes.

Approximately 7 minutes before pushback, the 1200Z forecast became available and was downloaded by the DST. The tool was rerun, and the updated display is shown in Fig. 6-2. Given the proximity of the update before departure, the flight crew did not receive the updated image in time, and was given a textual update once at cruise. There was a small increase in altitude of the tunnel towards the end of cruise, resulting in a recommended climb to FL380 approximately 250NM before the

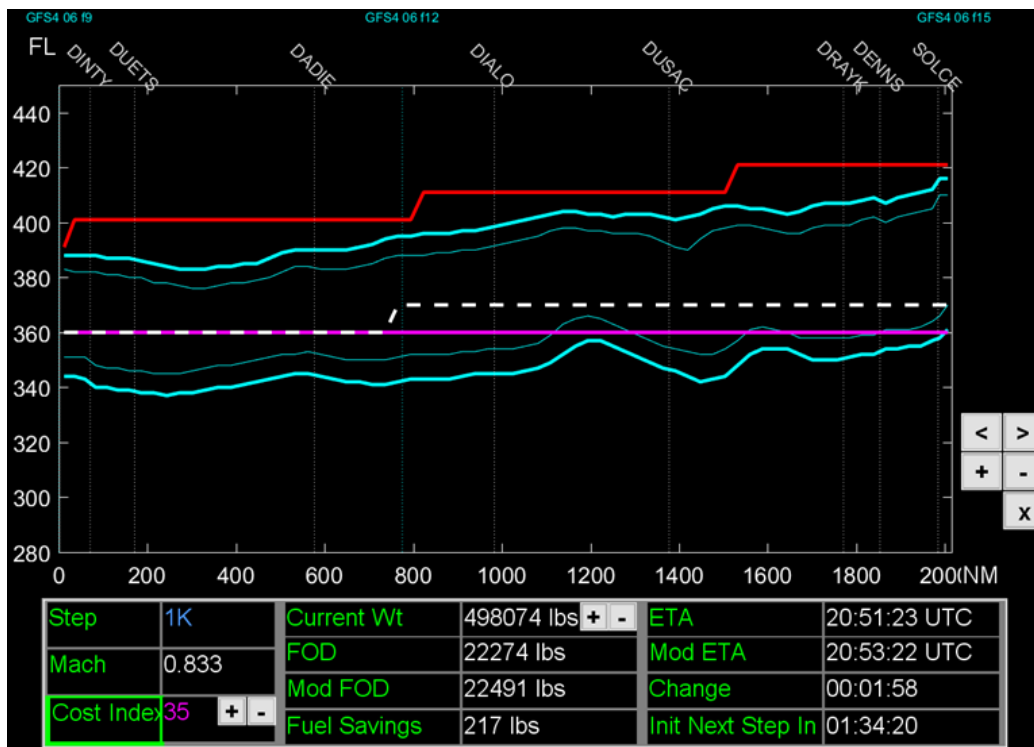


Figure 6-1: Flight 1 DST display, forecasts generated 0600Z

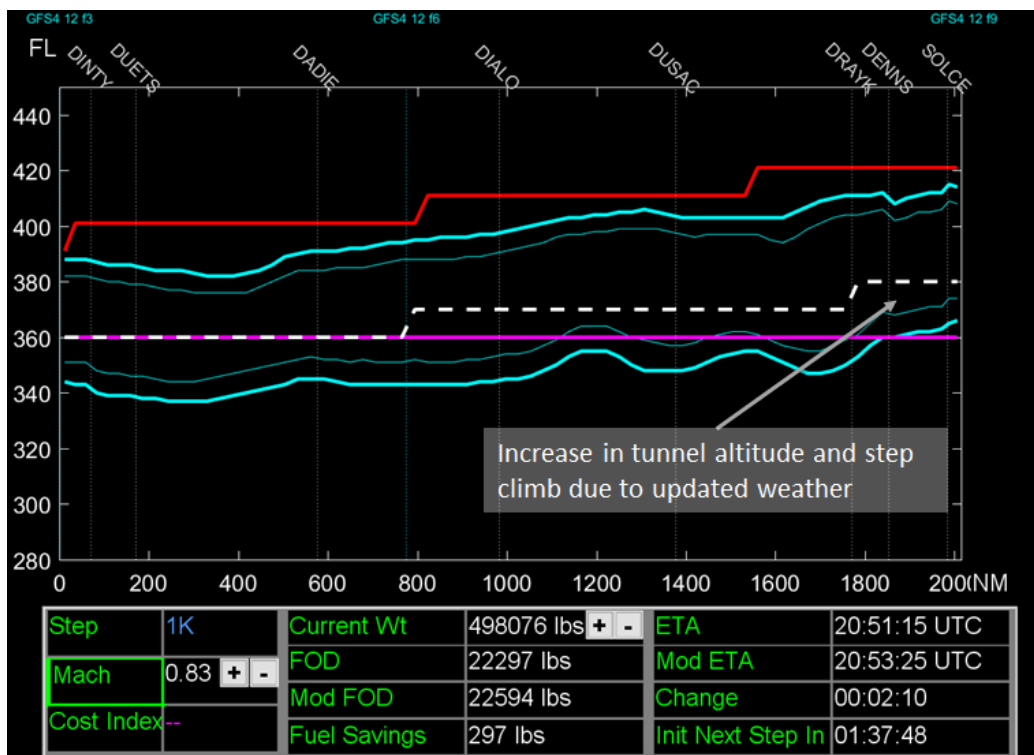


Figure 6-2: Flight 1 DST display, forecasts generated 1200Z

end of cruise. The DST was updated with the actual aircraft weight after the first 200 NM of cruise. However, there was no significant change in the tunnel or recommended profile.

The flight crew attempted to follow the DST recommended trajectory. The as-flown trajectory (green line) is overlaid on the altitude tunnel and shown in Fig. 6-3 with a flight plan guidance area for light turbulence in blue overlaid as part of the post-flight analysis. The flight plan guidance areas are from the significant weather chart included with the flight plan, but were not available on the DST for these flights. The flight followed the DST recommendation and climbed from FL360 to FL370 near the midpoint between waypoints 700 NM into cruise. At approximately 1500 NM, the flight encountered moderate turbulence at FL370. The turbulence was forecasted to be light on the significant weather chart included with the flight plan, however guidance from other turbulence products did not indicate forecasts of moderate turbulence. After hearing from an aircraft below that reported FL300 as being a significantly smoother ride than FL320, the crew requested and received clearance to descend to FL310, remaining at that altitude until approximately 50 NM prior to the top of descent, where significant turbulence reoccurred, causing an early descent.

In this case, the trajectory recommended by the DST did not expect significant benefit, with less than 0.5% difference in cost compared to the flight planned trajectory. Although the weather update did not result in significant changes in the cost tunnel or recommended trajectory in this case, the timing of the forecast update would have prevented the inclusion of the updated data in conventional flight planning procedures if there had been significant changes to the tunnel and recommended trajectory. For this flight, all altitude change requests made to ATC were granted, and turbulence was the only factor preventing the flight from following the recommended trajectory. It is notable that the turbulence forecasts available to the crews did not display the moderate turbulence that was encountered and was not anticipated during flight planning.

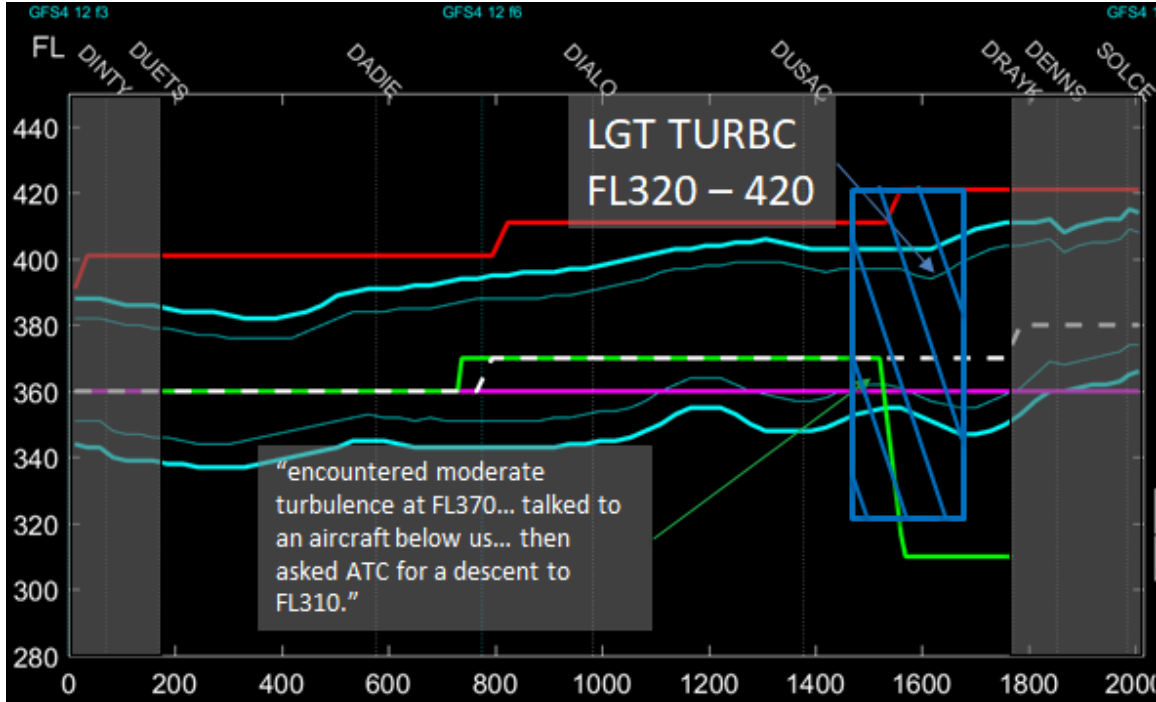


Figure 6-3: Flight 1 summary with as-flown trajectory (green), flight plan guidance regions (blue), and flight crew comments

6.2 Flight 2: HNL-SFO

For Flight 2, the DST generated image was uplinked to the crew during cruise and available for viewing directly. The flight plan was created approximately three hours prior to departure. The DST display generated from the flight plan and 0600Z weather forecast is shown in Fig. 6-4 with a fuel-optimal tunnel. The cost index for the flight was 283 in units of 100lbs/hr. In this case, the altitude tunnel and DST recommended trajectory were significantly different from the flight planned trajectory. The dispatcher planned the cruise at FL310 for 400 NM, followed by a descent to FL290 for 600 NM, before returning to FL370 at 1000 NM into cruise. Remarks included with the flight plan indicated “FL290 due turbs higher.” The DST recommended trajectory began at FL340, and included three sets of climbs up to FL380, which was held for the last 900 NM of cruise.

The 1200Z weather update occurred one and a half hours before departure, resulting in minor changes to the tunnel and recommended trajectory, as shown in Fig.

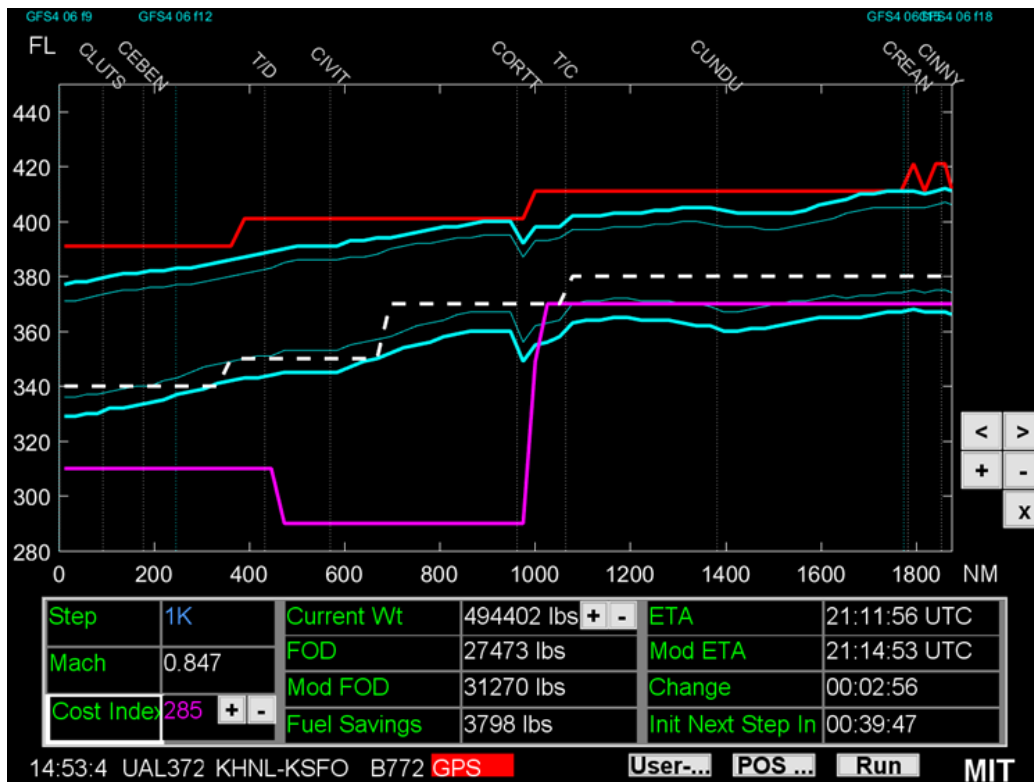


Figure 6-4: Flight 2 DST display, forecasts from 0600Z

6-5. With the updated weather, the recommended trajectory suggested a 2000 ft climb 300 NM from the start of cruise followed by a 1000 ft climb 700 NM into cruise, rather than the reverse order of a 1000 ft climb followed by a 2000 ft climb.

The flight plan was revised approximately 10 minutes after the weather update and approximately an hour and 15 minutes before pushback due to a decrease in payload weight. The DST was rerun with the revised weight. Fig. 6-6 shows the updated tunnel which increased in altitude due to the flight's decreased gross weight. The increased altitude of the tunnel resulted in an increase in expected fuel savings, as the center of the tunnel moved farther away from the flight planned trajectory.

Prior to departure, the flight crew reviewed the flight plan, the DST image, and the turbulence information available to them. The crew decided the turbulence forecast at higher flight levels looked acceptable and, after discussing with the dispatcher, elected to try flying above the turbulence, rather than under as flight planned. The as-flown trajectory is in green in Fig. 6-7. Flight plan guidance areas are overlaid

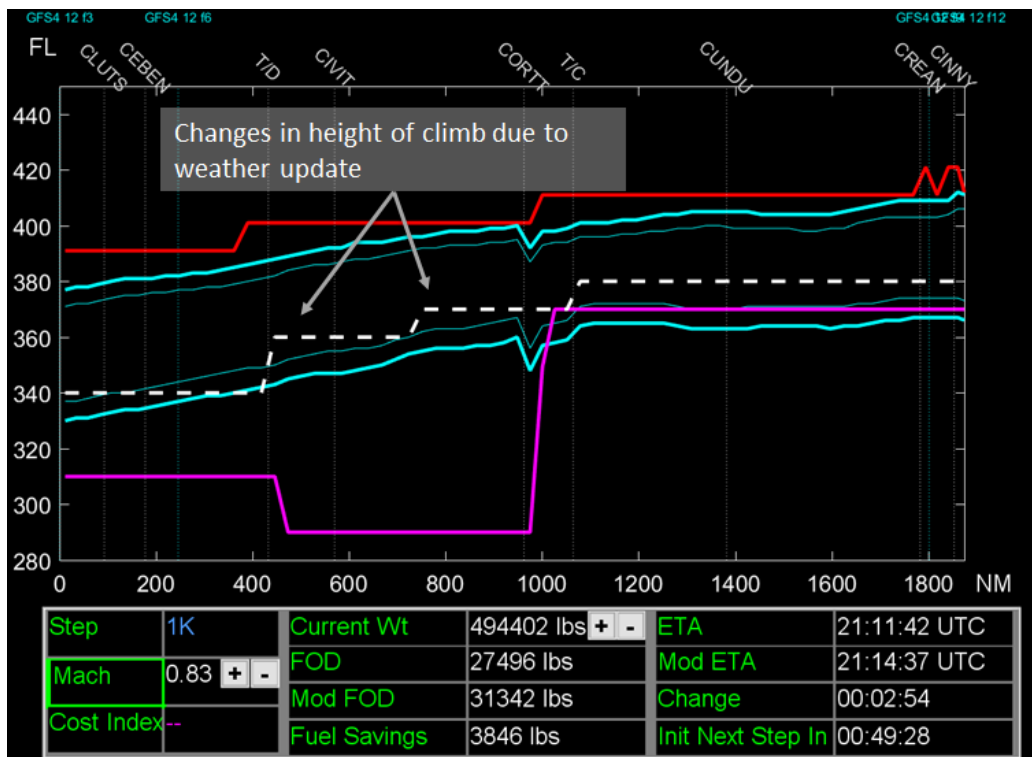


Figure 6-5: Flight 2 DST display, forecasts generated 1200Z

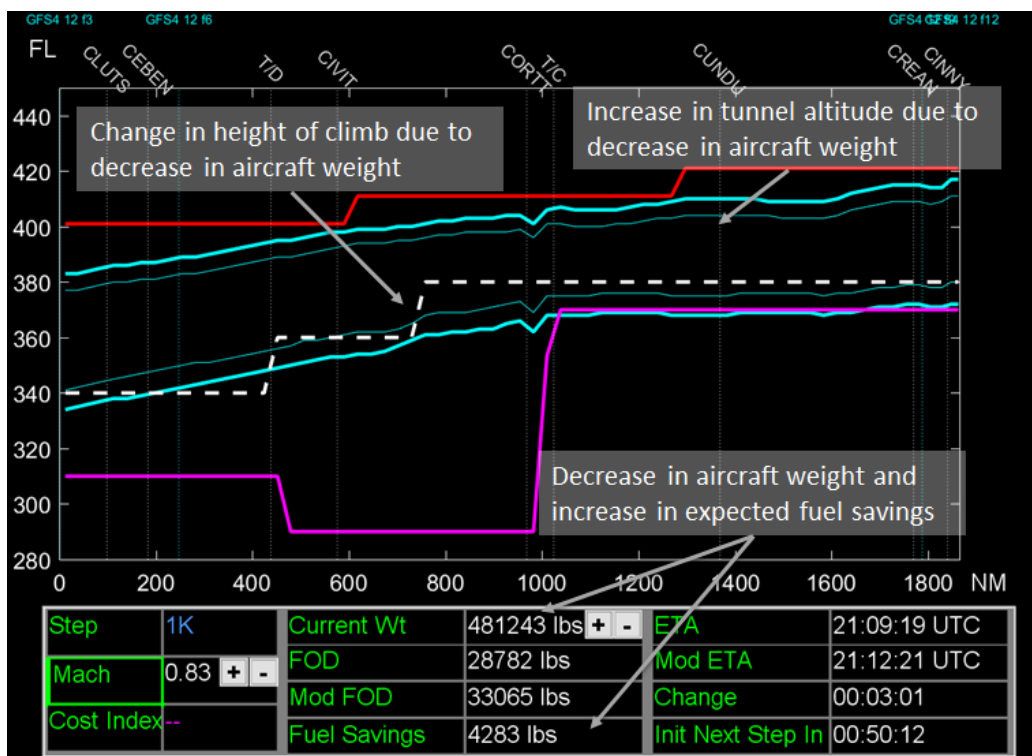


Figure 6-6: Flight 2 DST display, revised flight plan, forecasts generated 1200Z

from post-flight analysis, but were not available on the DST in flight.

At cruise, the flight encountered turbulence throughout the first three quarters of the flight and attempted to improve ride quality by climbing to higher altitudes. Fuel-on-board values recorded by the aircraft indicated that the flight saved over 3800 lbs of fuel with a penalty of four additional minutes of flight time by trying to climb over the turbulence, due in part to improved vertical situational awareness, compared to the flight planned fuel burn for the originally planned trajectory.

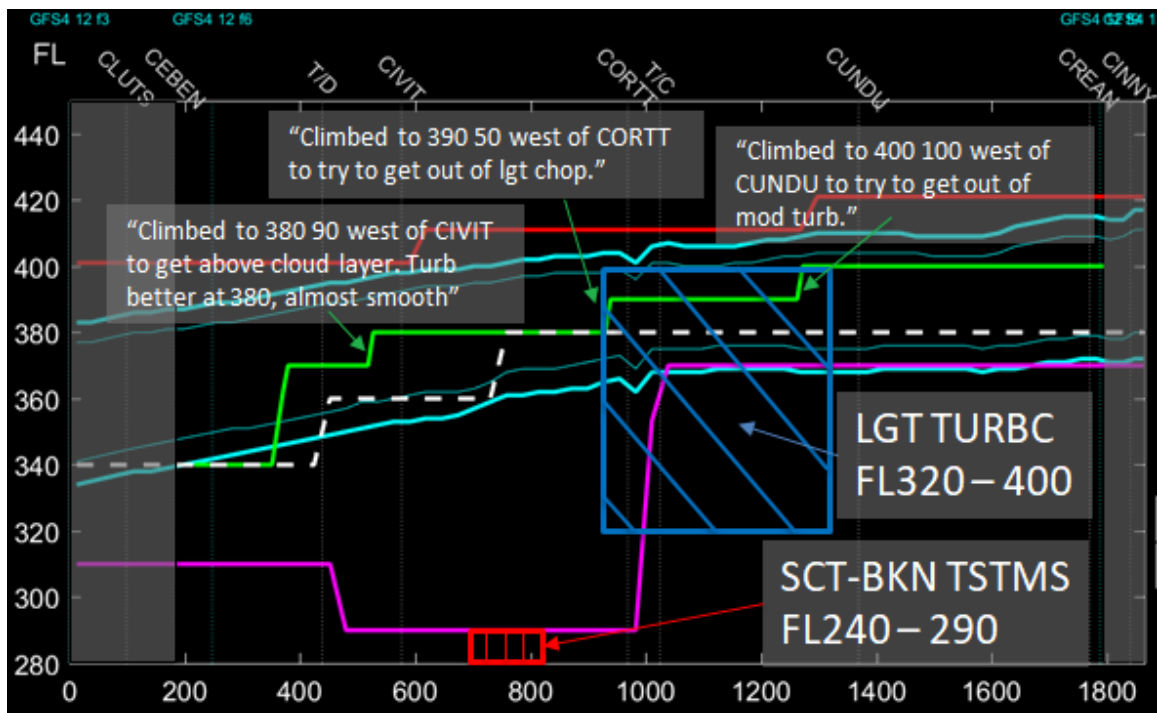


Figure 6-7: Flight 2 summary with as-flown trajectory (green), flight plan guidance regions (blue), and flight crew comments

In a post-flight debrief, it was noted that the flight planned trajectory did not correspond with the flight plan guidance areas from the significant weather chart included with the flight plan, shown in Fig. 6-8, as it appears to climb the flight through the flight plan guidance area with light turbulence.

Discussions revealed that the dispatcher planned the turbulence avoidance trajectory using a different turbulence product than the flight plan guidance areas on the significant weather chart. These turbulence forecasts were unavailable for retrieval after the flight. Post-flight discussions also revealed that the turbulence forecast

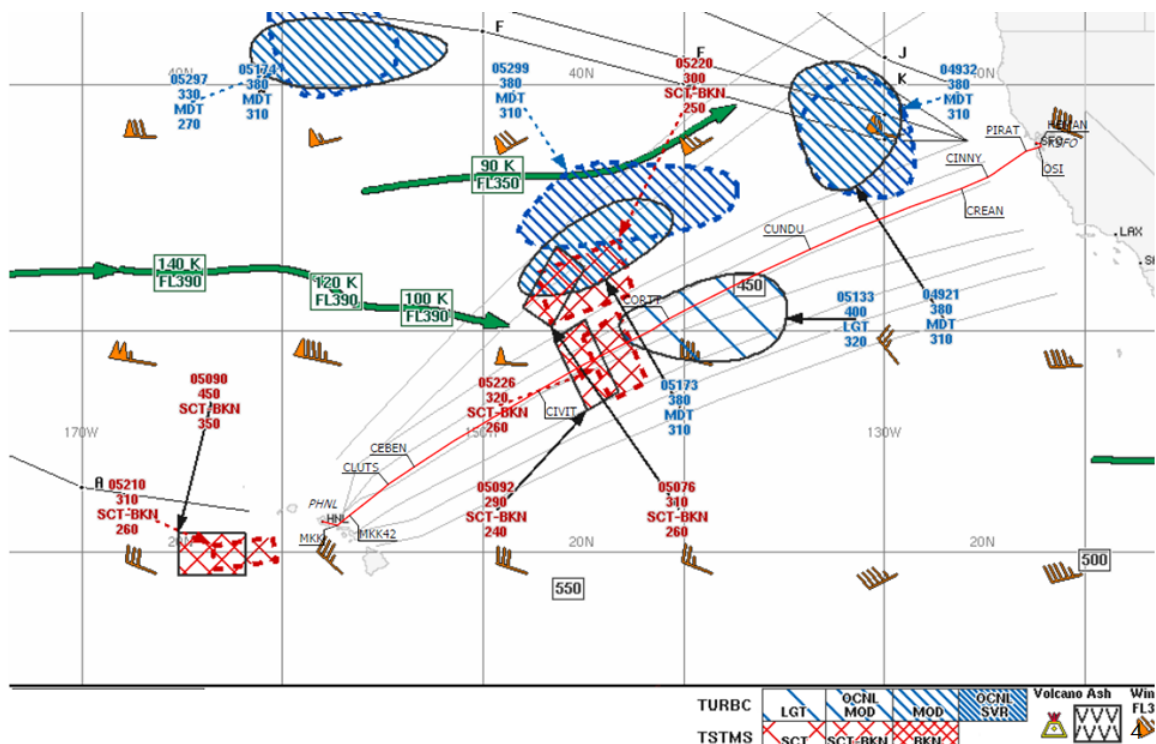


Figure 6-8: Flight 2 Significant Weather Chart included with flight plan

that was displayed to the flight crew was different from the turbulence forecast that was displayed to the dispatcher, despite both parties viewing the information from the same turbulence product. The flight crew also stated that some additional uncertainty resulted from having limited vertical resolution in the turbulence product, with information only available for every three or four thousand feet. The flight crew also expressed that if they had a more accurate forecast of actual turbulence at the higher flight levels, it is possible they may not have chosen to try and climb over the turbulence. The flight crew indicated that the tunnel was visually compelling compared to a number for optimum altitude.

6.3 Flight 3: ORD-PVG

Flight 3, from Chicago to Shanghai, had a cruise time of approximately 13 hours. The flight plan was generated approximately two hours before departure with 0600Z forecasts. The cost index was 33 in units of 100lbs/hr. The DST display with a

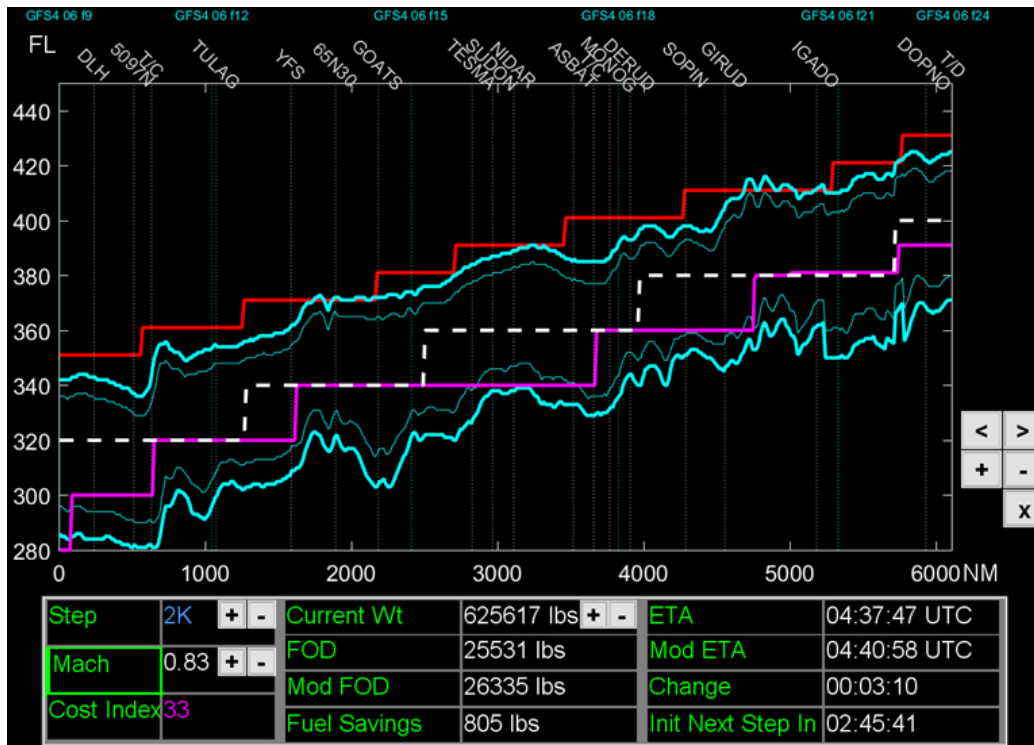


Figure 6-9: Flight 3 DST display, forecasts generated 0600Z

minimum cost tunnel was generated based on the flight plan, shown in Fig. 6-9, and sent to the flight crew. Afterwards, updates during cruise were sent to the aircraft using the onboard Wi-Fi. Approximately an hour before departure, the flight plan was revised with an updated zero fuel weight estimate that was decreased by about 8600 lbs. The updated CASO display following the second flight plan release is shown in Fig. 6-10. The flight crew attempted to follow the CASO recommended trajectory and was able to do so until the last recommended climb.

Ten minutes after departure, the 1200Z forecasts became available, and the DST was rerun, resulting in a change in recommended location for the climb to FL360. The location of the climb was shifted earlier by approximately 500 NM. However, the magnitude of expected fuel savings remained the same. Fig. 6-11 shows the CASO display with 1200Z forecasts.

Shortly after takeoff, the flight made a small lateral deviation from the flight plan to avoid a Military Operations Area (MOA) that was not properly included in the available Notices to Airmen (NOTAMs). Shown in Fig. 6-12, the lateral deviation is

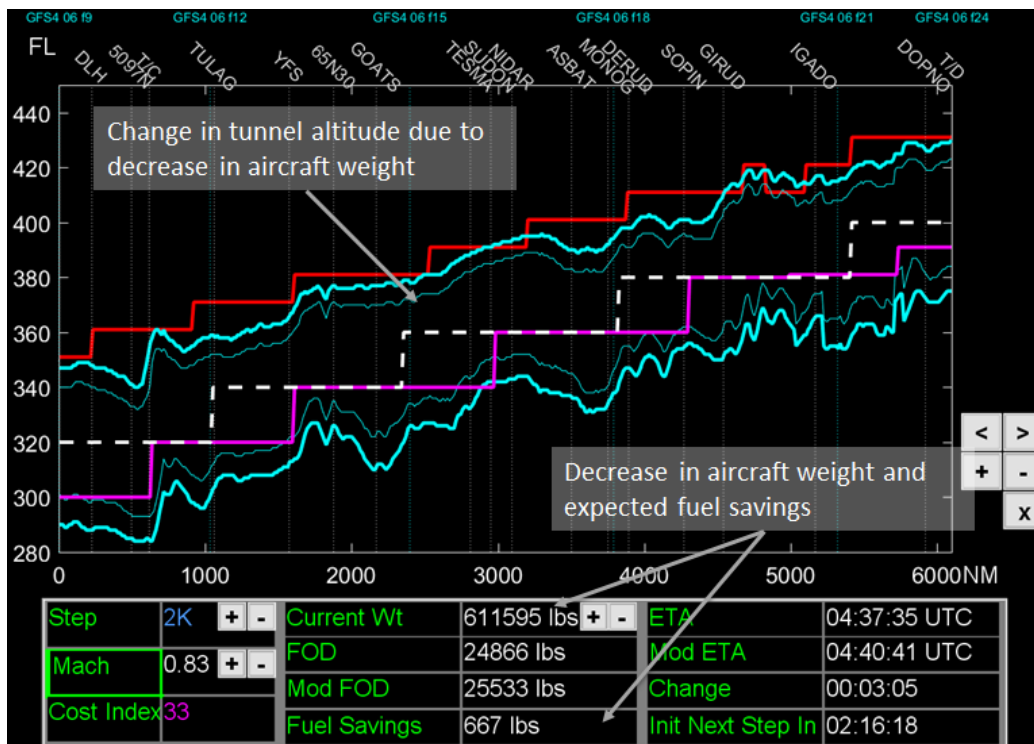


Figure 6-10: Flight 3 DST display, revised flight plan, forecasts generated 0600Z

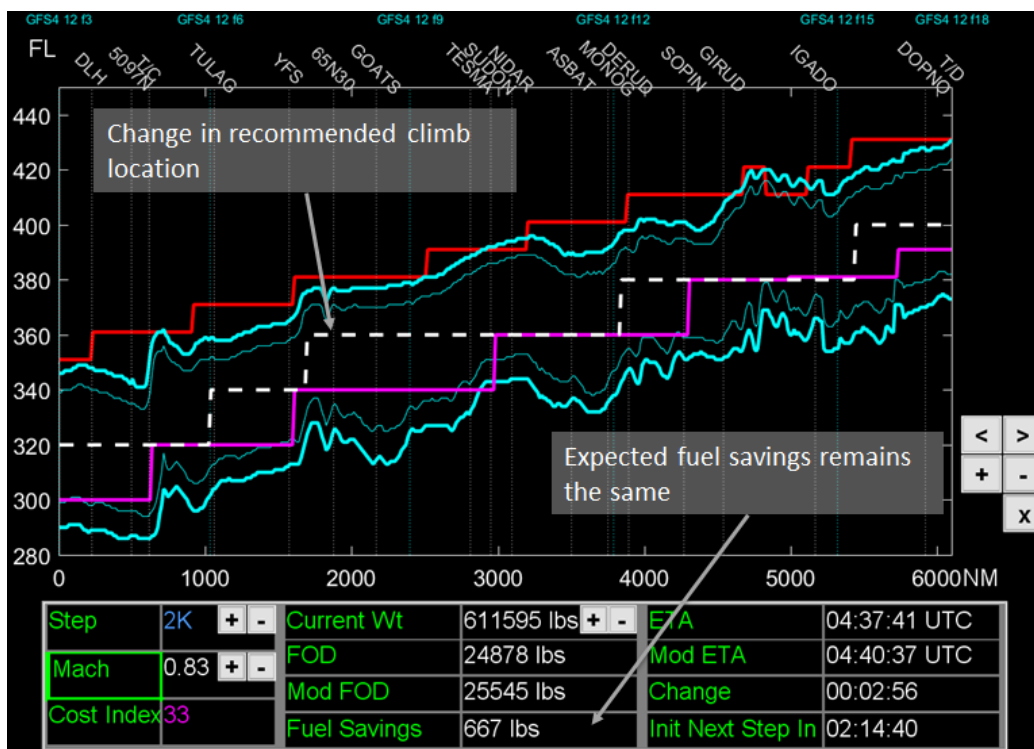


Figure 6-11: Flight 3 DST display, forecasts generated 1200Z



Figure 6-12: Flight 3 lateral deviation due to MOA with as-flown trajectory (green) and original planned trajectory (magenta)

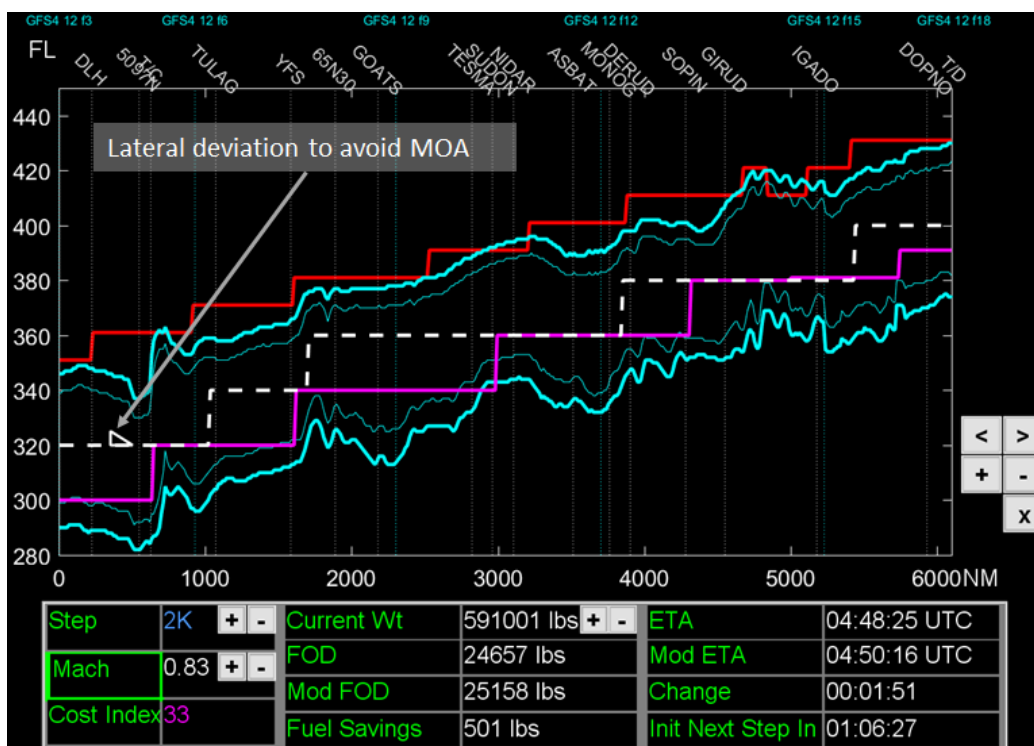


Figure 6-13: Flight 3 DST display, updated position, forecasts generated 1200Z

depicted by the green line, while the original flight plan route is shown in magenta. The aircraft weight, position, and time was also updated from a position report received from the dispatcher, shown in Fig. 6-13.

Six hours into the flight, the 1800Z forecast became available. However, no significant changes resulted from the weather update or the latest position report, as shown in Fig. 6-14.

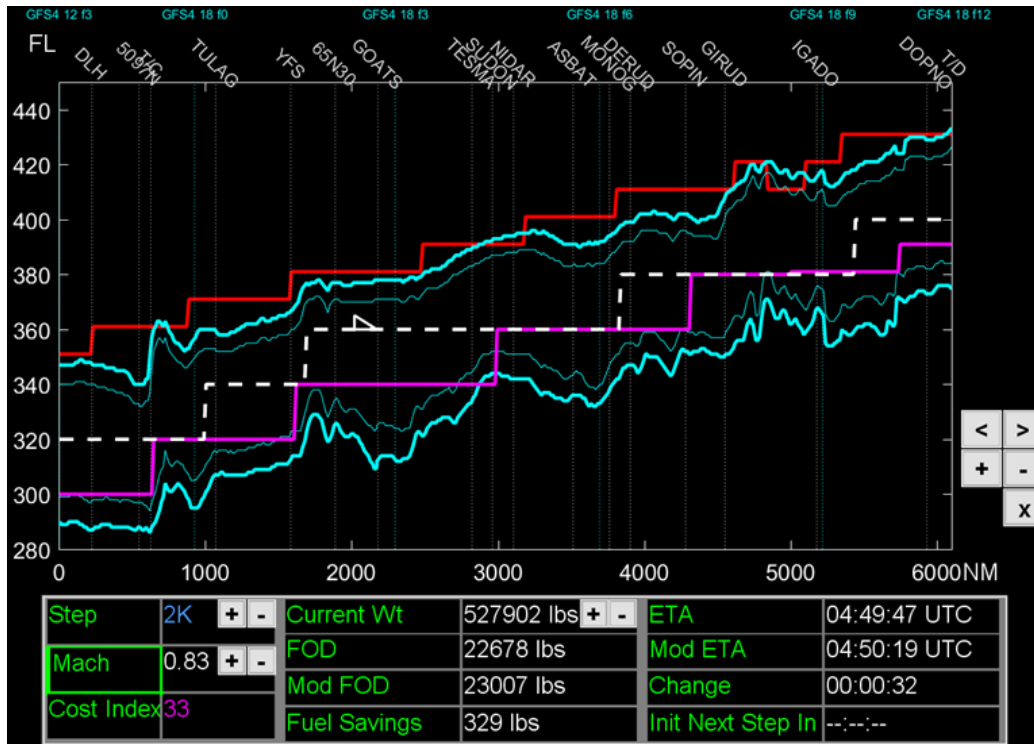


Figure 6-14: Flight 3 DST display, forecasts generated 1800Z

Approximately 5100 NM into cruise, the flight had a lateral deviation, shown in Fig. 6-15 and 6-16 after entering Chinese airspace, adding additional track distance and flight time of approximately three minutes. The actual flight path is shown in green and the original planned path in magenta in Fig. 6-15. Shortly after, an updated position report was used to rerun the CASO tool. The recommended trajectory increased by 1000 ft, due to the change in magnetic heading to an easterly direction, resulting in a switch from even flight levels to odd flight levels. The flight was unable to obtain permission to climb, however, and was forced to descend by ATC.



Figure 6-15: Flight 3 second lateral deviation with as-flown trajectory (green) and original planned trajectory (magenta)

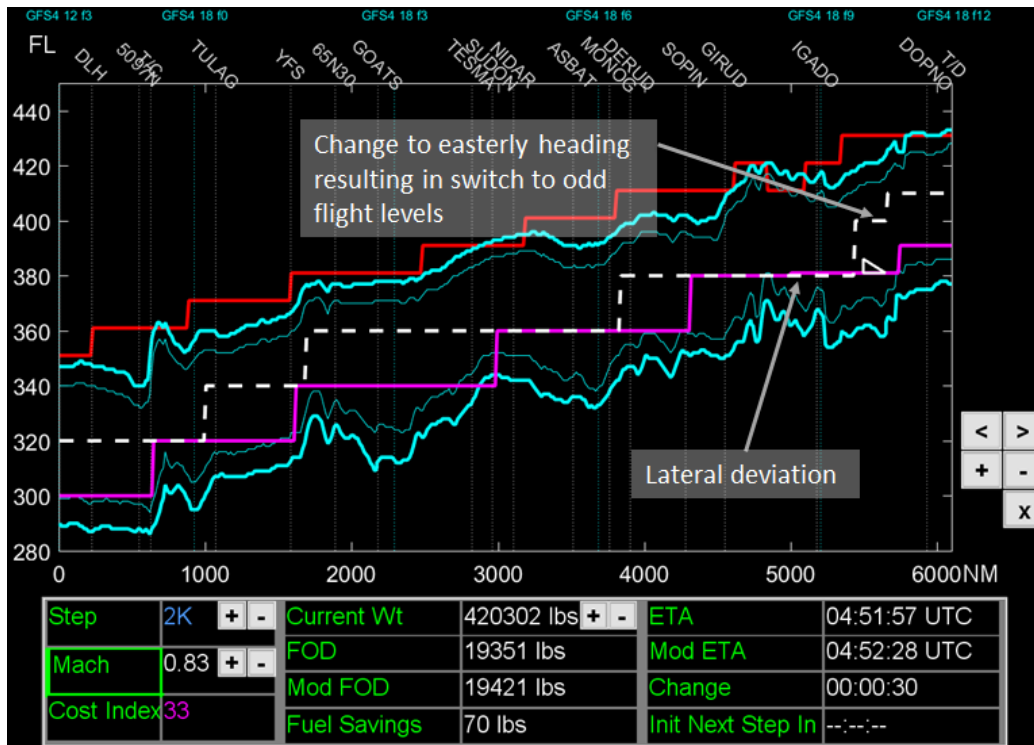


Figure 6-16: Flight 3 DST display, updated position, forecasts generated 1800Z

The flight crew was able to follow CASO guidance for most of the flight, with the exception of the last two recommended climbs, as indicated in Fig. 6-17. Fuel burn and flight time data recorded onboard the aircraft was available between 53N00 and DONVO. While CASO predicted a potential savings of 316 lbs of fuel and one minute of additional flight time between 53N00 and DONVO by following the CASO recommended trajectory, the recorded fuel burn was 1332 lbs more and four minutes longer than the flight plan prediction for following the flight planned trajectory. However, approximately 800 lbs and three minutes of the additional fuel burn and flight time occurred in the segment where there was a lateral deviation in China. The remaining 500 lbs of additional fuel burn represents less than 0.5% of the cruise fuel burn.

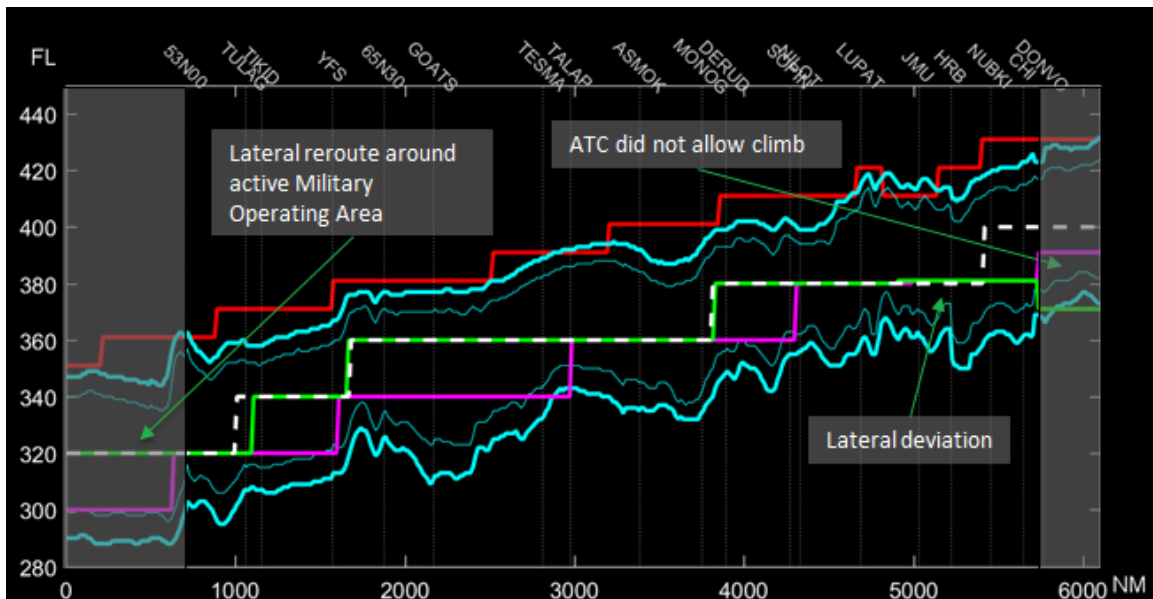


Figure 6-17: Flight 3 summary with as-flown trajectory (green)

6.4 Flight 4: PVG-ORD

The return flight from Shanghai to Chicago was seven hours behind schedule, because the aircraft arrived from its inbound leg seven hours late. As a result, the cost index for the flight was set at 400 in units of 100lbs/hr, which translates to each minute of flight time having equivalent value as 667 lbs of fuel. The flight plan was received 2 hours prior to departure. The output from the DST is shown in Fig. 6-18 based on

weather forecasts from the 1200Z analysis. The DST indicated potential fuel savings toward the start of cruise, with the flight plan remaining low at FL270 and FL290 for the first 800 NM of cruise compared to the CASO recommendation. Due to the high cost index, the tunnel is significantly more sensitive to the strength of the winds aloft. At approximately 2300 NM, 3400 NM, and 4900 NM along the track, the center of the tunnel dips in altitude due to stronger winds forecasted at lower altitudes. However, prior to departure, the DST was set such that the optimization was constrained to only allow climbs. Modifications were made to the optimization code to allow descents, but were not completed until after the flight reached cruise. As this flight did not have operational inflight Wi-Fi, updated images of the CASO output could not be given to the crew while en-route. Instead, text updates to the CASO recommended trajectory were passed to the crew via ACARS by the dispatcher. The CASO DST was updated after reaching cruise with a position report and with descents allowed in the optimization. The output is shown in Fig. 6-19.

While the tunnel shape remained largely unchanged with the position update,

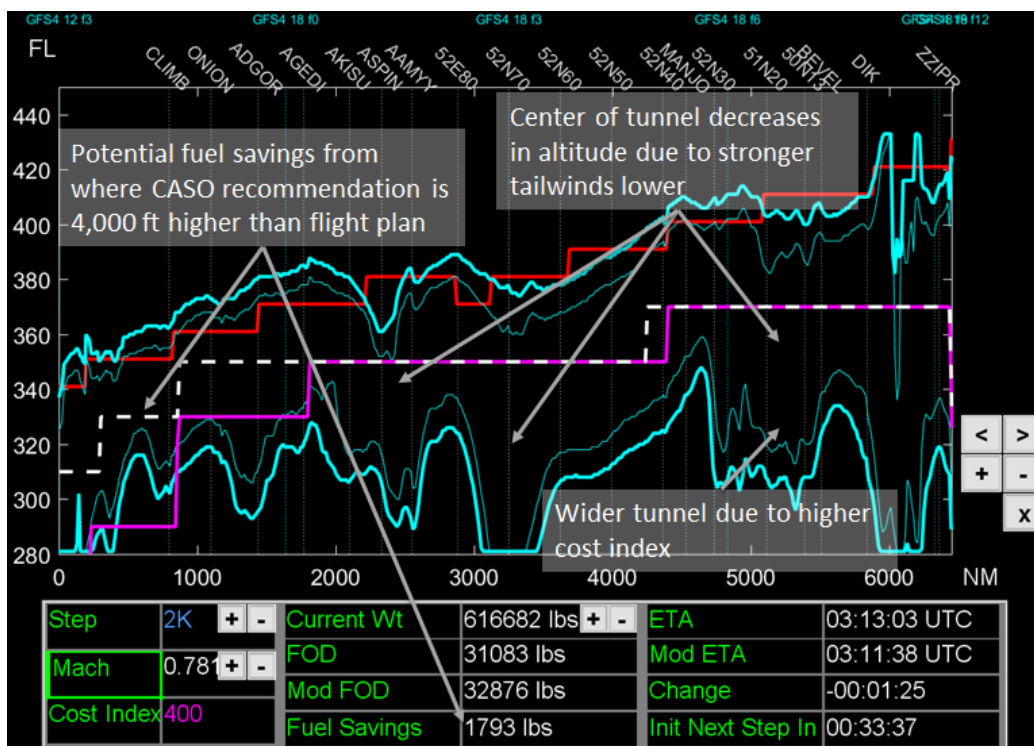


Figure 6-18: Flight 4 DST display with 1200Z forecasts

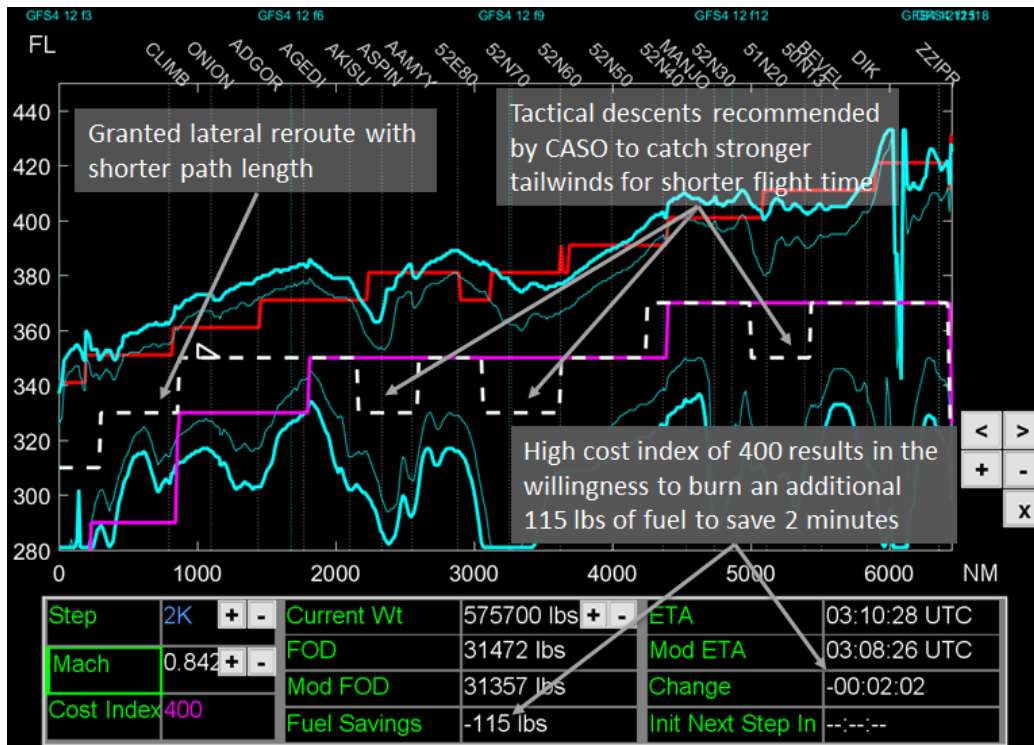


Figure 6-19: Flight 4 DST display, updated position with 1200Z forecasts

allowing descents in the optimization resulted in three tactical descents being recommended where the center of the tunnel decreased in altitude, due to stronger tailwinds at lower altitudes. The recommended trajectory with temporary descents was predicted to shorten flight time by 2 minutes at the cost of burning approximately 115 more lbs of fuel. The latter two tactical descents were sent to the flight crew through ACARS as the new recommended trajectory. However, the message was not sent in time for the first descent.

Near the start of cruise, the flight was granted a lateral reroute to take a more direct path over Japan. The lateral track is shown in Fig. 6-20, with green representing the reroute and as-flown trajectory, while the magenta shows the original flight planned path.

Approximately six hours after the beginning of the flight, the 1800Z forecasts became available. The updated CASO output is displayed in Fig. 6-21. An additional descent was recommended approximately 500 NM before the top of descent. However, the magnitude of the net benefit of the last descent was smaller than the magnitude of



Figure 6-20: Flight 4 lateral deviation with as-flown trajectory (green) and original planned trajectory (magenta)

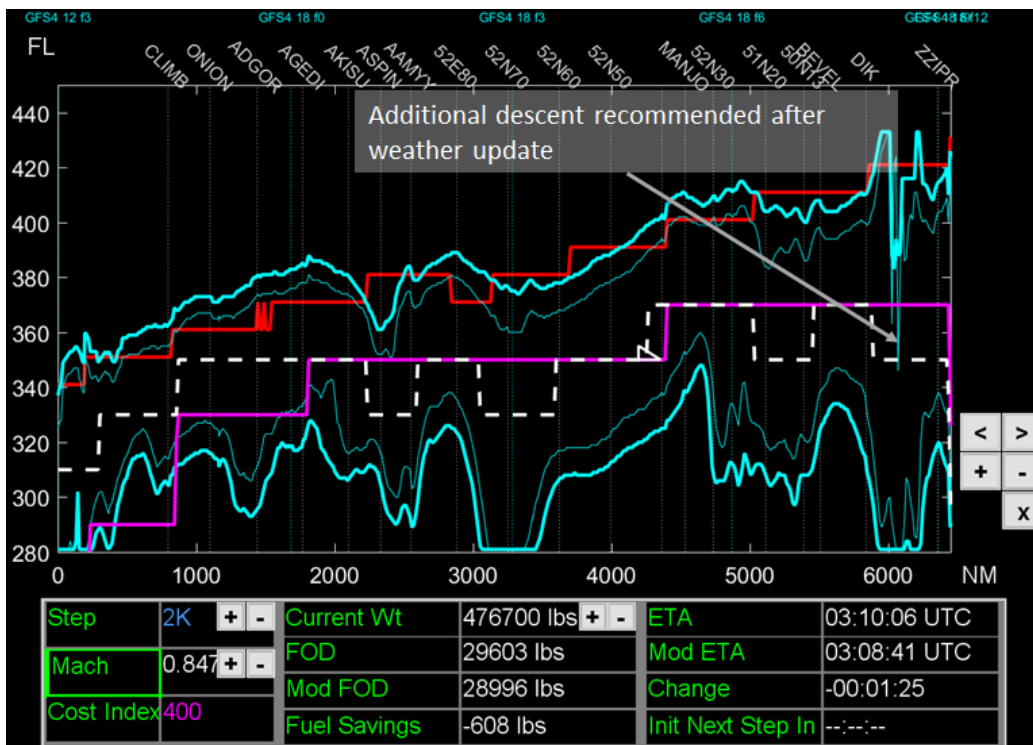


Figure 6-21: Flight 4 DST display with position update and forecasts generated at 1800Z

the previous tactical descents. It was attempted to communicate trajectory options with and without the new descent as well as their respective fuel burn and time savings to the flight crew. However, the message was not transmitted, likely due to a dispatcher shift change.

The flight crew generally followed CASO guidance, taking the second and third tactical descents. Fig. 6-22 shows the as-flown trajectory in green, the flight planned trajectory in magenta, and the CASO recommended trajectory as the white dash line. At the start of cruise, the flight was held low at FL250 temporarily by ATC, rather than beginning cruise at FL310 as recommended. The flight was able to climb to FL330 at the recommended time, however, instead of staying at FL290 as originally indicated in the flight plan. The flight crew was able to take the second and third tactical descents, but had the first climb to FL370 delayed by ATC. Towards the end of cruise, there was a small lateral deviation due to convective weather.

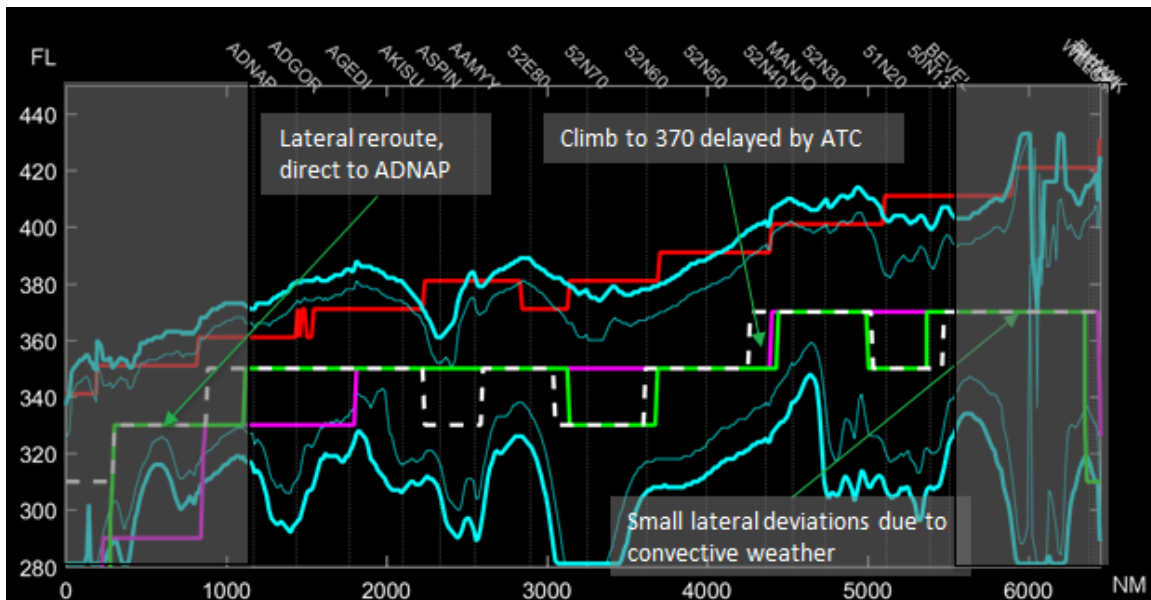


Figure 6-22: Flight 4 summary with as-flown trajectory in green

Onboard fuel burn and flight time data between ADNAP and BEVEL was examined. Because the as-flown altitude at ADNAP was 2000 ft above the flight planned altitude, an estimate for the additional fuel burn required for climbing the additional 2000 ft was calculated using the BADA4 performance model and added to the

recorded fuel burn. The recorded fuel burn between ADNAP and BEVEL, including the estimated climb burn was approximately 8 lbs more than the flight plan prediction, while the flight time was 4 minutes shorter, representing a large net savings based on the cost index of 400. The CASO estimate for following the recommended trajectory shown in Fig. 6-22 was 1070 lbs of additional fuel burn and 2 minutes shorter flight time.

Chapter 7

Discussion

7.1 Decision Support Tool Utility

In post-flight debriefings, flight crews indicated that the decision support tool improved situational awareness of the vertical trajectory decision space and costs of various trajectory options. This is consistent with the flight crew's demonstrated ability to identify and fly trajectories with reduced cost compared to the flight planned trajectory using the tool in the preliminary flight trials. In Flight 2, the flight crew identified that the flight planned trajectory was significantly off the optimal trajectory after viewing the decision support tool and also gained awareness of the relative cost of following the flight planned trajectory both by the altitude tunnel and by the fuel savings estimate. Although the flight crew was aware that the optimum altitude was above the flight planned altitude of FL290, the tool was able to provide a precise trajectory and display the relative costs. Consequently, the flight crew was also able to evaluate various other trajectories, besides the recommended trajectory, when turbulence was encountered while attempting to follow the recommended trajectory. In the case of Flight 2, the altitude tunnel indicated that climbing above the optimal trajectory was a lower cost option than descending. Similarly, in Flight 4, the flight crew was able to identify and fly tactical descents with expected time benefits that the crew would not have been aware of without the tool. The post-flight debrief discussions and the trajectories flown indicate that the decision support tool is useful.

The crew reported the tunnel to be compelling. For Flight 2, when asked if they would still have chosen to fly above the turbulence rather than under without the DST, the crew's response was "I may have still chosen to go high because I knew the optimum altitude for the flight was much higher than the planned FL310 descending to FL290. The altitude tunnel is visually more compelling than just a number for optimum altitude. It certainly reinforced my decision to climb higher rather than descend as the flight plan suggested." The flight crew also proactively asked about tactical descents in Flight 4 after viewing the tunnel, prior to the tool being configured to include descents in the optimization. The preliminary flight trials indicate that the tunnel helped motivate decisions made by the crew.

Because it was necessary to run the decision support tool from the ground, the positive results from the preliminary flight trials indicate that much of the decision support tool's utility can be achieved as a static image provided to the flight crew as part of the pre-flight briefing. By providing an image of the minimum cost tunnel as part of the flight plan, the flight crew is able to gain an awareness of the relative costs of the decision space across the entire flight, coordinate with the dispatcher if necessary, and consult the tunnel en-route if unexpected events arise. While the static image would not be updated during the flight, the minimum cost tunnel tends to retain its general shape, as seen in the preliminary flights, even for flights of over 10 hours. For flights outside the continental U.S., the update rate of once every six hours results in at most three relevant potential weather updates for even the longest flights. For flights within the continental U.S. that have the benefit of hourly-updated forecasts, the minimum cost tunnel and recommended trajectory can be monitored for significant changes. As a result of the limited changes observed from the weather updates in the four trial flights, it is currently unclear how much additional benefit is gained from weather updates. The tool can be run on the ground as a dispatcher tool, with any updates to the recommended trajectory that is deemed significant enough uplinked to the aircraft, minimizing bandwidth requirements. Updates to the recommended trajectory may be caused by new weather forecasts or other changes such as large reroutes. Flights 1 and 4 demonstrated the feasibility of this approach,

as both flights did not use inflight Wi-Fi to receive images updated with the latest weather forecast or aircraft information. Instead, updates to the recommended trajectory were sent to the aircraft via ACARS, and the flight crew was still able to follow the recommended trajectory to the extent allowed by air traffic and turbulence. In both cases, the general shape of the tunnel remained the same, with relatively small changes to climb and descent locations resulting from the weather updates.

The cost savings from each flight in the preliminary flight trials also suggest that the decision support tool is most useful for flights that are planned significantly off the optimal trajectory or that encounter unusual circumstances. Flight 2, planned significantly off cost-optimal due to turbulence, illustrates this with 3800 lbs of fuel saved and 4 minutes of additional flight time compared to the original flight plan. Similarly, Flight 4, which was delayed seven hours, showed time savings of 4 minutes flying at a cost index of 400 in units of 100 lbs/hr. For flights already planned near the optimal trajectory, the benefit achievable is dependent on the fidelity of the aircraft performance model and weather model.

7.2 Flight Crew and Dispatcher Coordination

Prior to departure on Flight 2, the flight crew called the dispatcher after viewing the decision support tool to discuss the planned turbulence avoidance trajectory, because the flight planned trajectory was significantly off the altitude tunnel, and turbulence forecasts appeared to show that flying above the turbulence was a viable option. The pre-departure communication between the flight crew and dispatcher, initiated after the flight crew viewed the tool, indicates that the decision support tool also helped facilitate coordination between the flight crew and dispatcher. During previous discussions with airlines, dispatchers have also stated that the altitude tunnel would be useful for communicating complex trajectories, such as those involving temporary descents as displayed and flown in Flight 4. Dispatchers expressed difficulties with communicating those trajectories to the flight crew using current flight plans due to the inability to explain effectively the reason behind the trajectory. Before

departure on Flight 4, while the decision support tool recommended trajectory was still configured to only allow climbs without descents, the flight crew viewed the tool and indicated that they expected descents based on the minimum cost tunnel. This indicates that the minimum cost tunnel is able to effectively communicate complex trajectories by visually providing the rationale for those trajectories.

As part of the feedback in post-flight debrief discussions, one of the dispatchers indicated that having an alert or notification from the website whenever an update occurred would be a desirable feature. This would be helpful for the dispatcher to know when changes occurred without having to constantly monitor for changes.

The discrepancy in turbulence information and the decisions made by the flight crew and dispatcher in Flight 2 suggests that flights would benefit from improved turbulence information and flight crew-dispatcher coordination. The difference between the flight planned trajectory and the trajectory selected by the flight crew is in part attributable to differences in available turbulence information. The debrief discussion following Flight 2 indicated that the dispatcher had turbulence information that was different from the flight crew's turbulence information, despite using similar products. Discussions with a pilot from another airline also indicated that their dispatchers planned routes using one product, while flight crews tended to rely on a separate product. The differences in available information may create unnecessary uncertainty, resulting either in unnecessary flight costs or more instances of flying into avoidable turbulence. This is especially pronounced when the differences are observed while using the same turbulence product. Having synchronized turbulence information would reduce unnecessary uncertainty and facilitate clearer communication of rationale between dispatcher and pilot. The flight crew also expressed a desire for higher accuracy and higher resolution turbulence forecasts, indicating that decisions may have been different if better forecasts were available.

The difference between the dispatcher planned trajectory and the initial trajectory that the captain decided to fly in Flight 2 may also be in part influenced by potential differences in conservatism regarding turbulence. For example, the dispatcher may prefer to be more conservative, as they are the ones planning the initial trajectory.

The flight crew may be less conservative, as they are in control of the aircraft and are able to modify the initial trajectory later on, if they desire. Synchronizing turbulence information would allow for clearer communication of preferences and facilitate negotiation and agreement between dispatcher and pilots.

Chapter 8

Conclusions

A cruise altitude and speed optimization decision support tool for aiding crew and dispatcher situational awareness and decision-making based on the minimum cost altitude tunnel was developed. A prototype of the tool has been implemented, and preliminary flight trials were conducted on a Boeing 777.

The DST provided improved situational awareness in vertical trajectory costs to the flight crew before and during the flights. The flight crew reported the minimum cost tunnel to be compelling. The DST was also found to be useful for facilitating coordination between the flight crew and the dispatcher. The preliminary flight trials also showed that trajectory decision-making would be aided by improved turbulence information, particularly a synchronization of the turbulence information available to the flight crew and to the dispatcher. The largest potential benefits are seen with flights that are planned significantly off the optimal trajectory. In the preliminary flight trials, one flight achieved fuel savings of over 3800 lbs due to the flight being planned low for turbulence. Savings for flights with relatively good agreement between the flight plan and the CASO DST will depend on the fidelity in the aircraft performance model and weather forecasts. The preliminary flight trials indicate that the DST would still be useful even as a static image provided with the flight plan prior to departure.

Potential future research would include refining the fidelity of the performance estimation by improving the climb and descent models and including climb and descent

costs in the optimization. Integration of turbulence information in the tool is another area for continued work. Future research may examine incorporating turbulence into the cost function and optimization. The synchronization of information and development of tools to improve coordination between flight crews, dispatchers, and air traffic controllers may also be investigated.

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