ICAS 2016
30th Congress of the International Council of the Aeronautical Sciences
DCC, Daejeon, Korea ; September 25-30, 2016

BENEFITS ASSESSMENT ON TIME-BASED OCEANIC ARRIVALS TO THE TOKYO METROPOLITAN AREA

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Keywords: *DARP, 4D- TBO, Required Time of Arrival, Trajectory Optimization*

Abstract

The increasing demand for air travel has propelled R&D projects in a global scale to investigate new solutions to enhance the efficiency of the current air transportation system. Dynamic Airborne Reroute Procedures (DARP) is one of the strategies implemented in oceanic arrivals to the Tokyo metropolitan area as a part of the CARATS project proposed by the Japan Civil Aviation Bureau. DARP provides lateral route alteration capability while 4D-trajectory based operations (4D-TBO) is considered to be critical in meeting future challenges in the aviation industry. This paper provides a framework to investigate the benefits through DARP procedures in the conventional operations and potential benefits through introducing 4D- TBO procedures to oceanic operations in an ideal operational environment. A series of DARP implemented data provided by a national airline is used to quantitatively evaluate the aircraft performance, mainly fuel consumption and flight range. Reference tracks are generated based on flight plans, position data and radar data and DARP data. Results show that dynamic re-routing can produce fuel saving benefits for airline operators. Furthermore, trajectory optimization proves to be a potential enhancement for DARP operations in oceanic operations as the optimizer was able to reduce 5 ~ 17% of fuel consumption through reducing flight range and selecting optimal altitude compared to DARP operated tracks.

1 Introduction

The increasing demand for air travel has propelled R&D projects in a global scale to investigate new solutions to enhance the efficiency of the current air transportation system. Simulation studies predict that the larger portion of air traffic would increase over the Japanese airspace due to international flights and overflights. The long-term project, Collaborative Actions for Renovation of Air Traffic Systems (CARATS) is proposed by the Japan Civil Aviation Bureau (JCAB) to address the modernization of the state's air traffic control (ATC) system. According to the proposed objectives, increasing the efficiency of arrival procedures to the Tokyo metropolitan area is one of the major challenges to overcome in a future air traffic management (ATM) system [1].

Regarding the promotion of CARATS, JCAB has initiated various trial procedures targeting Japanese hub airports to investigate the benefits of introducing new operational procedures to the national system with the cooperation of Federal Aviation Administration (FAA), air navigation service providers (ANSP) and airline operators. Dynamic Airborne Reroute Procedures (DARP) is one of the strategies introduced in the User Preferred Routes (UPR) implementation for Northern and Southern Pacific regions. DARP is a procedure for re-route clearance which contributes towards more efficient traffic flow and cost savings by implementing dynamic lateral-route alterations from the initial flight plan upon considering updated weather conditions. Since 2012, JCAB began trial operations between Oakland Flight Information Region (FIR) and Fukuoka FIR with the collaboration of FAA and national airline companies. Several requirements are mandated for DARP implementation such as [2],

- Operating aircraft's capability for *Controller Pilot Data Link Communications* (CPDLC).

- Request 60 minutes prior to FIR crossing to permit *Air Traffic Services Interfacility Data Communications (AIDC)* messaging.
- Notification 20 minutes prior to the divergence point to allow processing between flight crew and ATC.

Though DARP is considered to be a potential fuel saving strategy, airline operators are not that optimistic in applying the procedure often in current day operations because the profits are not significant compared to the required manpower cost to initiate such procedure. On the other hand, 4D- trajectory based operations (4D- TBO) is considered to be one of the key technologies to cope with the future demands in the aviation industry. Studies are abundant in understanding the benefits of applying new operational techniques with TBO within the national airspace [3-5]. Considering the unavoidable constraints in the national airspace structure and domestic operational environment (longest flight is less than 3 hours), benefits are expected to be not so significant through these new procedures in the local airspace. In order to broaden the application scope of such techniques which would eventually increase the benefits in a future system, the plausibility of applying such techniques to international flights has to be evaluated and investigated.

ENRI is involved in various research studies among which *optimizing oceanic tracks including arrival routes* and *Full-4D operations* are two major projects assigned to seek solutions to improve the current ATC system. The former project investigates the impact of innovative procedures such as continuous descent arrival (CDO) operations, flight-deck interval management (FIM) and airborne surveillance application systems (ASAS), while the latter project reviews the challenges towards the application of 4D- optimal trajectories into the system. This paper provides a framework to associate the above research environments by investigating potential benefits based on the assumption that the TBO concept is validated and applied for oceanic arrivals to the Tokyo metropolitan area. Information regarding a series of DARP implemented flights provided by a national airline company is used as reference to implement the study by optimizing the corresponding trajectories for fuel consumption and flight time with a proposed 4D- trajectory optimizer, introduced in previous studies by the authors [6]. Performance parameters are calculated by applying meteorological data from the Japan Meteorological Agency (JMA) [7] and aircraft performance data from the Base of Aircraft Data (BADA) data from the EUROCONTROL [8]. Obtained results are used to discuss the improvements that can be proposed for oceanic routes and issues to overcome in validating such proposals in a real operational environment.

2 Utilized Data and Models

This section introduces different data types and models used in the study.

2.1 Reference Data

In this study, Information regarding a series of DARP implemented flights provided by a national airline company is used as reference data (indicated as ‘reference data’). The flights are originated from the Honolulu International Airport (PHNL) and the destinations are the Tokyo International Airport (RJTT) and Narita International Airport (RJAA) as shown in Fig. 1. The 3D- position data required for analysis are acquired through the integration of Oceanic Air Traffic Control Data Processing System (ODP) data and Radar Data Processing System (RDP) data. ODP data are generated according to flight plan data and position reports downlinked by the aircraft. RDP data are radar data tracked by the Oceanic Route Surveillance Radars (ORSR) and Air Route Surveillance Radars (ARSR). The data are further processed by a smoothing algorithm to treat irregular data patterns and data loss [9].

Performance parameter estimations are considerably sensitive to weather data and time histories of the position data. Furthermore, access to ODP and RDP data are limited. Hence, the general speculations are made based on overall data while the delicate calculations are conducted based only on accessible data, five flights in total.

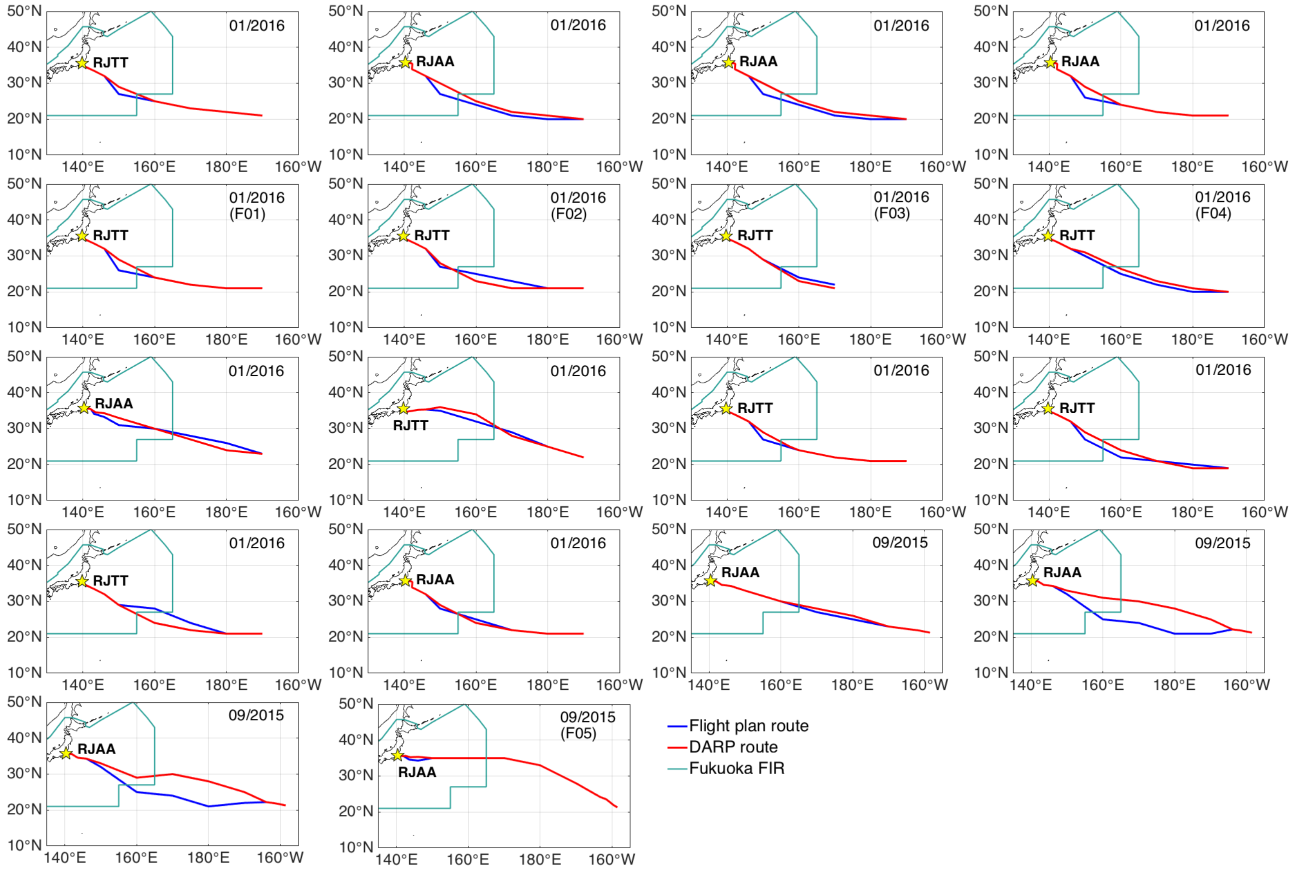


Fig. 1. *Reference Data* (DARP Routes, September 2015 and January 2016)

Corresponding flights for numerical analysis are mentioned as F01~ F05 in Fig. 1.

Flight plan data are available as 3D trajectory profiles with waypoint data and, altitude and speed assigned at each waypoint. Hence data interpolation is necessary to generate trajectories for performance estimation. On the other hand, ODP data is updated at a 1-minute interval compared to the 10-second interval of RDP data. These dissimilarities have influenced to adopt following assumptions in trajectory preparation in order to implement a fair analysis on operational performance between predetermined flight plans and corresponding DARP. The context of this paper refers to trajectories generated based on flight plan data as ‘plan tracks’ and trajectories generated based on airline provided information as ‘DARP tracks’.

- Aircraft performs at a cruising speed of Mach 0.80. This is the standard airline procedure value defined in the BADA model for the subjected aircraft.
- Aircraft performs from the initial point of reference data to the initial point available from ODP data at the cruising altitude identical to the altitude at the initial point of ODP data.
- The aircraft follows the vertical profile acquired by the corresponding ODP and RDP data in both plan tracks and DARP tracks.
- Aircraft passes the merging point of plan track and DARP track at the same time, hence the starting time between the two tracks are not identical. The difference of weather conditions due to this reason is considered negligible.

2.2 Meteorological Data

JMA distributes a variety of numerical weather prediction (NWP) grid point value (GPV) weather forecast data on global and local atmospheric conditions. The Global Spectral Model (GSM) nowcast data is used in the analysis, of which the forecast data is updated at an interval of 6 hours. The precision of forecast data is already validated in a previous study [10].

2.3 Aircraft Performance Data

Aircraft performance calculations of conventional and optimal operations are based on the BADA (version 3.12) model data. As aircraft mass data is unknown, aircraft mass at the initial point of each flight is estimated as a ratio of the maximum take-off mass defined in the BADA model. The ratio is considered based on the fact that fuel consumption is approximately proportional to flight time [10]. Table 1 shows the flight time estimated from the plan tracks with total flight time in brackets, acquired by flight plan data, and the estimated initial mass value for each flight case.

Table 1. Estimated Aircraft Initial Mass

Flight	Flight time (s)	Initial mass (kg)
F01	23,280 (33,000)	133,704
F02	23,610 (33,600)	131,928
F03	15,390 (32,880)	88,154
F04	22,350 (32,520)	131,655
F05	19,670 (26,640)	137,985

2.4 Trajectory Optimization Method

A trajectory optimization model based on the Dynamic Programming (DP) method has been developed by the authors which minimizes fuel consumption according to given arrival time constraints by exerting maximum aircraft performance. Point mass approximations are considered to address the aircraft's 3D-translational motion defined by Eqs. (1) – (4) in an environment assumed free of ATM-imposed constraints on route and altitude; that is free-routing, commonly known as 'free flight'.

$$\frac{d\theta}{dt} = \frac{1}{(R_0 + H)\cos\phi}(V_{TAS}\cos\gamma_a \sin\psi_a + W_x) \quad (1)$$

$$\frac{d\phi}{dt} = \frac{1}{(R_0 + H)}(V_{TAS}\cos\gamma_a \cos\psi_a + W_y) \quad (2)$$

$$\frac{dH}{dt} = V_{TAS}\sin\gamma_a \quad (3)$$

$$m\frac{dV_k}{dt}\cos(\gamma_a - \gamma)\cos(\psi_a - \psi) = T - D - mg\sin\gamma_a \quad (4)$$

ϕ : Latitude
g : Gravitational force
θ : Longitude
m : Aircraft mass
H : Altitude
V_k : Inertial speed
V_{TAS} : True airspeed
T : Engine thrust
γ : Path angle
D : Aerodynamic drag
ψ : Azimuth angle
R_0 : Earth radius
t : Time
W : Wind

Subscripts

a : Respect to air flow
x : Zonal component
y : Meridional component

Application of the DP algorithm uses fours state variables, namely the aircraft's 3D- position (longitude, latitude and altitude) and speed, and three control variables, namely flight path angle, azimuth angle and engine thrust. A combinatorial optimization process is applied in a discretized state space grid, by defining downrange as the independent variable with altitude, speed and cross-range as state variables and the optimal solution is derived among all the state transitions.

In this study, the performance index is defined by considering the minimum cost with a trade-off between fuel consumption and flight time. The optimization cost function is defined in Eq. (5) and the concept of Cost Index (CI) is taken into account in defining the cost function as shown in Eqs. (6) and (7).

$$J_{opt}(H_{h_{k+1}}, V_{i_{k+1}}, \eta_{j_{k+1}}, \xi_{k+1}) = \min_{\substack{h_k \to h_{k+1} \\ i_k \to i_{k+1} \\ j_k \to j_{k+1}}} \left[H_{h_k}, V_{i_k}, \eta_{j_k}, \xi_k + FF|_{\xi_k}^{\xi_{k+1}} \Delta t \right] \quad (5)$$

$$\min J = \int_{t_0}^{t_f} C_{\text{fuel}} \cdot FF(t)dt + \int_{t_0}^{t_f} C_{\text{time}} dt \quad (6)$$

$$\min J = \mu(t_f - t_0) + \int_{t_0}^{t_f} FF(t)dt \quad \left(CI = \frac{C_{\text{time}}}{C_{\text{fuel}}} = 79.37\mu \right) \quad (7)$$

ξ : Downrange angle
η : Cross-range angle
V : Calibrated airspeed
μ : Weighting parameter
FF : Fuel flow
J : Performance index
C_{time} : Time cost
C_{fuel} : Fuel cost

Subscripts

h, i, j : Arbitrary waypoints along state variable axes
k : k^{th} segment along independent variable axis
0 : Initial
f : Final
opt : Optimal

The weighting parameter μ enables various settings of the optimizer to generate trajectories optimized only for fuel or trajectories optimized for fuel with flight time constraints. This capability is used to evaluate the feasibility of enhancing the 4D- TBO scope towards oceanic operations.

3 Analytical Results

Figure 2 shows the lateral route deviations of DARP tracks for all the flights compared to the corresponding plan tracks. Deviations are plotted with respect to longitude.

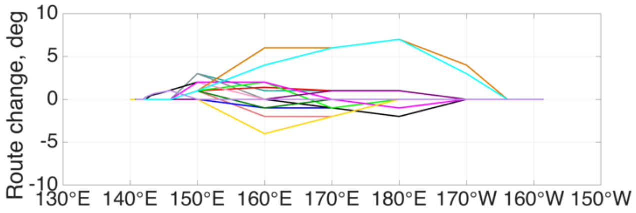


Fig. 2. Lateral Route Deviations due to DARP Operations

Most of the DARP operations are initiated around the 180°E meridian except for two flights which record the largest deviation of 7 degrees. The next sections review the benefits obtained by DARP operations and potential benefits through introducing 4D- TBO to oceanic operations.

3.3.1 Benefit assessment of DARP operations

This section compares the aircraft performance, mainly fuel consumption between plan tracks and DARP tracks to understand the benefits obtained by implementing DARP. Flight time is the other key parameter which is compared to review the benefits obtained through implementing DARP operations. Table 2 denotes the numerical values of total fuel consumption, flight time and flight range for the five subjected flight cases.

Table 2. Conventional Aircraft Performance

Flight		Fuel (kg)	Time (s)	Range (m)
F01	plan	25,584	23,280	5.489×10^6
	DARP	24,723	22,640	5.334×10^6
F02	plan	25,109	23,610	5.474×10^6
	DARP	24,969	23,480	5.510×10^6
F03	plan	12,331	15,390	3.344×10^6
	DARP	11,986	15,090	3.412×10^6
F04	plan	23,579	22,350	5.376×10^6
	DARP	23,128	22,000	5.303×10^6
F05	plan	22,066	19,670	4.747×10^6
	DARP	21,870	19,500	4.705×10^6

Numerical results show that DARP operations were successful in reducing fuel consumption for all flights. Figure 3 shows the bar plot for fuel consumption difference for each flight. Flight F02 records the lowest fuel difference since the DARP track has deviated significantly from the plan track and has recorded the largest positive range difference among the subjected five flights. Hence, it is assumed that a larger amount of fuel was reduced when considering the total flight. Figure 3 depicts the percentage of fuel consumption difference with respect to flight range difference. Similar to Fig. 3, both parameters are evaluated based on plan track performance parameters. It is speculated that tradeoff with longer flight path has paid off well in reducing fuel consumption for flights F02 and F03. It is also considered that airline companies are eager to implement DARP operations when dynamic re-routing provide benefits on fuel burn

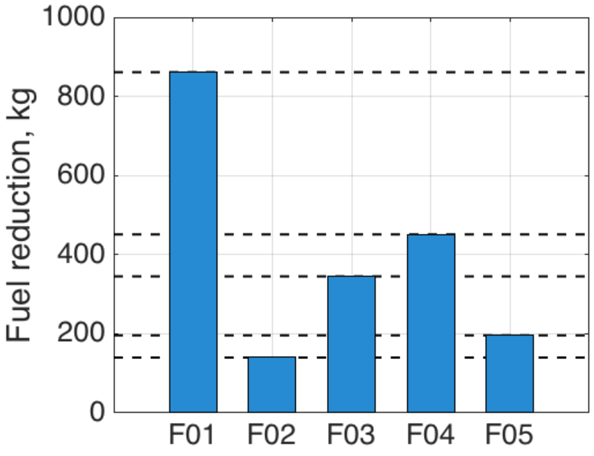


Fig. 3. Fuel Consumption Difference with DARP

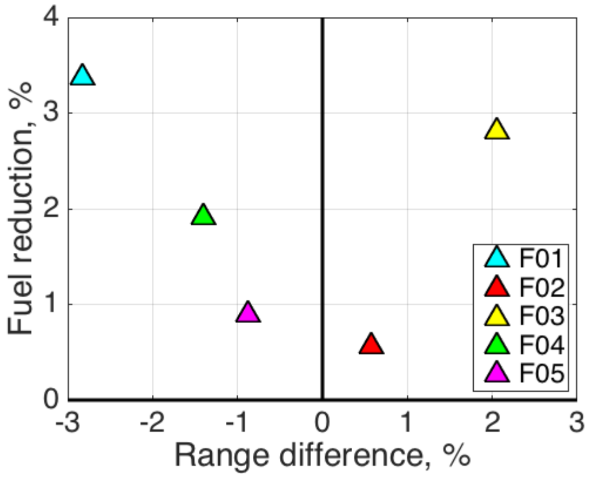


Fig. 4. Tradeoff between Fuel and Range with DARP

and/or flight time. Effect on flight time due to DARP operations is not reviewed in this study, because the time parameter was not available in the acquired DARP information. The next section quantitatively reviews the enhanced benefits through the introduction of 4D- TBO into oceanic operations.

3.3.2 Benefits Assessment of 4D- TBO

This section focuses on two aspects of trajectory optimization; 4D- TBO with free arrival time and 4D- TBO with fixed arrival time. Table 3 denotes the numerical values of fuel consumption and flight time corresponding to each optimal flight. Results show that fuel consumption could be reduced by allowing the aircraft to optimize its trajectory through considering real-time weather conditions in an ideal 3D- operational environment.

Table 3. Optimal Performance with 4D- TBO

Flight	Fuel (kg)	Time (s)	Range (m)
F01	20,442	21,051	4.991×10^6
F02	20,523	21,431	5.064×10^6
F03	10,418	14,889	3.287×10^6
F04	21,132	22,027	5.121×10^6
F05	20,756	20,622	4.640×10^6

Figures 5 and 6 show fuel consumption difference and fuel difference percentage versus flight range difference between optimal tracks and DARP tracks respectively. It is understood that a significant reduction of fuel consumption was obtained by the introduced trajectory optimizer.

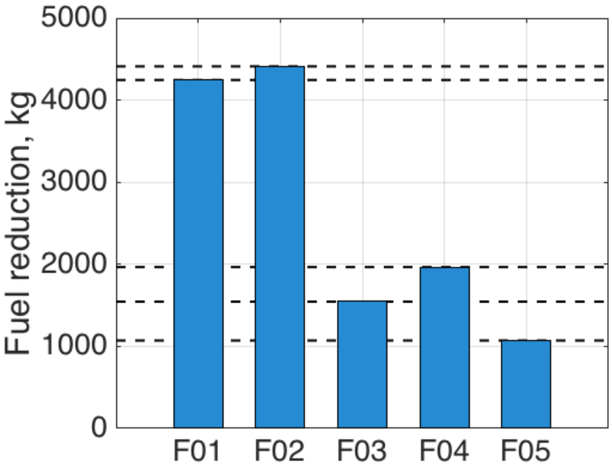


Fig. 5. Fuel Consumption Difference with 4D- TBO

These results include the assumption errors in trajectory generation for DARP flights. Yet, it can be speculated that even without considering the assumption errors, the optimizer could reduce fuel consumption compared to the subjected DARP flights. Results also show that flight range was also reduced for all five flights. It is considered that this difference has mainly caused the reduction of fuel consumption. Also, altitude and route profiles are illustrated for flight F05 in Figs. 7 and 8.

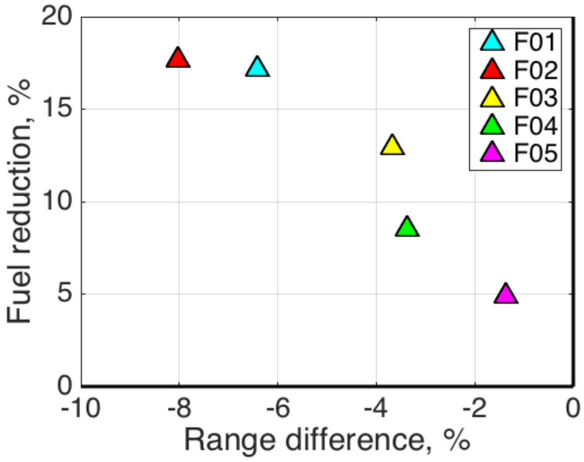


Fig. 6. Tradeoff between Fuel and Range with 4D- TBO

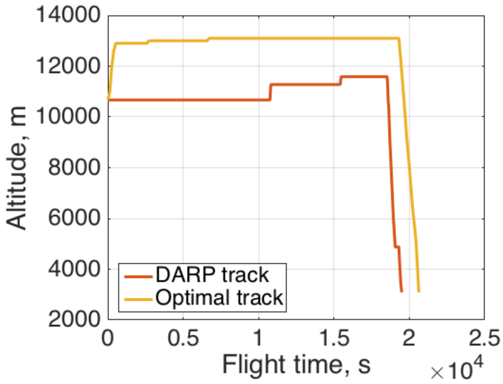


Fig. 7. Altitude Profile Comparison

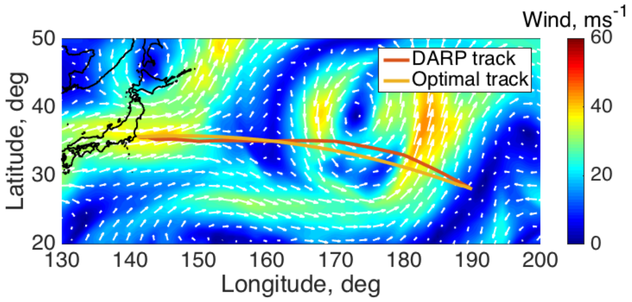


Fig. 8. Lateral Route Profile Comparison

The results show that altitude selection has also contributed to the reduction of fuel consumption. According to BADA model, aircraft exerts its maximum performance when flying close to its service ceiling. Therefore, the aircraft on the optimal track climbs to the service ceiling before performing its cruise phase. Though the contribution towards fuel reduction is minor, the optimal track initiates its Top of Descent (ToD) relatively earlier to its counterpart. From the preceding studies, it is understood that this allows the aircraft to descend at a lower speed while gaining a high lift-to-drag ratio which causes lesser fuel compared to conventional step down descent. Figure 8 shows that the optimal track selects the minimum distant track, commonly known as the Great Circle Route compared to its counterpart. Contours represent the wind distribution at 250 hPa pressure altitude (approximately 33,000 ft). The maximum fuel reduction is recorded at about 17% while the maximum range reduction is recorded at approximately 8%.

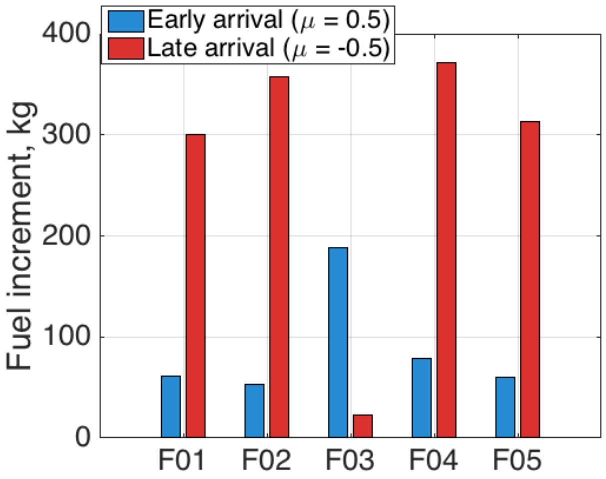
The next section focuses on reviewing the effect of arrival time constraint on the benefits obtained from the optimal tracks. As the exact total flight time is not available for the subjected flights, fixed CI values are given to simulate two scenarios; First is to impose the aircraft to arrive at the final point with a shorter flight time than the corresponding optimal track (weighting parameter $\mu = 0.5$), which simulates the time prioritized conventional operational environment and the second is to impose the aircraft to absorb delay $\mu = -0.5$ and extend the flight time compared to the corresponding optimal track.

Table 4. Early Arrival Scenario ($\mu = 0.5$)

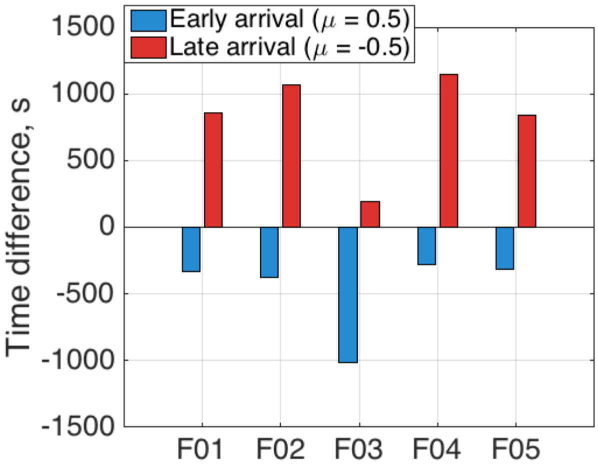
Flight		Fuel (kg)	Time (s)	Range (m)
F01	$\mu = 0$	20,442	21,051	4.991×10^6
	$\mu = 0.5$	20,503	20,722	4.991×10^6
F02	$\mu = 0$	20,523	21,431	5.064×10^6
	$\mu = 0.5$	20,576	21,052	5.064×10^6
F03	$\mu = 0$	10,418	14,889	3.287×10^6
	$\mu = 0.5$	10,606	13,871	3.287×10^6
F04	$\mu = 0$	21,132	22,027	5.121×10^6
	$\mu = 0.5$	21,211	21,745	5.121×10^6
F05	$\mu = 0$	20,756	20,622	4.640×10^6
	$\mu = 0.5$	20,816	20,307	4.640×10^6

Table 5. Late Arrival Scenario ($\mu = -0.5$)

Flight		Fuel (kg)	Time (s)	Range (m)
F01	$\mu = 0$	20,442	21,051	4.991×10^6
	$\mu = -0.5$	20,742	21,910	4.991×10^6
F02	$\mu = 0$	20,523	21,431	5.064×10^6
	$\mu = -0.5$	20,880	22,498	5.064×10^6
F03	$\mu = 0$	10,418	14,889	3.287×10^6
	$\mu = -0.5$	10,441	15,083	3.288×10^6
F04	$\mu = 0$	21,132	22,027	5.121×10^6
	$\mu = -0.5$	21,503	23,176	5.121×10^6
F05	$\mu = 0$	20,756	20,622	4.640×10^6
	$\mu = -0.5$	21,069	21,465	4.641×10^6



(a) Fuel Increment



(b) Flight Time Difference

Fig. 9. Performance Comparison for Arrival Time Constraints (compared with optimal track results)

Tables 4 and 5 provide the numerical results of the two scenarios respectively compared with the corresponding optimal track performance and the Fig.9 illustrates how the optimizer output optimal tracks according to given arrival time constraints. Fuel consumption increases for both scenarios due to the speed increase in early arrival scenario to shorten the flight time and flight time extension in the late arrival scenario. According to the numerical results, flight range has not changed in both scenarios. Hence it can be speculated that arrival time constraint is treated only by adjusting the optimal track's vertical and speed profiles. Results in Fig. 9 show that arrival time constraint has imposed a substantial impact on the late arrival scenario as the fuel increment and time difference due to the constraint are more noticeable than the results on early arrival scenario. Also, results prove that a larger CI value is required to prioritize the arrival time (shorten the flight time as in conventional operations) which can be considered to be less efficient in means of performance. From the obtained results it can be revealed that application of 4D- TBO with arrival time management capability could be a potential enhancement for oceanic operations.

4 Conclusion

A study was conducted to review the benefits of DARP from an operational perspective and to investigate the potential benefits of enhancing DARP to 4D- TBO in oceanic operations. A series of DARP information provided by a national airline and JCAB provided position track data and flight plan data were used to compare the possible fuel consumptions between trajectories based on flight plans and DARP operations. Results show that dynamic re-routing according to weather conditions provide fuel saving benefits to airline operators. It is speculated that, though fuel savings from a standalone flight would not be so significant, cumulative evaluations would show that DARP could bring significantly positive impact to airline operators.

A trajectory optimizer developed by the authors is used to exert the aircraft's maximum performance in an ideal 3D- operational environment and the impact of flight time constraints are evaluated based on the performance of conventional operations. Results show that 4D- TBO applications in oceanic operations record significant fuel savings compared to conventional procedures and arrival time management capability added 4D- TBO would be a potential enhancement for oceanic operations.

The scope of this study has to be enhanced to obtain more realistic conclusions on the subject. Detailed analyses were based only on five flights due to the limited access of data. Further rigorous and quantitative estimations on the aircraft performance would provide more concrete conclusions on the impact of DARP in aircraft operations. This would permit more detailed comparisons between optimal and conventional performance in oceanic operations and understand the needs and challenges to improve the operational perspective to meet the future demands in the industry.

Overall, results show that DARP is a potential procedure to improve the performance of conventional operations and 4D- TBO is a potential enhancement to DARP operations that could be applied in a future ATM system.

Acknowledgement

Authors convey their sincere gratitude to the All Nippon Airways Co., Ltd. for providing DARP data information and the Japan Civil Aviation Bureau for providing access to flight plan data, ODP data and RDP data. Authors also acknowledge Prof. Yoshikazu Miyazawa of Kyushu University for providing guidance on the trajectory optimizer development and, Mr. Ralph E. Bach of Aerospace Computing, Inc. and Mr. Russell A. Paielli of NASA Ames Research Center for distributing the technical coding of the data smoothing algorithm.

References

[1] *Long-term vision for the future air traffic systems, Collaborative actions for renovation of air traffic systems (CARATS)*. Ministry of Land, Infrastructure and Tourism (MLIT) Japan, 2010.

[2] *Global Operational Data Link Document (GOLD)*. 2nd edition, International Civil Aviation Organization, 2013.

[3] Wickramasinghe N K, Brown M, Fukushima S, Fukuda Y, Miyazawa Y and Harada A. Correlation between flight time and fuel consumption in airliner

flight plan with trajectory optimization. *AIAA Guidance, Navigation and Control Conference, SCITECH2015*, Florida, 2015.

[4] Miyazawa Y, Matsuda H, Shigetomi S, Harada A, Kozuka T, Wickramasinghe N K, Brown M and Fukuda Y. Potential benefits of arrival time assignment, dynamic programming trajectory optimization applied to Tokyo International Airport. *11th USA/Europe Air Traffic Management Research and Development Seminar*, Lisbon, 2015.

[5] Itoh E, Wickramasinghe N K, Hirabayashi H, Uejima K and Fukushima S. Analyzing feasibility of continuous descent operation following fixed-flight path angle from oceanic route to Tokyo International Airport. *AIAA Modeling and Simulation Technologies Conference*, *SCITECH2016*, San Diego, 2016.

[6] Wickramasinghe N K, Harada A, Totoki H, Miyamoto M and Miyazawa Y. Flight trajectory optimization for modern jet passenger aircraft with dynamic programming. *Air Traffic Management and Systems*, *Lecture Notes in Electrical Engineering*, Vol. 290, pp 87-104, 2014.

[7] Japan Meteorological Business Support Center Online Data Service. URL: http://www/jmbsc.or.jp/hp/online/f-online0a.html

[8] Eurocontrol Experiment Center. User Manual for the Base of Aircraft Data (BADA) Revision 3.11. *EEC Technical/Scientific Report*, No.13/04/16-01, 2013.

[9] Bach R E and Paielli R A. A user guide for smoothing air traffic radar data. *NASA Technical Reports*, NASA/TM 216520, 2014.

[10] Wickramasinghe N K, Brown M, Miyamoto M and Miyazawa Y. Effects of aircraft mass and weather data errors on trajectory optimization and benefits estimation. *AIAA Modeling and Simulation Technologies Conference*, *SCITECH2016*, San Diego, 2016.

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