

Potential Benefits of Arrival Time Assignment

Dynamic Programming Trajectory Optimization applied to the Tokyo International Airport

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Abstract—Increasing the efficiency and capacity of flights arriving at a congested airport is one of the most challenging problems in air traffic management research. The efficiency of commercial jet airliner flights arriving at the Tokyo International Airport, the busiest airport in Japan, is analyzed using integrated Air Route Surveillance Radar information. Fuel consumption is estimated for each flight from the surveillance data using meteorological and aircraft performance data. The actual flight is compared with the optimized trajectory in terms of fuel consumption and flight time, which introduces the potential benefits of optimizing the flight. A total performance index, which comprises the fuel consumption and flight times of each flight, is proposed to optimize all flights arriving at the airport under the constraint of safe time separation at the terminal point. Dynamic programming is used to optimize not only each trajectory but also the arrival time assignment, where arrival times are assigned to each flight to minimize the total performance index. The results show that a rational arrival sequence and time assignment are generated by the optimization method, and the potential benefit deterioration due to imposing the arrival time separation constraint is limited.

Keywords—arrival management; arrival time assignment; potential benefit; trajectory optimization

I. INTRODUCTION

Today's busy air transportation system demands not only ensured flight safety but also greater efficiency. Realizing more efficient operations while increasing capacity is expected to be achieved by introducing new communication, navigation, surveillance, and air traffic management (CNS/ATM) technologies. As part of the NextGen program in the United States and Single European Sky ATM Research (SESAR) in Europe, many research projects are exploring innovations, and many research papers have been published on such new technologies. In Japan, Collaborative Actions for Renovation of Air Traffic Systems (CARATS) [1] has been defined by the government as a roadmap to develop Japan's future air transportation system, and universities are encouraged to participate in its research.

As a response to the CARATS plan, Kyushu University and the Electronic Navigation Research Institute (ENRI) conducted a collaborative research project analyzing air traffic efficiency,

in which they employed surveillance radar data to analyze actual flights compared with their optimized trajectories. The data were from a single secondary surveillance radar (SSR) that was experimentally operated by ENRI and covers the area surrounding Tokyo with a radius of approximately 200 NM[2], [3]. As the analysis provided an estimation of the maximum benefit achievable for each flight, i.e., the potential benefit that could be realized under ideal airspace conditions, it revealed that arrival flights to the Tokyo International Airport have great potential for efficiency improvement, as they are controlled by air traffic control (ATC) with vectoring procedures before entering the airport terminal airspace. In the study, trajectory information, which consists of times and three-dimensional positions, is proposed to be combined with meteorological data and aircraft performance information to estimate fuel flow. The reconstructed flight performance is then compared with the optimized trajectory by Dynamic Programming (DP) with identical meteorological conditions and aircraft performance information.

This paper's study is an extension of our previous study; however, the two studies differ in two respects. First, the present study uses surveillance information integrated from multiple Air Route Surveillance Radar (ARSR) systems, which cover the entire airspace over Japan. Therefore, our current analysis can optimize all flight phases of a domestic flight from climb to descent, whereas our previous study focused on the descent phase and was covered by a single radar. Second, arrival time assignment for each aircraft is studied by minimizing the total performance index with a constraint condition of arrival time separation. Deterioration of the performance indices due to the imposition of the time separation condition can be minimized by optimization.

Arrival management is one of the most intensive research subjects in the field of ATM, because the terminal area is a bottleneck of air traffic flow, and improvements to the efficiency of inbound flights to congested major airports are commonly necessary around the world. The Center TRACON Automation System (CTAS) and the Arrival Manager (AMAN) system are well-known triumphs of ATM research; they produced actual advisory systems that reduced the workload of air traffic controllers and improved flight

efficiency. However, the Tokyo International Airport, which is the busiest airport in Japan, has not implemented a similar system, and the feasibility of the arrival management system has been an issue of great concern. This study aims to provide maximum potential benefits to be achieved by an ideal system in order to be used for reference during possible future development.

Potential benefits have long been discussed in ATM research because benefit and cost evaluation provides basic data for planning a new system development. Many studies on potential benefits of arrival management have been published in previous ATM Seminars, such as [4]-[8], for the same purpose as this paper. The distinctive points of this paper are; (1) Analysis is performed by using integrated surveillance data, which provide a coverage of almost all the commercial flights in Japanese air-space. (2) Actual flights are compared with optimal trajectories in terms of fuel consumption and flight time. (3) Arrival times are optimized in the same framework with trajectory optimization.

Sections II and III introduce the analytical tool used in this study, which consists of flight data reconstruction from surveillance data and trajectory optimization of the corresponding flight to analyze the potential for improvement. A majority of this approach has already been published in the literature listed in the references. Section III discusses arrival time assignment by extending the optimization of individual flights to all flights with the constraint of arrival time separation at the terminal merging point. Performance indices are proposed for the optimization method, and a numerical method of DP is employed for the optimization. In Section IV, an example of the analysis applied to the Tokyo International Airport using integrated surveillance information of Japan's controlled airspace is presented to demonstrate the proposed method. This example reveals that it is possible to substantially improve the efficiency of flights arriving at the Tokyo International Airport.

II. RECONSTRUCTION OF FLIGHT TRAJECTORIES

The flight efficiency of commercial jet airliners was analyzed in terms of fuel consumption and flight time using position data from the GPS logger inside an airborne airliner cabin and the SSR experimentally operated by ENRI [9]-[12]. Estimated fuel flow is a critical parameter for flight efficiency analysis. Figure 1 illustrates the concept of flight data reconstruction. The velocity vector in the inertial frame is estimated by filtering numerical time derivatives of the position data, and then the velocity vector relative to the atmosphere can be estimated by subtracting the wind vector, which is estimated by interpolating meteorological grid point value (GPV) data released by the Japan Meteorological Agency [13]. Air data parameters, such as calibrated air speed and Mach number, are estimated using the interpolated temperature and pressure from the meteorological GPV data. Performance variables such as the lift-to-drag ratio, thrust, and fuel flow are estimated using a point mass approximation of the flight dynamics and the Base of Aircraft Data (BADA) model ver. 3.9 developed by EUROCONTROL [14]. The accuracy of the estimated flight parameters depends on the quality of the meteorological GPV data and the aircraft performance information. Comparing

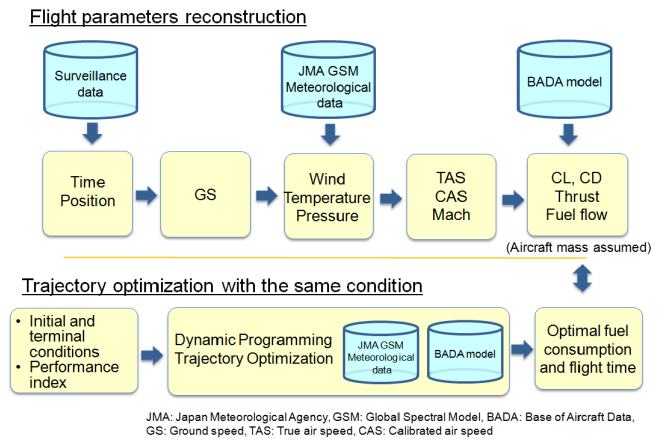


Figure 1. Reconstruction of flight data from time and position data.

these estimates with flight data recorded by the aircraft's onboard systems, such as the quick access recorder (QAR) [15], [16], has shown that the errors are so small that estimated flight parameters are sufficiently accurate to analyze flight efficiency [17]. Similar findings concerning the accuracy of meteorological GPV data have been obtained by the analysis of SSR Mode S downlink aircraft parameters [18] as well as QAR flight data analysis.

In this study, previously developed analytical tools are applied to integrated surveillance data, which extend the investigative scope immensely because trajectories of almost every flight within the Japanese national airspace can be analyzed.

III. TRAJECTORY OPTIMIZATION AND OPTIMAL ARRIVAL TIME ASSIGNMENT

The optimal trajectory of the flight is calculated for comparison with the actual flight trajectory using the same meteorological data and performance model as in the flight reconstruction analysis. This method assumes the same initial and final positions and velocities as those of the actual flight. Regarding the time, the initial time t_0 is identical to that of the actual flight; however, the terminal time t_f is assumed to be free to study flight efficiency with arrival time assignment.

A performance index that incorporates fuel consumption and flight time is minimized by DP. The performance index J_k for the k th flight is defined as

$$J_k = \int_{t_{0k}}^{t_f} \mu_k(t) dt + \frac{m_k}{m_0} a_k (t_f - t_{0k}), \quad (1)$$

where μ_k [kg/s] is the fuel flow, m_k is a reference mass of the k th aircraft, and m_0 is a commonly used representative mass. The first term on the right-hand side of Eq. (1) denotes fuel consumption, and the second denotes weighted flight time. $(m_k/m_0)a_k$ is a weighting parameter of the flight time [s], where a_k [kg/s] is a constant to transform the value of time to fuel. As the time cost is considered proportional to the scale of the aircraft, the weighting parameter is compensated by m_k/m_0 to allow a_k to remain independent from the aircraft scale. The weighting parameter is equivalent to the cost index

CI_k used in actual flight operations, because the performance index is defined as the cost of the flight in dollars $J_{k,dollar}$:

$$J_{k,dollar} = \frac{c_{fuel}}{100 \times 0.4536} \left\{ \int_{t_{0k}}^{t_f} \mu_k(t) dt + \frac{45.36}{3600} CI_k (t_f - t_{0k}) \right\}, \quad (2)$$

where the cost index CI_k is defined as,

$$CI_k = \frac{c_{time} [\text{dollar}/\text{hour}]}{c_{fuel} [\text{cent}/\text{pound}]} \quad (3)$$

Eqs. (1) and (2) produce the following relation:

$$CI_k = 79.37 \frac{m_k}{m_0} a_k. \quad (4)$$

As shown in Fig. 2, the weighting parameter, or cost index, is a free parameter for each flight performance to be optimized; therefore, it is generally set according to airline operators' policies.

If the terminal time is free, however, conflicts would possibly occur, because each aircraft would freely arrive at the terminal merging point. To satisfy the condition of safe arrival time separation, the following inequality constraint is imposed on the arrival time:

$$|t_{f_k} - t_{f_l}| > t_{min\,separation}, \quad (5)$$

for any k and $l, k \neq l$. Although all the flight phases have other constraints that would deteriorate the performance index, such as air routes, adverse meteorological conditions, and conflicts with other aircrafts, this study neglects those constraints to examine the benefits of arrival time assignment under the assumption that the constraint given in Eq. (5) is the most influential.

As arrival time delays tend to occur when the airport is congested, a ruled cost index should be used to ensure that the arrival sequence is fair. The weighting parameter plays an important role in arrival sequence control, because each weighting parameter of the conflicting inbound flights must be adjusted to allow safe arrival time separation. The following total performance indices are defined for the optimization of

multiple arriving flights:

$$J_1^* = \sum_k J_k = \sum_k \left\{ \int_{t_{0k}}^{t_{f_k}} \mu_k(t) dt + \frac{m_k}{m_0} a_k (t_{f_k} - t_{0k}) \right\}, \quad (6)$$

$$J_2^* = \sum_k \frac{m_0}{m_k} J_k = \sum_k \left\{ \frac{m_0}{m_k} \int_{t_{0k}}^{t_{f_k}} \mu_k(t) dt + a_k (t_{f_k} - t_{0k}) \right\}. \quad (7)$$

Two performance indices that differ in priority depending on the aircraft weight, which is roughly proportional to the number of passengers, are proposed. If there is no conflict in the arrival times of the optimal trajectories, both performance indices provide the same solution, because the cost index, which is the ratio of the time cost to the fuel cost, is the same for each k th flight. The performance indices differ if the arrival time separation condition given in Eq. (5) is violated. Since the first performance index J_1^* is fuel oriented, the arrival time of a heavier aircraft is adjusted to less than that of a lighter aircraft; in other words, heavier aircrafts are prioritized. The second performance index J_2^* is time oriented, and thus priority does not depend on the scale of the aircraft. Therefore, time adjustments are roughly equal for aircrafts of different types.

Optimization of the total performance index J^* with an inequality constraint is conducted in two steps. The first step is optimizing the trajectory of each flight, and the second step is sequencing and adjusting arrival time; DP is used in both steps. In the first step, trajectory optimization is conducted for three free variables: altitude, velocity, and lateral deviation from the great circle route. DP is a combinatorial optimization method in which variables are quantized by a grid, and the path that optimizes the flight, or in this study, minimizes the performance index J_k , is selected from possible grid point-to-grid point transitions. A four-dimensional grid is defined for the three free variables and the flight distance along the great circle route. The simplest isogrid, or equidistant (uniform) grid, is adopted for the calculation. For the second step of arrival time assignment, not only the optimal trajectory of the given cost index is calculated, but multiple additional cost index solutions are also found, with the weighting parameter a'_k in the cost index digitized over an appropriate range (a_{min}, a_{max}). As the optimal trajectories of different weighting parameters a'_k are Pareto solutions for different combinations of fuel

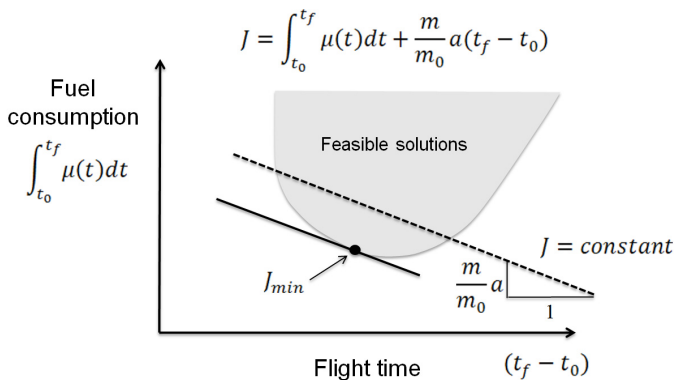


Figure 2. Performance index for varying fuel consumption and flight time.

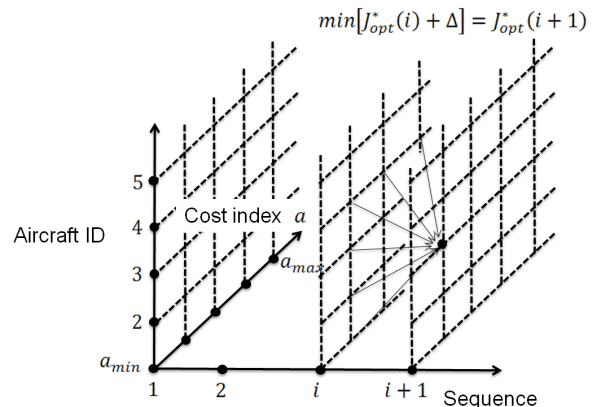


Figure 3. Concept of arrival time assignment optimization.

consumption and flight time, they are candidates for the final solution that minimizes the total performance index under the arrival time separation constraint.

In the second step, one of the total performance indices given by Eqs. (6) and (7) is optimized by sequencing and arrival time selection from the Pareto solutions for different combinations of fuel consumption and flight time obtained in the first step for each flight. Fig. 3 shows the concept of combinatorial optimization using DP. DP calculations are performed for two free parameters: flight number and weighting parameters a'_k . The independent variable is the sequence of flights from the first arrival to the last arrival. This approach is an extension of the approach given in reference [19] by adding one more variable to optimize the sequence of arriving flights.

IV. RESULTS AND ANALYSIS

A. Surveillance data

ARSR data provided by the Japan Civil Aviation Bureau to promote basic research in ATM are used in this analysis. The data called CARATS Open data were integrated using information from multiple ARSR devices to provide appropriate position data for each aircraft. The data cover the entire Japanese national airspace and its vicinity. The data consist of time, masked ID number, latitude, longitude, and barometric altitude. The sampling frequency is once per ten

seconds.

The subject of this paper is inbound flights to the Tokyo International Airport, which is used by more than half of all air travelers in Japan. It has four runways; during northern wind conditions, two runways—34R and 34L—are used for landing. Runway 34L, which has no interaction with take-off flights, is mainly used for flights arriving from the west, south, and east and for some flights from the north. Since runway 34R has some interaction with flights taking off from runway 34R and 05, it is only used for flights arriving from the north. Fig. 4 shows flights arriving on runway 34L during a single day, May 9, 2012. The stochastic properties of the time and separation distance at the merging fix ARLON are shown as histograms in Fig. 5. The non-dimensional separation distance shown in Fig. 5 is a parameter normalized by the wake turbulence separation distance, which depends on the aircraft mass. In the next section, arrival flights that used runway 34L at the busiest hours are analyzed to determine the feasibility and benefits of arrival time assignment.

B. Optimal trajectories at busiest hours

Flights arriving at ARLON between 20:00 and 23:00 (Japan Standard Time), a timeframe that includes the airport's busiest hours, were selected for trajectory optimization analysis. The image to the left in Fig. 6 shows the trajectories to ARLON of the flights that landed on runway 34L within a 200 NM radius from the airport. The graph to the right in Fig. 6

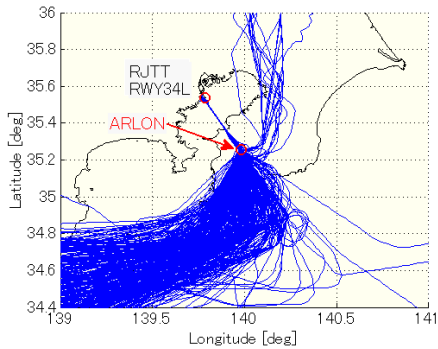


Figure 4. Trajectories of flights arriving on runway 34L at the Tokyo International Airport RJTT. (May 9, 2012)

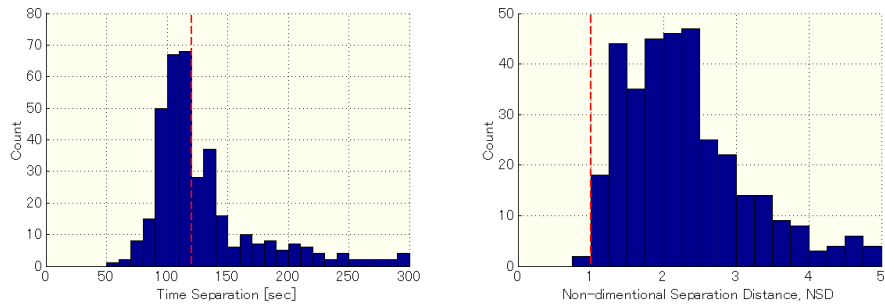


Figure 5. Time separation and non-dimensional separation distance at ARLON. (May 9, 2012)

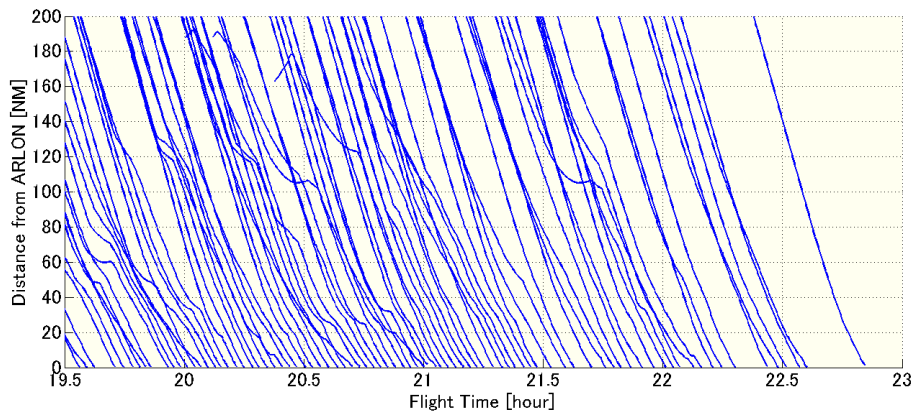
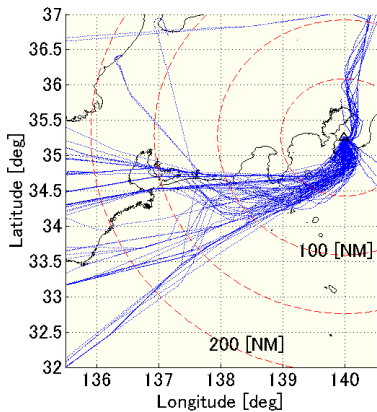


Figure 6. Trajectories of flights arriving on runway 34L (left) and distance from ARLON vs. time (right) from 19:30 to 23:00 on May 9, 2012.

shows the distance from ARLON versus the flight time. Deviation from the straight line indicates that the vector is being directed by ATC. Some of the flights that arrived at ARLON between 20:00 and 21:00 were intensely controlled to generate safe arrival time separations.

In trajectory optimization, the initial point of the optimization is given as 10,000 ft in the climb phase, because the initial point can be considered to be the starting point of the user-preferred flight. The initial time, latitude, longitude, and velocity are equal to those of the actual flight. The location of the final point is defined as the position of the merging fix ARLON, and the altitude and velocity of the final point are equal to those of the actual flight. The time of the final point is assumed to be free. The weighting parameter in the performance index defined in Eq. (1) is given as $a_k = 0.5$, and the common representative mass is $m_0 = 208.7$ ton. The

reference mass given by the BADA model is used as the mass of each aircraft m_k . The weighting parameter $a_k = 0.5$ yields a relatively small cost index.

All 73 flights that arrived at ARLON between 20:00 and 23:00 were analyzed. If the arrival time constraint given in Eq. (5) is neglected, each flight is considered to be independent from other flights; therefore, minimizing the total performance index is equivalent to independently minimizing each performance index J_k . Figure 7 shows the differences in fuel consumption, flight time, and flight length of the optimized and actual flight trajectories in terms of absolute values and percentages relative to those of the actual flight. Figures of arrival time constraint OFF in Table I show the average of each difference. The average fuel consumption reduction was 783 kg, and the average reduction relative to the actual fuel consumption was 16.3 %. The average flight length reduction

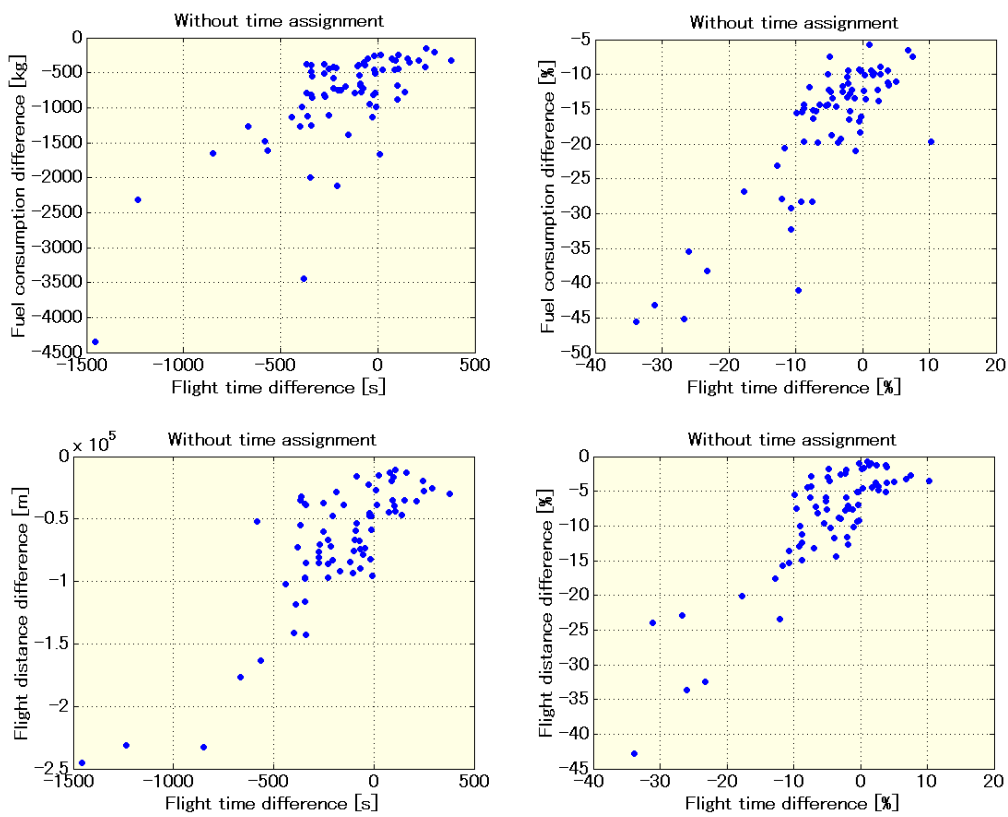


Figure 7. Benefits of trajectory optimization without arrival time assignment. (20:00 to 23:00, May 9, 2012)

TABLE I. STOCHASTIC PERFORMANCE, AVERAGE AND DIFFERENCE BETWEEN OPTIMAL TRAJECTORIES AND ACTUAL FLIGHTS (73 FLIGHTS)

	Estimated actual flights	<i>Optimal trajecotries (Difference, ratio relative to actual flight)</i>		
		(a) Arrival time constraint OFF	(b) Arrival time constraint ON	(b) – (a)
Fuel consumption (kg)	5064	4281 (-783, -16.3%)	4309 (-755, -15.7%)	28
Flight length (km)	974.9	909.7 (-65.2, -8.4%)	909.8 (-65.1, -8.4%)	0.1
Flight time (s)	4266	4082 (-184, -5.1%)	4042 (-224, -6.2%)	-40

was 65 km, and the average reduction relative to the actual flight length was 8.4 %. The amount of fuel reduction was larger than that in the previous analysis, which was limited to an area around the airport[2]. This is because all the flight phases starting from the climb phase at an altitude of 10,000 ft are optimized in the present analysis. Therefore, the effect of free routing is included in the reduction as well.

The average flight time reduction was 184 s, and the average reduction relative to the actual flight time was 5.1 %. Based on the reduction in flight time and length, the optimal trajectory can be seen to use a slower velocity than the actual flight; There are cases of later optimized arrivals than actual arrivals because the cost index (a weighting parameter on the flight time $a_k = 0.5$) of the optimization is relatively small.

C. Arrival time assignment with trajectory optimization

Figure 8 shows the arrival times at ARLON between 19:50 and 22:50, where ATA is the actual time of arrival; ETA is the estimated time of arrival, which is the result of the optimization model without the time separation condition. Figure 9 gives histograms of the time separation at ARLON between two

consecutive arriving flights. As the final time, i.e., the arrival time at ARLON, of each optimal trajectory is free in the preceding analysis, conflicts or violations of the minimum time separation condition $t_{min\ separation} = 90\ s$ at the merging fix are generated. The ETAs violate the 90 s minimum separation condition as shown in Fig. 9. The time separation condition at the merging fix given in Eq. (5) is then considered in the optimization of the total performance index. For this numerical analysis, the more equal performance index J_2^* is adopted. In Figs. 8 and 9, the STA, scheduled time of arrival, is a result of the optimization with the time separation constraint. Figure 8 shows that the optimization generates optimal sequences that do not necessarily adhere to the first come, first serve principle. It also shows that the arrival time assignment can be a time advancement or a time delay. This is reasonable, because the arrival time changes at around the bottom of the performance index-vs-time curvature, or the optimal point of each flight, has some impact on the total performance index in both sides, time advance and time delay. The histogram of the separation between consecutive STAs in Fig. 9 clearly shows that the optimal solution satisfies the time separation constraint.

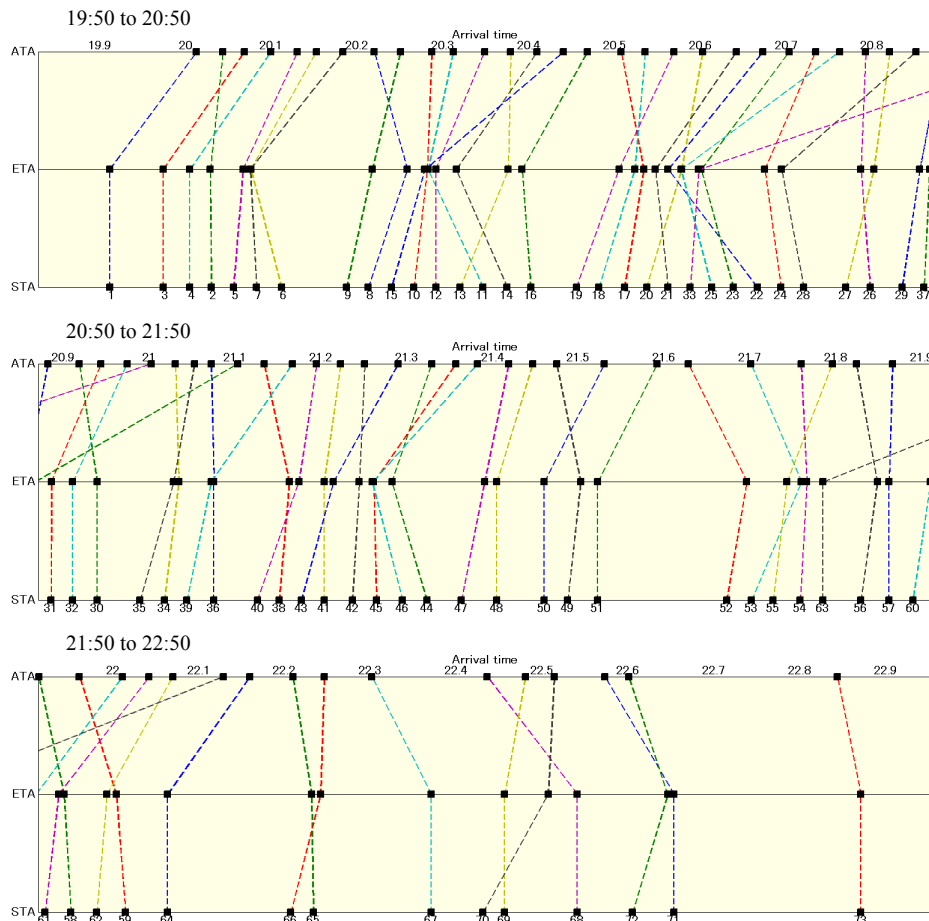


Figure 8. Arrival time chart from 19:50 to 23:00 on May 9, 2012, ATA: Actual time of arrival, ETA: Estimated time of arrival (Optimized without time assignment), STA: Scheduled time of arrival (Optimized with time assignment).

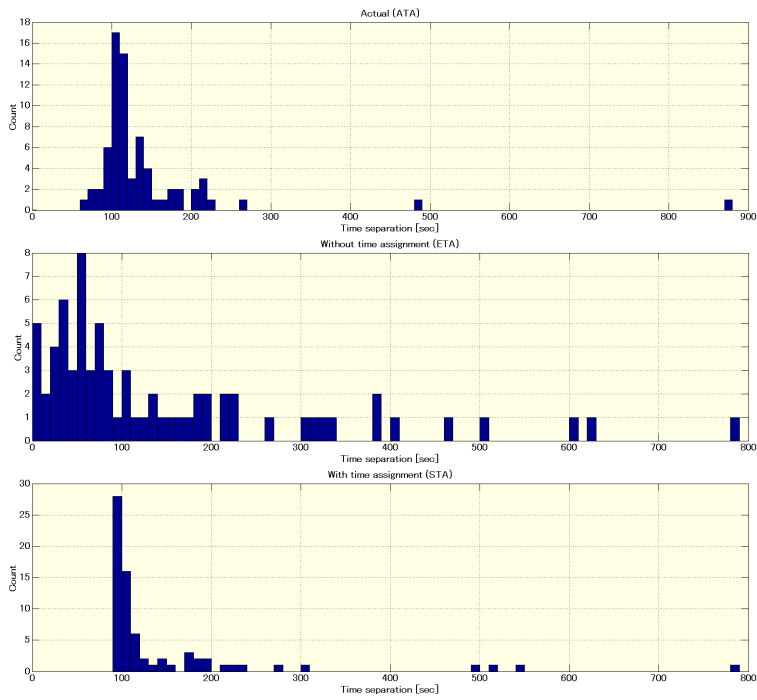


Figure 9. Histograms of arrival time separation from 20:00 to 23:00 on May 9, 2012.
 Top: Actual flight (ATA), middle: Optimized without time assignment (ETA),
 bottom: Optimized with time assignment (STA).

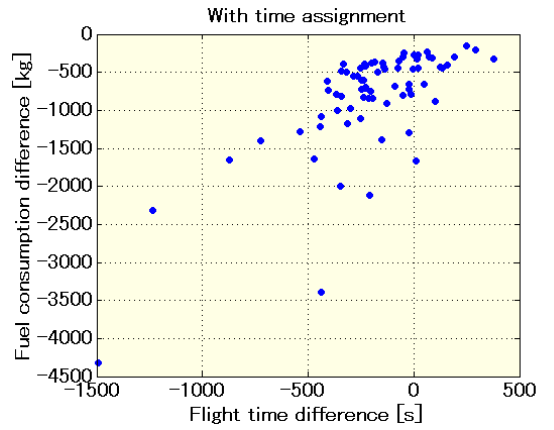


Figure 10. Benefits of trajectory optimization with arrival time assignment. (20:00 to 23:00 on May 9, 2012)

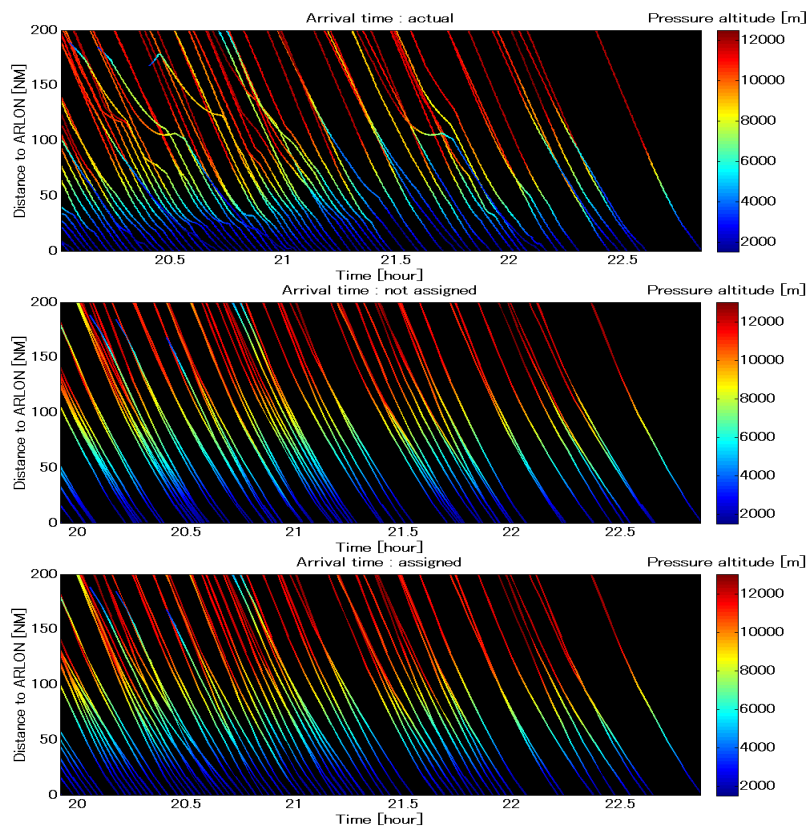


Figure 11. Distance from ARLON versus time for three cases from 20:00 to 23:00 on May 9, 2012.
 Top: Actual flight (ATA), middle: Optimized without time assignment (ETA),
 bottom: Optimized with time assignment (STA).

Figure 10 shows the differences in fuel consumption and flight time of the optimal and actual flight trajectories. These results can be compared with those presented in Fig. 7. There is no significant change in the performance. The averages of these variables are listed in Table I as arrival time constraint is ON, which shows that the arrival time constraint introduces limited performance deterioration. The average increase in fuel consumption and decrease in flight time due to the arrival time adjustment are 28 kg and 40 s, respectively. This indicates that the advancement of arrival times is slightly more than the delay of arrival times. The flight length does not significantly change because of the arrival time adjustment.

Figure 11 shows the distance from ARLON versus the time for three cases, i.e. actual flights equivalent to Fig. 6, the trajectories optimized individually without arrival time assignment, and the trajectories optimized with arrival time assignment. The figure clearly shows the trajectories with arrival time assignment realize time separation at ARLON by smoothly changing their velocity, faster for the time advance and slower for the time delay.

V. CONCLUDING REMARKS

A method of potential benefit analysis was proposed for application to flights arriving at a busy airport. In this case, arrival sequencing and time separation at the terminal merging point are critical issues for air traffic control to avoid conflicts between aircrafts. Performance indices that optimize all arriving flights were proposed to generate the optimal arrival times for each flight.

The approach was applied to the Tokyo International Airport using surveillance data. First, the optimal trajectory that minimizes the performance index, which was defined on the basis of fuel consumption and flight time without any constraints to air traffic, is calculated for each flight. These trajectories are then compared with the reconstructed parameters including fuel consumption of the original actual flights. The optimal trajectories show that significant benefit could be obtained in fuel consumption and flight time. The optimal trajectories, however, arrive at the terminal merging fix randomly, violating time separation with other arriving aircrafts. Then, a constraint defining the minimum arrival time separation was imposed to avoid conflicts at the final terminal merging fix. A total performance index, defined as the weighted summation of each performance index, was proposed to introduce rational sequencing of arrival flights and assignment of new arrival times that satisfy the safe time separation condition at the terminal merging fix. The numerical example shows that appropriate time assignments are generated by the optimization, and the potential benefit deterioration due to imposing the arrival time separation constraint is limited.

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EUROCONTROL are effectively used to reconstruct flight parameters from surveillance information data and to optimize flight trajectories. These organizations' support to the research is greatly appreciated.

REFERENCES

- [1] Study Group for the Future Air Traffic Systems, Long Term Vision for the Future Air Traffic Systems, CARATS, Collaborative Actions for Renovation of Air Traffic Systems, URL: <http://www.mlit.go.jp/common/000128185.pdf>, 2010.
- [2] Harada, A., Kozuka, T., Miyazawa, Y., Wickramasinghe, N.K., Brown, M., and Fukuda, Y., "Analysis of Air Traffic Efficiency using Dynamic Programming Trajectory Optimization," ICAS 2014, Saint Petersburg, Russia, September 2014.
- [3] Wickramasinghe N.K., Miyamoto Y., Harada A., Kozuka, T., Shigetomi, S., Miyazawa Y., Brown M., and Fukuda Y., "Flight Trajectory Optimization for Operational Performance Analysis of Jet Passenger Aircraft," 2013 Asia-Pacific International Symposium on Aerospace Technology, Takamatsu, Japan, 2013.
- [4] Shresta, S., Neskovic, D. and Williams, S.S., "Analysis of Continuous Descent Benefits and Impacts During Daytime Operations," 8th USA/Europe Air Traffic Management Research and Development Seminar, Napa, California, 2009.
- [5] Ryerson, M.S., Hansen, M. and Bonn, J., "Fuel Consumption and Operational Performance," 9th USA/Europe Air Traffic Management Research and Development Seminar, Berlin, Germany, 2011.
- [6] Knorr, D., Chen, x., Rose, M., Guldung, J., Enaud, P., and Hegendoerfer, H., "Estimating ATM Efficiency Pools in the Descent Phase of Flight, Potential Savings in both Time and Fuel," 9th USA/Europe Air Traffic Management Research and Development Seminar, Berlin, Germany, 2011.
- [7] Cao, Y., Kotegawa, T., Sun, D., DeLaurentis, D. and Post, J., "Evaluation of Continuous Descent Approach as a Standard Terminal Airspace Operation," 9th USA/Europe Air Traffic Management Research and Development Seminar, Berlin, Germany, 2011.
- [8] Smedt, D.D., Bronsvoort, J. and McDonald, G., "Controlled Time of Arrival Feasibility Analysis," 10th USA/Europe Air Traffic Management Research and Development Seminar, Chicago, Illinois, 2013.
- [9] Wickramasinghe N.K., Harada A., and Miyazawa Y., "Flight Trajectory Optimization for an Efficient Air Transportation System," 28th ICAS, Brisbane, ICAS2012-5.8.3, 2012.
- [10] Wickramasinghe N.K., Totoki H., Harada A., Miyamoto Y., Kozuka T. and Miyazawa Y., "Flight Trajectory Optimization for Jet Passenger Aircraft using Dynamic Programming," 2012 Asia-Pacific International Symposium on Aerospace Technology, Jeju, Korea, 2012.
- [11] Wickramasinghe N.K., Totoki H., Harada A. and Miyamoto Y., "A Study on Benefits Gained by Flight Trajectory Optimization for Modern Jet Passenger Aircraft," EN-41, ENRI International Workshop on CNS/ATM, Tokyo, 2013.
- [12] Miyazawa Y., Wickramasinghe N.K., Harada A., and Miyamoto Y., "Dynamic Programming Application to Airliner Four Dimensional Optimal Flight Trajectory," AIAA Guidance, Navigation and Control Conference, AIAA-2013-4969, Boston, 2013.
- [13] Japan Meteorological Business Support Center Online Data Service, URL: <http://www.jmbc.or.jp/hp/online/f-online0.html>
- [14] Eurocontrol Experimental Center, User Manual for the Base of Aircraft Data (BADA) Revision 3.9: EEC Technical/Scientific Report No. 11/03/08-08, April 2011.
- [15] Harada A., Miyazawa Y., and Funabiki K., "Accuracy evaluation of an aircraft performance model with airliner flight data," Transactions of JSASS on Aerospace Technology Japan, Vol. 11, 2013, pp.79-85.
- [16] Totoki H., Kozuka T., Miyazawa Y. and Funabiki K., "Comparison of JMA Numerical Prediction GPV Meteorological Data and Airliner Flight Data," in Japanese, JSASS Kouku-Uchu Gijutu (Aerospace Technology), Vol. 12, 2013, pp. 57-63.
- [17] Miyamoto Y., Wickramasinghe N.K., Harada A., Miyazawa Y. and Funabiki K., "Analysis of Fuel Efficient Airliner Flight by Dynamic Programming Trajectory Optimization," Transactions of JSASS Aerospace Technology Japan, vol. 11, 2013, pp. 93-98.

- [18] Shigetomi S., Kozuka T., Totoki H., Miyazawa Y., Brown M. and Fukuda Y., "Evaluation Analysis of Seasonal GPV Meteorological Data with SSR Mode S Surveillance Data," Proceedings of ICRA2014, Istanbul, Paper 592, 2014.
- [19] Bayen, A.M., Callantine, T., Tomlin, C.J., Ye, Y., Zhang, J., "Optimal Arrival Traffic Spacing via Dynamic Programming," AIAA 2004-5228, AIAA Guidance, Navigation and Control Conference, Province, 2004.

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