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ANALYSIS OF AIR TRAFFIC EFFICIENCY USING DYNAMIC PROGRAMMING TRAJECTORY OPTIMIZATION

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Abstract

The efficiency of commercial jet airliner flights into Tokyo International Airport, the busiest airport in Japan, is analyzed using Secondary Surveillance Radar (SSR) data. Each flight is reconstructed from surveillance data combined with meteorological and aircraft performance information in order to estimate fuel flow and thence fuel consumption, and is compared with a trajectory optimized for fuel consumption and flight time by a dynamic programming method based on the same meteorological and performance information. The comparison quantifies the potential benefits of ideal flight trajectories, and introduces effective measures to increase the efficiency and capacity of airspace.

1 Introduction

Today's busy air transportation system strongly demands not only safe flight but also greater efficiency. Realizing more efficient operations while increasing capacity is expected to be achieved by introducing new CNS/ATM technologies. Under the NextGen program in the United States and SESAR in Europe, many research projects are exploring innovations and many research papers have been published. In Japan, CARATS (Collaborative Actions for Renovation of Air Traffic Systems) [1] has been defined by the government as a roadmap for developing Japan's future air transportation system, and universities are encouraged to participate in its research. This study is being conducted as one of the collaborative research projects between universities and research institutions to support the program.

The purposes of this paper are to analyze current air traffic efficiency in order to evaluate the potential benefits of CARATS, and to propose effective measures to increase the efficiency and capacity of airspace. The analysis is based on the flight trajectories of commercial airliners operating in Japan's most heavily congested airspace around Tokyo. Trajectory information for each flight obtained by an experimental Mode S secondary surveillance radar (SSR Mode S) developed by the Electronic Navigation Research Institute (ENRI) is combined with meteorological data and aircraft performance information in order to estimate each flight's fuel consumption. The reconstructed flight performance is then compared with that of a trajectory optimized for fuel consumption and flight time by a dynamic programming algorithm for the same meteorological conditions and aircraft performance data. This analysis estimates the maximum benefit achievable for the flight, neglecting conflicts caused by other traffic, or the potential benefit which could be realized by an ideal air traffic management system.

Sections 2 and 3 explain the analytical method in brief, since most of the details have been published in references [2]–[5]. In section 4, the results obtained using one day of SSR data for arrival flights to Tokyo International Airport are discussed. The analysis is limited to arrivals largely by the coverage of the radar, but flight time and fuel efficiency are most influenced by the position of the TOD (Top of Descent) and flight speed during the descent. Although only three types of aircraft are analyzed, these cover about 60% of all inbound flights. The analysis reveals stochastic characteristics of the air traffic efficiency. A part of this paper has previously been presented in the APISAT 2013 conference in Takamatsu Japan [6].

2 Reconstruction of Airliner Flight Trajectories

The authors have previously analyzed the flight efficiency of commercial jet airliners in terms of fuel consumption and flight time by using GPS logger data obtained inside an airborne airliner cabin. Flight parameters such as calibrated air speed, true air speed, Mach number, temperature, and wind are estimated from the GPS data and meteorological GPV (Grid Point Value) data released by the JMA (Japan Meteorological Agency) [7], and then performance variables such as L/D (lift/drag ratio), thrust, and fuel flow are estimated using the BADA (Base of Aircraft Data) model published by EUROCONTROL [8]. Although each flight is effectively selected randomly because GPS logger data are obtained by a passenger, the analysis gives highly useful information on passenger aircraft operating in an air traffic controlled environment.

The accuracy of the flight parameter estimates depends critically upon the quality of the meteorological GPV data and the aircraft performance information. Comparing estimates with flight data obtained from aircraft on-board systems [9], [10] has shown that the errors are at a reasonable level and that flight parameter values estimated from GPS data are of sufficient quality for analyzing flight efficiency [11]. Similar findings concerning the accuracy of the meteorological GPV data have been obtained by analysis of SSR Mode S DAPs (Downlink Aircraft Parameters) [12] as well as onboard flight data analysis.

In this study, the tool developed for the GPS logger data analysis is applied to SSR data since the data are similar. Using SSR data extends the scope of the study immensely because data can be obtained on the trajectories of almost every aircraft within the surveillance system's coverage area. Data obtained for flights in Japan's most congested air space by ENRI's secondary surveillance radar located in Chofu, Tokyo, are used for the analysis. Figure 1 shows a photograph of the antenna operated on the top of a building at ENRI. Table 1 lists the major characteristics of the system. Figure 2 shows an example of flight trajectories from the SSR data.

Table 1. Characteristics of ENRI's SSR Mode S.

	Properties
Radar Site Name	Chofu SSR Mode S Test Ground Station
Position	ENRI (Tokyo, Japan)
Rotation cycle	10 [sec]
Coverage	250 [NM] at 40,000 [ft]

Fig. 1 ENRI's experimental Mode S SSR.

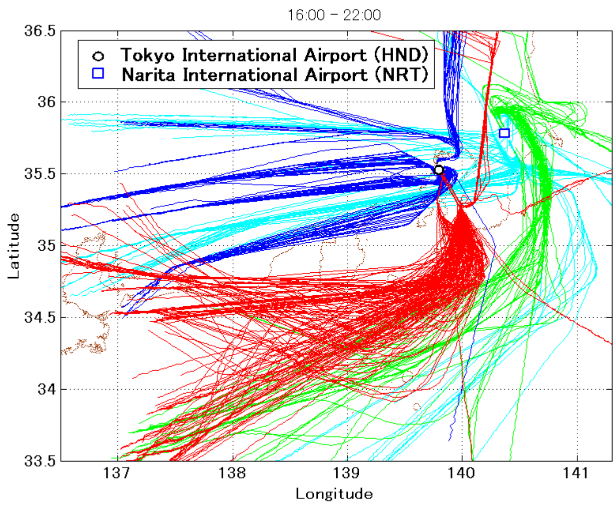

Fig. 2 Flight trajectories from Mode S SSR data. (red: HND arrival, blue: HND departure, green: NRT arrival, cyan: NRT departure)

3 Trajectory Optimization by Dynamic Programming

Each flight is analyzed by comparing its trajectory (including state parameter estimates) obtained from SSR, meteorological and performance information with an optimal trajectory calculated using the identical meteorological data and performance model as the flight analysis, assuming the same initial and final positions and velocities. A performance index which incorporates fuel consumption and flight time is minimized by dynamic programming (DP). The trajectory optimization is carried out for three free variables: altitude, velocity, and lateral deviation from the Great Circle path between the initial and final points. DP is a combinatorial optimization whereby variables are quantized on a grid and the path which minimizes the performance index is selected for each possible gridpoint to gridpoint transition. A four-dimensional grid is defined for the three free parameters and flight distance along the Great Circle path. An equidistance (uniform) grid, the simplest, is adopted for the calculation.

The performance index J for the optimization is defined as

$$J = \int_0^{t_f} (\mu(t) + a)\,dt \qquad (1)$$

where μ [kg/s] is fuel flow and a [kg/s] is a weighting parameter for the flight time. The weighting parameter is equivalent to the so-called "cost index" used in actual flight operations, where the performance index is defined as the cost of flight [dollars],

$$J_{dollars} = \int_0^{t_f} \left(\frac{1}{100} C_{fuel} \frac{1}{0.4536} \mu(t) + C_{time} \frac{1}{3600}\right) dt \qquad (2)$$

C_{fuel} is the fuel cost in cents/lb and C_{time} is time cost in dollars/hour. Comparing equations (1) and (2) gives the following relation, where CI is the cost index:

$$CI = \frac{C_{time}}{C_{fuel}} = \frac{3600}{100 \times 0.4536} a = 79.37a \qquad (3)$$

The weighting parameter, or cost index, is a free parameter which is set according to aircraft operators' policies, but in general it is selected to generate relatively high speed in the descent phase even though a flight may be later delayed by air traffic control scheduling of the landing sequence.

4 Results of Potential Benefits Analysis

4.1 Efficiency of arrival flights

Figure 3 shows the number of flights per hour and trajectories of outbound (left) and inbound (right) flights from and to Tokyo International Airport on an arbitrary day of North Wind Operation in February 2012. Trajectories are plotted below 20,000 ft, and are color-coded by altitude. It can be recognized from the plots that streams of traffic are merged at three fixes, KAIHO, ARLON and CREAM, on the Tokyo International Airport STARs (Standard Instrument Arrival). Although arrival streams from different directions are merged at KAIHO and ARLON, most aircraft arrived from the west and were "radar vectored" over the ocean to the south and west of the airport in order to adjust their arrival spacing as shown by the wide spread of trajectories in Figure 2.

It is clear that the trajectories flown prior to the three merging fixes heavily influences operational efficiency and so should be analyzed in terms of performance. On the other hand, the trajectories after the merging three fixes should be considered in terms of capacity and safe separation. Therefore, the final points of the trajectories subject to optimization analysis are defined at the three fixes, and the initial points are defined by the point of start of the data, (i.e. the point of entering SSR coverage). Operational efficiency during climb and most of the cruise phases of flight is excluded from this analysis because of the limited coverage of the single SSR antenna.

The trajectory optimization was carried out for three types of aircraft, Type-A, Type-B, and Type-C, the reference masses of which are 208.7 tons, 154.6 tons, and 65.3 tons respectively. These are three most common types operating at the airport and represent

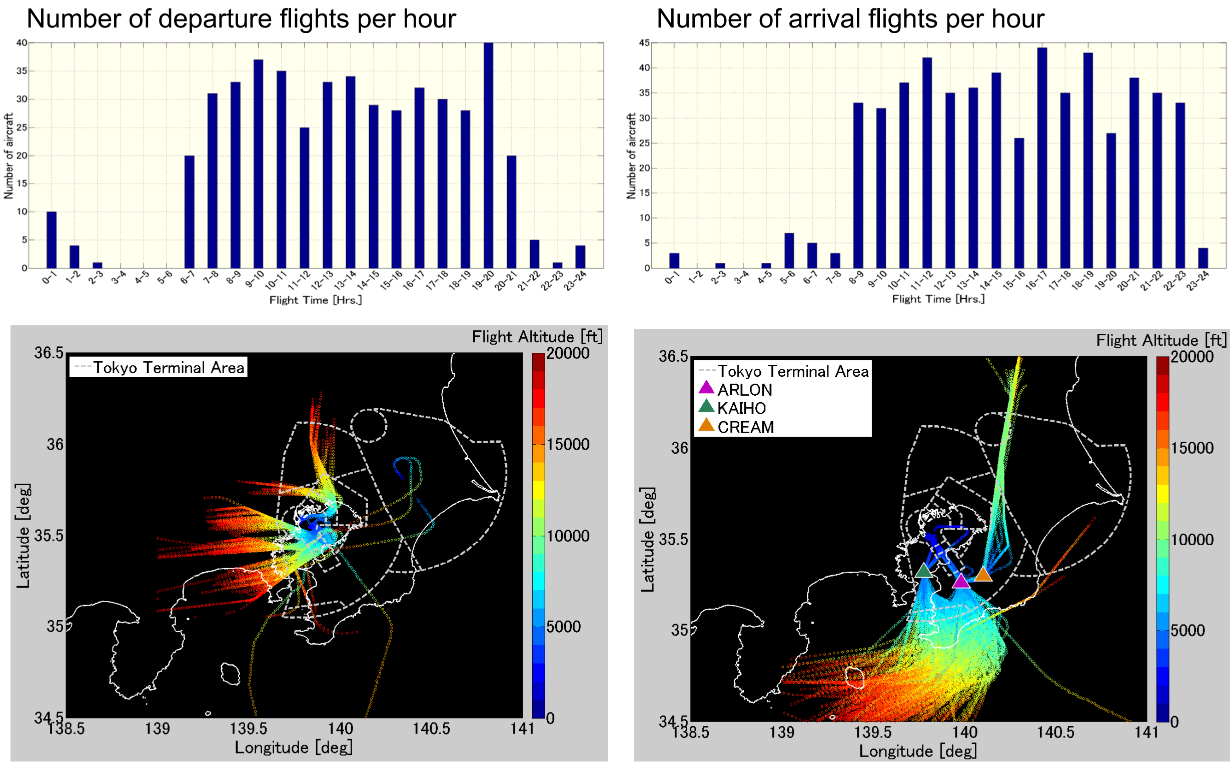

Fig. 3 Outbound (left) and inbound (right) flights at Tokyo International Airport, on an arbitrary day in February 2012.

Table 2 Comparison of reconstructed actual flight and the optimal trajectory.

	Estimated from SSR data (SSR)	Optimal trajectory (Opt.)
Flight time [second]	1464	1647 (+183)
Fuel consumption [kg]	1141	644 (-497)
Flight length [km]	364.6	358.1 (-6.5)

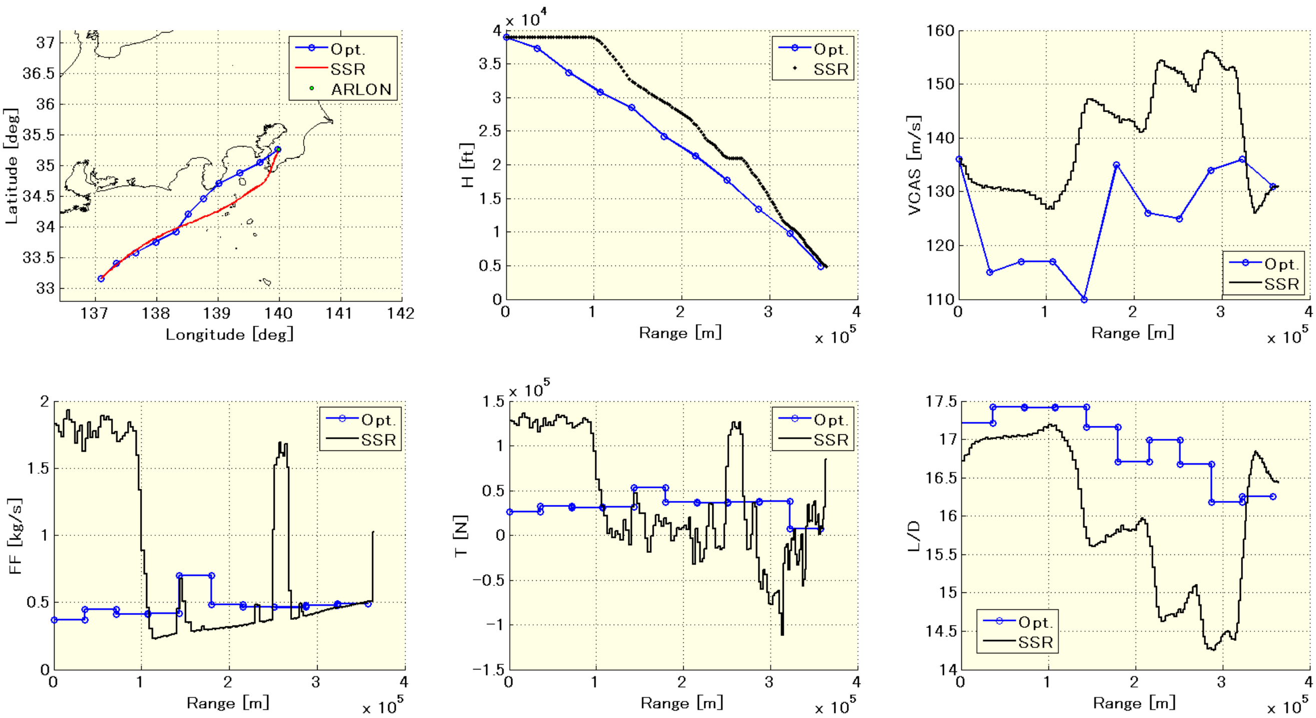

Fig. 4 Example of reconstructed actual trajectory and the optimal trajectory, fuel saving by the optimal trajectory.

about 60 % of all arrivals to the airport.

Although strictly speaking the particular mass of each aircraft is necessary to estimate its flight parameters, the reference mass of each aircraft type is used in the analysis.

Two different values of weighting parameter in the performance index are used for the trajectory optimization: a value of zero, which means "optimize only for fuel consumption" ignoring flight time, and a value of 0.5 [kg/s] which corresponds to Cost Index of about 40. As the latter value is relatively small it does not have a significant effect on fuel consumption, but it gives some influence on the flight time.

4.2 A typical example of optimized flight

Figure 4 shows a sample surveillance trajectory of a Type-A aircraft inbound to Tokyo International Airport which is analyzed for air efficiency. "SSR" denotes time histories of parameters reconstructed from SSR position data, meteorological and performance information, while "Opt" denotes time histories of the optimal trajectory calculated using the same initial and final conditions and the same meteorological and performance information. The flight time weighting parameter is set at a=0.5. Although actual ground tracks generally deviate from the Great Circle route due to air traffic control intervention for sequencing and spacing with other traffic before the ARLON fix, the deviation of this case is small. The optimal trajectory's ground track also slightly deviates from the Great Circle route in order to optimize the effect of wind profile. At the final point, the

Table 3 Average differences of the optimal trajectories relative to actual flights, a=0 and a=0.5.

	Weighting parameter a=0	Weighting parameter a=0.5
Fuel difference, average [kg]	-386	-362
Range difference, average[m]	-36,228	-36,615
Time difference, average[second]	-66	-202
Number of flights analyzed	256	256

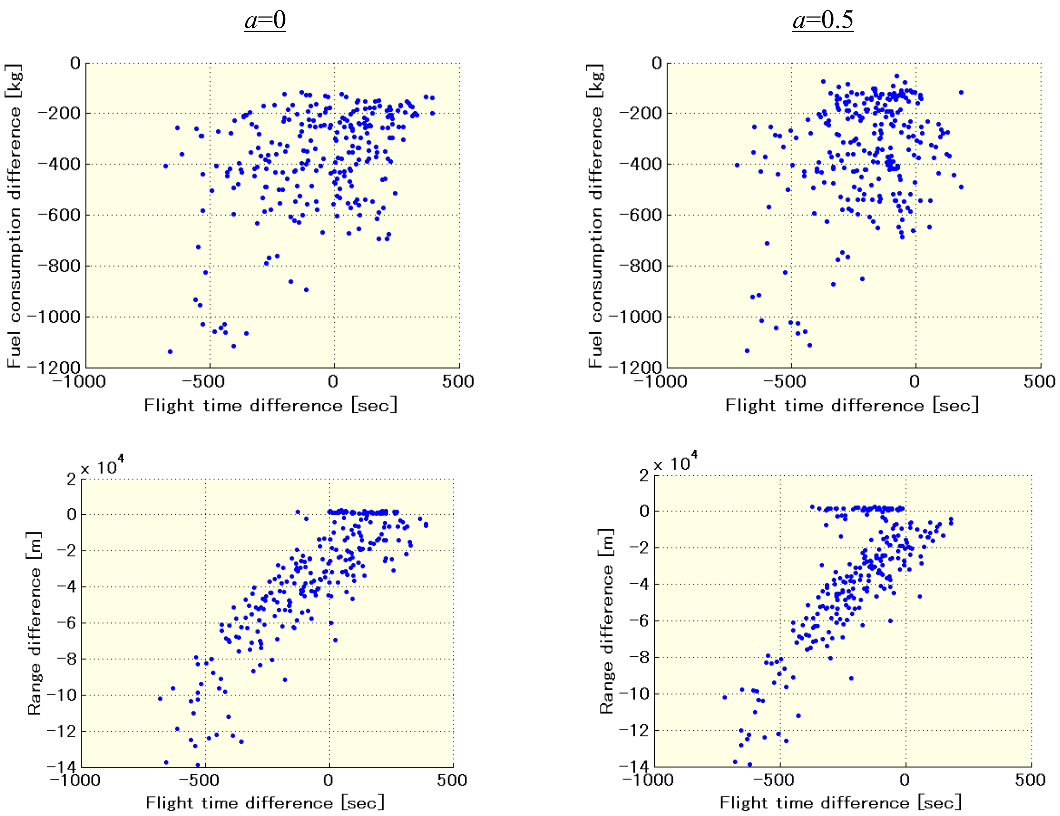

Fig. 5 Fuel, range, and time differences of the optimal trajectories relative to actual flights, a=0 (left) and a=0.5 (right).

track angle of the optimal trajectory is aligned with the runway by a turn of 25 degrees bank angle at a constant velocity.

As the altitude shows, the optimal trajectory's TOD (top of descent) is reached earlier than the actual flight to reduce fuel consumption. The fuel flow plots show a marked difference in fuel consumption. The longer descent flight by the optimal trajectory can be explained by the aircraft achieving efficiency by flying at a higher L/D which is realized by lower speed. Furthermore, the reconstructed actual flight uses "negative thrust", which means using speedbrakes.

The fuel consumption and flight time of the actual and optimal trajectories are compared in Table 2. The optimal trajectory gives a fuel saving of about 497 kg, which is the benefit achievable by an ideal flight for the conditions. On the other hand, the flight time is greater than the actual flight because of the lower speed during descent.

4.3 Stochastic characteristics analysis

Data of an arbitrary day in February 2012 were analyzed for the three types of aircraft, three merging fixes, and two values of the performance index weighting parameter. A total of 256 flights were analyzed, which is about 40% of the number of arrivals on that the day.

Figure 5 shows differences of fuel consumption, range (flight path length), and flight time for all the analyzed flights. The *a*=0 cases (i.e. zero weighting on flight time) are shown on the left and the *a*=0.5 cases on the right. The average fuel saving is 362 kg and the average flight time saving is 202 seconds for *a*=0.5. Comparing the two weighting parameter values by Table 3 and plots in Figure 5, it is

Table 4 Average differences of the optimal trajectories relative to actual flights, three merging fixes.

	Merging Fix, ARLON	Merging Fix, KAIHO	Merging Fix, CREAM
Fuel difference, average [kg]	-327	-381	-396
Range difference, average[m]	-38,305	-54,268	-14,898
Time difference, average[second]	-154	-279	-191
Number of flights analyzed	108	77	71

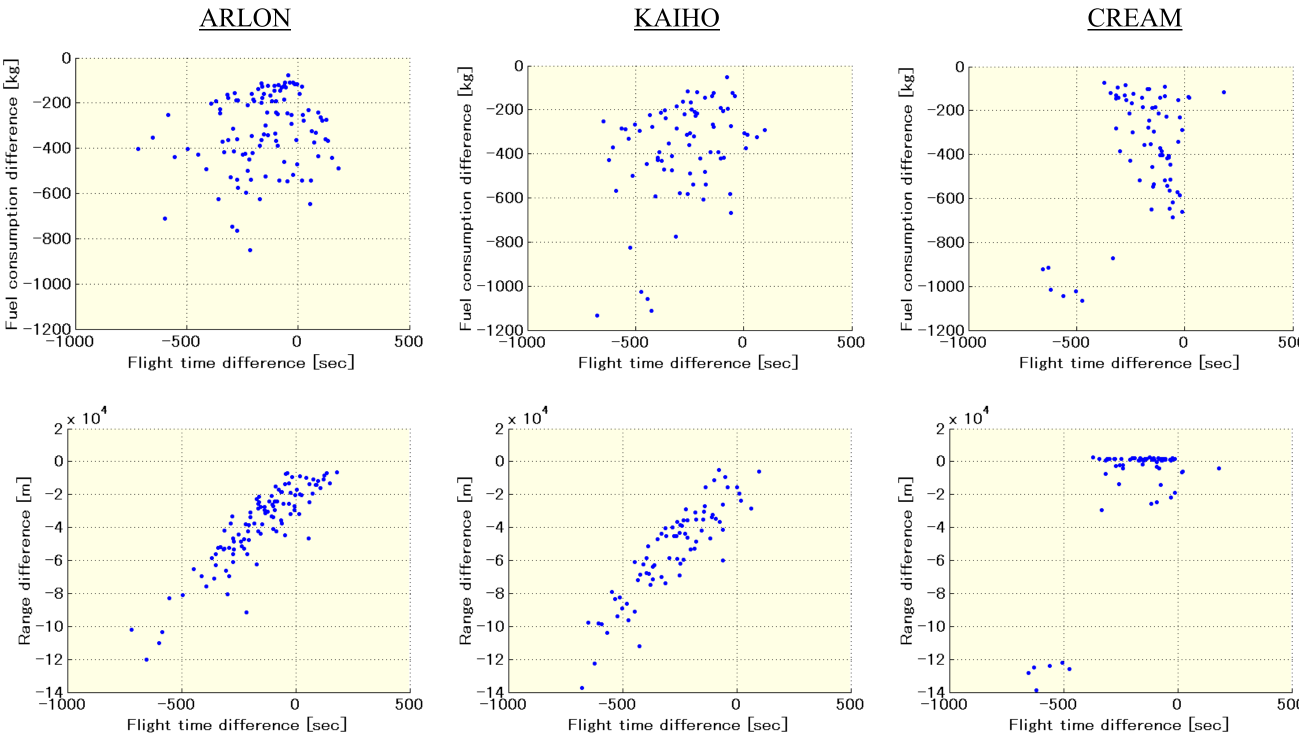

Fig. 6 Fuel, range, and time differences of the optimal trajectories relative to actual flights, three merging fixes.

understood that the weighting parameter does not greatly alter fuel consumption but has an influence on flight time. This justifies the claim that setting the weighting parameter to a small value instead of zero gives an operationally practical trajectory with negligible fuel penalty.

Figure 6 shows differences of fuel, range, and time relative to the actual flights for the three merging fixes, ARLON, KAIHO and CREAM. The weighting parameter is set as *a*=0.5. Concerning the range and flight time of actual flights, the KAIHO trajectories are longer than those for ARLON but have similar characteristics. On the other hand, CREAM gives different characteristics; i.e. one group is close to the shortest path, and the other has long range and time. Flights from the north of Japan pass CREAM and land on one of the two runways, 34R and 34L. 34L is mainly used by flights passing ARLON and KAIHO, but 34R is used by flights passing CREAM, which are fewer than that of 34L. Since their descent profile is step-down with a relatively long level flight at a low altitude to avoid interference of the traffic of Narita International Airport, the optimal trajectory can generate fuel and time savings. Some flights passing CREAM arriving from the north-west take flight routes that are originally longer than the Great Circle path, which can explain the long range and time cases.

Figure 7 shows differences of fuel, range and time for three aircraft types, Type-A, B, C. There are no significant differences between types except for the fuel consumption. These differences are reasonable because fuel consumption is proportional to aircraft mass, and the reference mass of Type-C is about one thirds of that of Type-A.

From the stochastic analysis, it can be recognized that there are two dominant sources

Table 5 Average differences of the optimal trajectories relative to actual flights, Type-A,B, and C.

(reference mass [ton])	Aircraft Type-A (208.7)	Aircraft Type-B (154.6)	Aircraft Type-C (65.3)
Fuel difference, average [kg]	-541	-410	-180
Range difference, average[m]	-40,063	-37,280	-33,336
Time difference, average[second]	-201	-169	-234
Number of flights analyzed	72	90	94

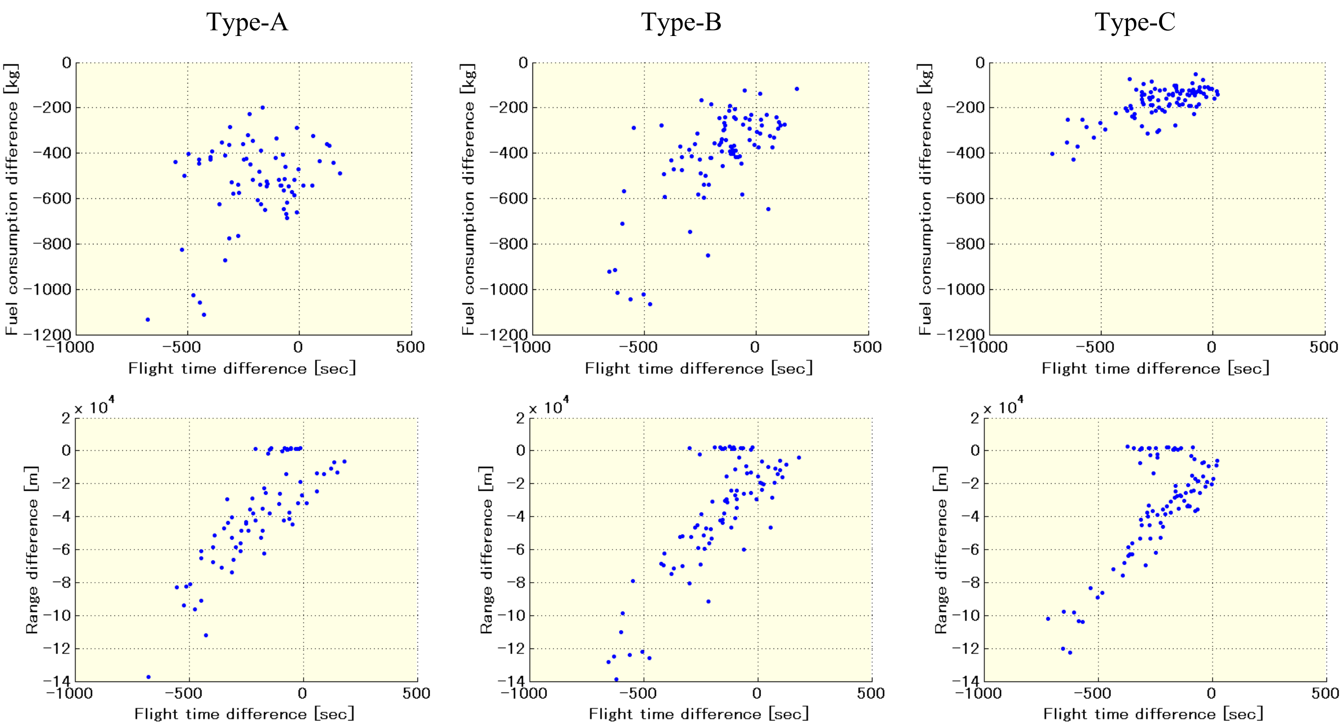

Fig. 7 Fuel, range, and time differences of the optimal trajectories relative to actual flights, Aircraft Type-A, B, and C.

of fuel saving of the optimal trajectory: a shorter flight path length than the actual flown path due to controller intervention for sequencing and spacing, and a more efficient descent profile derived by setting a smaller cost index than the standard, which is rational for flights to uncongested airports.

5 Concluding remarks

Operational efficiency is analyzed for inbound flights to Tokyo International Airport. Surveillance data obtained from an experimental Mode S SSR station operated by ENRI are used for the analysis. The optimal trajectory which minimizes a performance index defined considering fuel consumption and flight time is calculated for each flight, and is compared with reconstructed parameters of the original flight. A total of 256 flight cases are analyzed. From the analysis, possible savings of fuel and flight time on average are estimated as 362 kg and 202 seconds, respectively. These results quantitatively reveal potential benefits which might be obtained by improving the air traffic management system, and encourage further research into the Japanese CARATS CNS/ATM modernization program. Furthermore, information on the sources of the benefits is useful for prioritizing the research topics and to set research and development goals.

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