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EFFICIENT CONTROL OF ARRIVAL TIME AT A CONGESTED AIRPORT'S TERMINAL AREA

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Abstract

Arrival management is a promising solution to the issue of delays and inefficiencies surrounding inbound flights at a congested airport such as Tokyo International Airport. In our previous work, we proposed a method for sequencing and arrival time assignment; it forms a key part of an arrival management system. This study focuses on controlling the arrival time, which is another critical part of the time-based arrival management system. We devised a strategy to accurately control the required time of arrival at a meter fix located on the terminal area's boundary by utilizing a currently operational flight management system's required time of arrival function. Experiments using flight management system simulators showed robust control logic and performance against wind error disturbances.

1 Introduction

Today's busy air transportation system demands not only safe flights but also greater efficiencies and capacities. More efficient operations with greater capacities are expected to be achieved by introducing new technologies in CNS/ATM. Under the NextGen program in the United States and SESAR in Europe, many research projects are being conducted to explore innovation in this area. The Japanese government also has a road map, namely Collaborative Actions for Renovation of Air Traffic Systems (CARATS), to define the future of air transportation systems; universities are widely encouraged to participate in such research [1]. This study is being conducted as one such responding research project, which strives to drive forward the aim of CARATS.

Among the research projects in CARATS, increasing the efficiency and capacity of flights arriving at a congested airport is one of the most demanding problems. Arrival management systems are already in operation at many airports in an attempt to solve this problem, e.g., via Center TRACON Automation System (CTAS) in the US and Arrival manager (AMAN) in Europe, which have developed advisory systems that improve flight efficiency and reduce the workload of air traffic controllers. However, Tokyo International Airport, which is the busiest airport in Japan, has not yet implemented a similar system, although trials for arrival flow management have been carried out.

Although we consider that effective arrival management systems could be realized using new technologies such as air-ground trajectory synchronization and dynamic routing via air-ground data link, there will be costs, implementation will take some time and there will be transition issues. If new technology is to be introduced, it is necessary to estimate the benefits to justify the investment. Further, it is necessary to consider how arrival management control will be carried out: for example, using airborne speed control or ground-based speed control to achieve a specified meter fix arrival time. Creating an arrival management concept that will be effective with existing airborne technologies while being able to leverage new technology as it becomes available, is a challenge.

In Section 2, our previous research regarding a possible arrival management system for

Tokyo International Airport is introduced, which has been published in references [2 − 4]. It consists of a potential benefit analysis and optimal arrival time assignment, both of which showed promising results. The next key issue is the control of the arrival time at a meter fix on the boundary of a terminal area. In Section 3, we therefore discuss the required time of arrival (RTA) function of a flight management system (FMS) to realize the assigned arrival time via onboard equipment. A flight management workstation (FMW) operated by the ENRI is used for this research. Auto-flight commands generated by the FMS are examined by comparing off-line trajectory optimizations. The simulation aims to act against wind error disturbances and has shown promising results and provides useful information for future ground control strategy development.

2. Previous work

2.1 Efficiency analysis of inbound flights to Tokyo International Airport

As congested airports generally suffer from flight delays and resulting flight inefficiencies, it is useful to conduct a quantitative objective analysis of the potential benefits (i.e., a comparison between the current state and an ideal but still achievable state) since it will enable future plans for improvements to be drawn up. We conducted a potential benefit analysis for inbound flights to Tokyo International Airport, in which surveillance data from an SSR Mode S, experimentally operated by the ENRI, Tokyo, were used and in which the initial points depended on radar coverage, i.e., they were located within approximately 200 NM of the airport.

For the analysis, we developed a flight parameter estimation approach (including a fuel consumption estimation) from surveillance radar positioning data using the Japan Meteorological Agency's numerical weather prediction Grid Point Value (GPV) data [5] to estimate the air data parameters, such as true air speed, calibrated airspeed, and Mach number. Additionally, Base of Aircraft Data (BADA, Rev. 3.11), developed by EUROCONTROL, were used to estimate performance data, such as drag and fuel flow [6]. Furthermore, we calculated the optimal trajectory for each flight with dynamic programming (DP) by inputting the initial and terminal condition of the actual flight and using the corresponding meteorological condition's GPV and the BADA performance model. This revealed that a significant amount of flight time and fuel are wasted during the descent phase; therefore, arrival management for inbound flights is definitely necessary [2].

2.2 Optimal sequencing and arrival time assignment

One of the key issues of an arrival management system is the fair assignment and accurate control of the arrival time at a meter fix on the boundary of the terminal area, which is essential to achieve safe separations between the aircraft

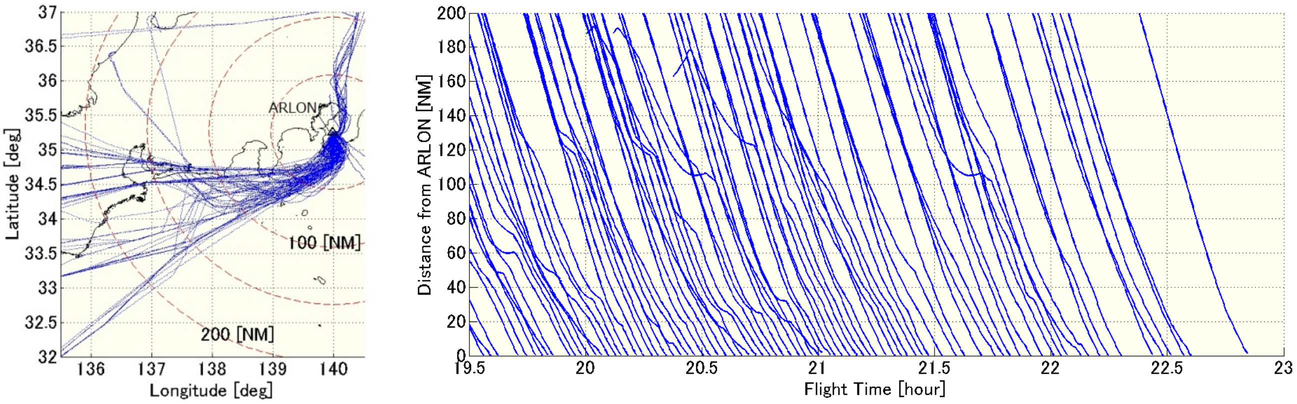


Fig. 1 Horizontal plane trajectories of inbound flights landing on RWY34L (left) and the distance to the approach fix ARLON as a function of flight time (right) between 19:30 and 23:00, May 9th, 2012.

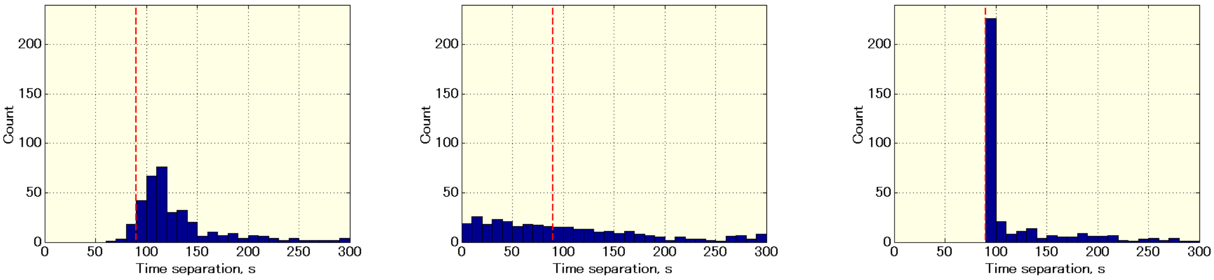


Fig. 2 Arrival time separation at ARLON from 7:00 to 23:00 on May 9th, 2012 (left: actual; center: optimal trajectory without constraint; and right: optimal trajectory with 90 s time separation constraint).

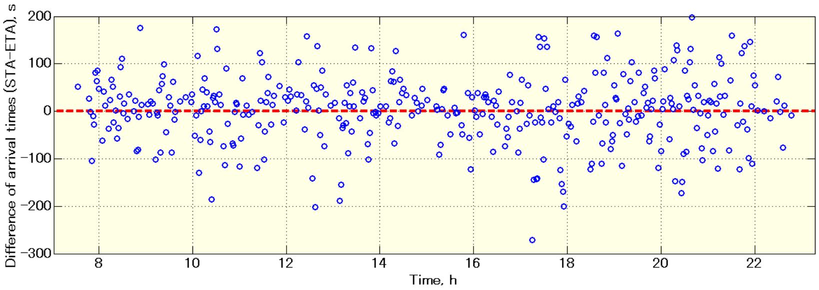


Fig. 3 Difference of arrival times of optimal trajectories with and without time separation constraint, STA–ETA (STA: scheduled time of arrival; ETA: estimated time of arrival), May 9th, 2012.

Table 1 Average fuel consumption and flight time for 375 flights.

	Actual flight	Optimal trajectories (difference, ratio relative to actual flight)				
		(a) Without time constraint		(b) With time constraint		(b)–(a)
Fuel burn (kg)	4217	3658	(−559, −13.24%)	3691	(−526, −12.47%)	+33
Flight time (s)	3741	3592	(−149, −4.00%)	3594	(−147, −3.93%)	+2

on the predetermined route to the runway. Arrival sequencing and arrival time assignment by the ground system should consider the wind conditions and each aircraft's performance. In our previous work, we proposed a concept for sequencing and arrival time assignment that adequately provided efficient flight paths for all arrival flights. [3][4] The total performance indices, consisting of the performance indices of each flight, were optimized so that they would equally share the effects caused by the constraints of the time separation at the meter fix. The concept was examined by applying to the arrival flights to Tokyo International Airport using surveillance data from the entirety of Japanese airspace (CARATS Open Data [7]).

Figs. 1−3 are examples of the results of all flights that landed on RW34L during one day. Fig. 1 shows that sequencing and time separation are currently accomplished by vectoring to add delays in most cases. Fig. 2 shows the time separation at an approach fix ARLON for three cases: actual, optimal without time separation constraint, and optimal with time separation constraint. Table 1 shows that the differences in fuel savings and flight times between those obtained with and without the arrival time constraint were fairly minimal. In particular, the average flight time was almost the same, which means that the arrival time adjustment was not only achieved with time delays but also time advances. Fig. 3 shows the each flight's arrival time adjustment (STA-ETA) necessary for the time separation constraint, i.e., the positive value is time delay and the negative value is time advance.

3. Arrival time control

3.1 FMS with all-phase RTA

Arrival time assignment based on our potential benefit analysis has shown that significant improvements in air traffic efficiency are possible. Arrival time control should be performed by utilizing speed instead of being based on detours (i.e., vectoring) to achieve an ideal performance. Currently, an onboard FMS optimizes its own flight profile using performance-related parameters such as take-off weight and meteorological information. Most FMSs have an RTA function. Some of the RTA functions, however, are limited to the cruising phase only, while others, referred to as all-phase RTA functions, can control the arrival time at a meter fix on the boundary of the terminal area. Approximately half of all currently operational aircraft in Japan are equipped with all-phase RTA functions, but the proportion is increasing.

As the control strategy of an operational FMS can be a reference for ground control for future possible developments, all-phase RTA functions were evaluated. The ENRI's GE Aviation FMW for a single-aisle jet passenger aircraft (Fig. 4), which can simulate an FMS-in-the-loop flight, was used for that purpose. The simulation scenario conducted was from Fukuoka Airport to Tokyo International Airport, as shown in Fig. 5. The analyzed extent was from 15,000 ft during the climb phase to the meter fix ADDUM at 10,000 ft. The flight plan followed standard air routes. The flight distance was about 500 NM.

An FMS essentially optimizes fuel burn and flight time, where the trade-off parameter is called the cost index (CI), which is the ratio of the flight time value against the fuel value. The arrival time is controlled by changing the CI to ensure that the estimated time of arrival (ETA) is equal to the RTA. Fig. 6 plots assignable RTAs, which are limited by the earliest arrival and the latest arrival time relative to the arrival time obtained by the simulation with CI = 25. Plots with different CIs (between 0 and 100) show the time difference with relation to the trajectory of CI = 25. They show which CI value should be chosen at each position to change the arrival time. The flight time delay of the latest arrival is more than that for CI = 0, which means that a negative CI is used in the FMS, although pilots cannot input negative CI values.

Our trajectory optimization by DP essentially conducts the same optimization, except that it uses the BADA performance model, which utilizes different performance data than those implemented in the FMS. The relation between the CI and the performance parameters, i.e., the fuel burn and the flight time, was evaluated by comparing the simulation results with optimal trajectories calculated via the DP and BADA performance models. Fig. 7 shows the results. As the direct output of fuel burn from the simulation is not accurate, it was calculated using both flight parameters and the BADA model. A flight parameter for the DP calculation was modified to follow the limitations of FMSs, i.e., that the minimum speed is limited to 230 kt, which is the given terminal speed at the meter fix. A simple three-parameter-model optimal trajectory (3 Param. Opt.) in which only three parameters, i.e., climb CAS, cruise Mach, and descent CAS are optimized is also considered to simulate the FMS outputs. Fig. 8 plots the time histories of the FMS's simulator output and the optimal trajectories.

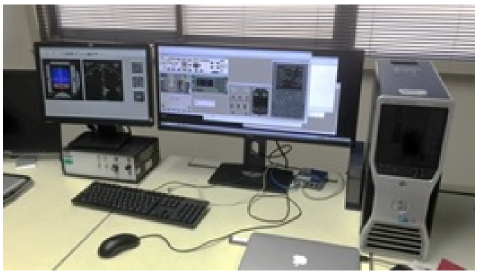


Fig. 4 Flight Management Workstation.

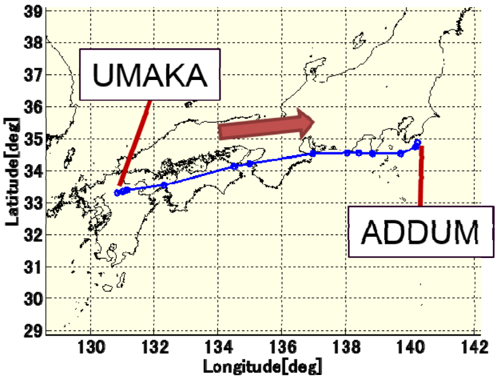


Fig. 5 Horizontal plane trajectory of the flight plan.

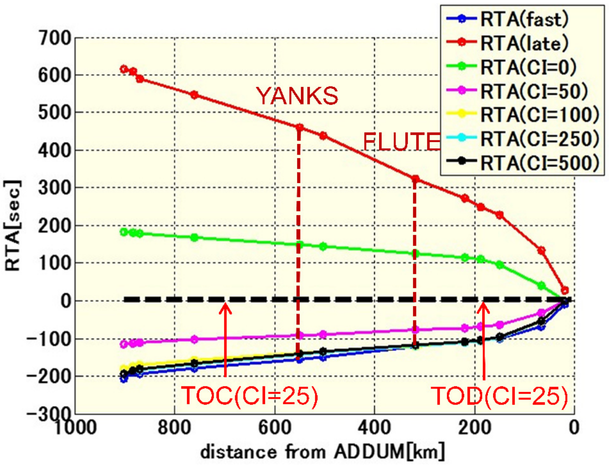


Fig. 6 Assignable RTA depending on distance to the target waypoint (CI = 25).

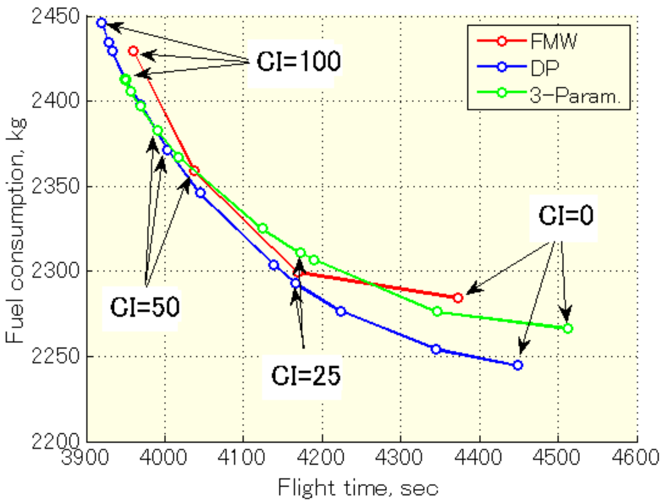


Fig. 7 Fuel burn and flight time trade-off of FMS simulator and trajectory optimizations.

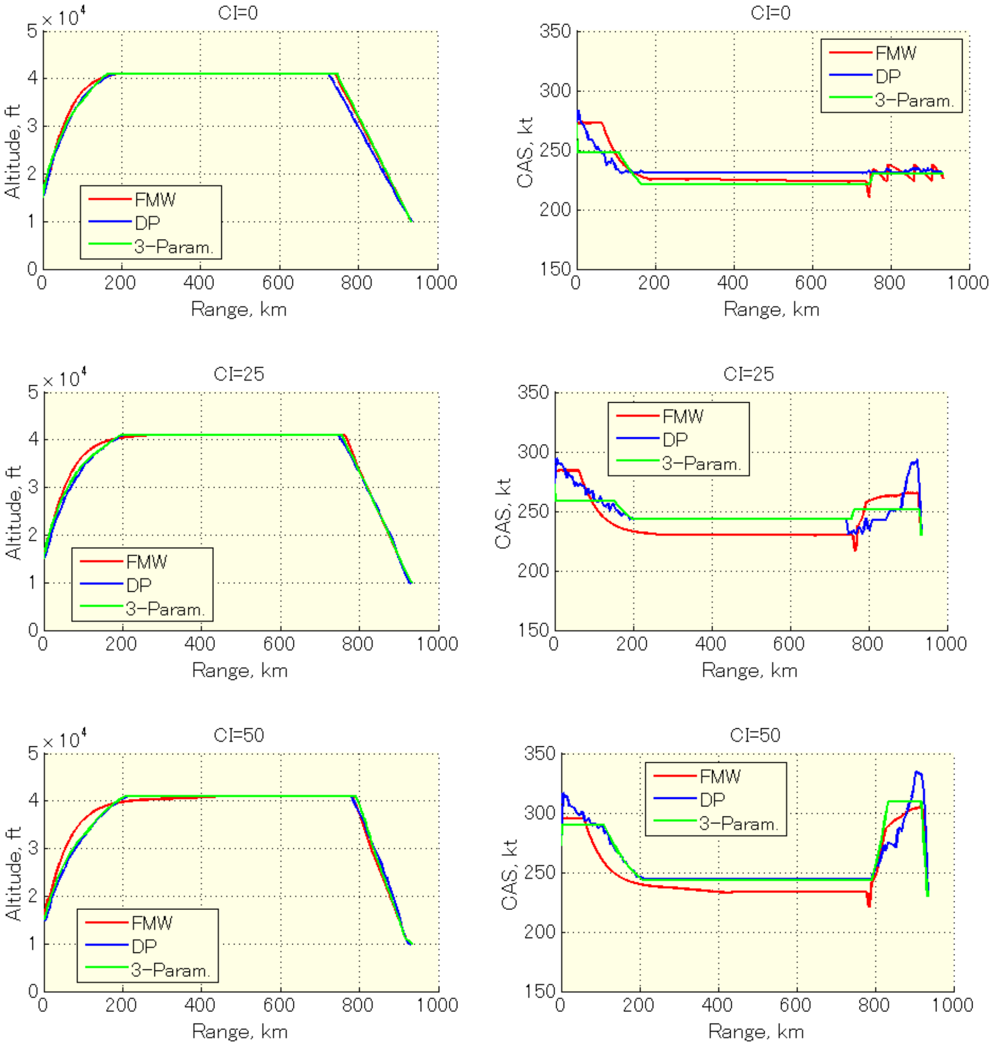


Fig. 8 Fuel burn and flight time, simulation results and off-line trajectory optimization.

Although the accuracy of the arrival time is critical for time separation at the meter fix, it can deteriorate owing to wind prediction errors; therefore, an evaluation of the RTA function's performance is an important issue in actually implementing an FMS RTA function in an arrival management system [8]–[10]. Arrival time errors owing to wind prediction errors were evaluated by using the same flight scenarios. Fig. 9 shows the wind error profile. The error varied between −30% and 30% in 10% steps. This means that the error level was much larger than in our weather forecast data analysis using quick-access recorder (QAR) data or SSR mode S downlink aircraft parameter data [11][12]. As the table shows, however, the arrival time errors were less than 12 s.

Next, a step input of the wind error was considered to identify the feedback control strategy. As explained in Ref. [13], FMSs recalculate the flight profile when the difference between the RTA and ETA exceeds a threshold that depends on the time-to-go, i.e., the difference between the RTA and the present time.

Table 3 shows six cases of the wind error and the RTA performance of each simulation. Figs. 11–16 show the time histories of each case. Except for Case 1-2, the RTA error was less than 10 s. As shown in Fig. 6, the early arrival capability was less than the late arrival capability, arrival time control against strong head-wind bias errors (like for Case 1-2) was more limited than that against tail-wind bias errors. The threshold for recalculation illustrated in Fig. 17 was confirmed by the simulation.

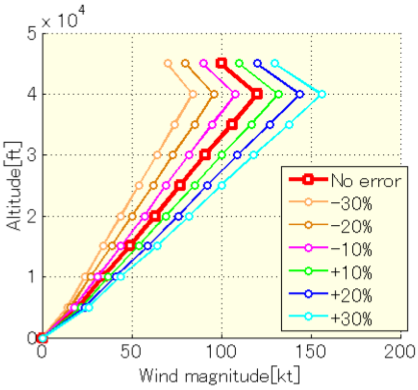
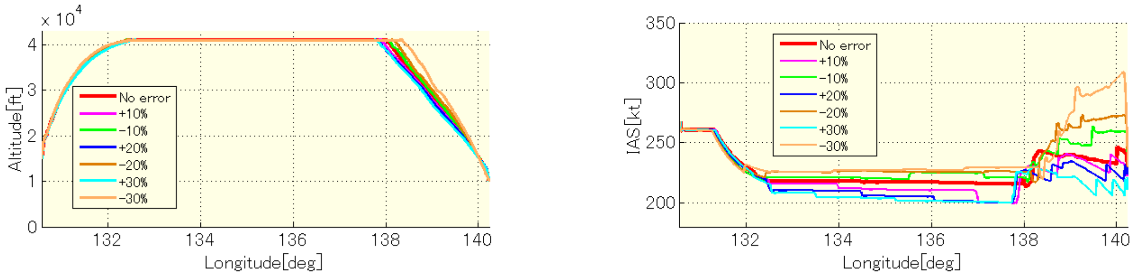


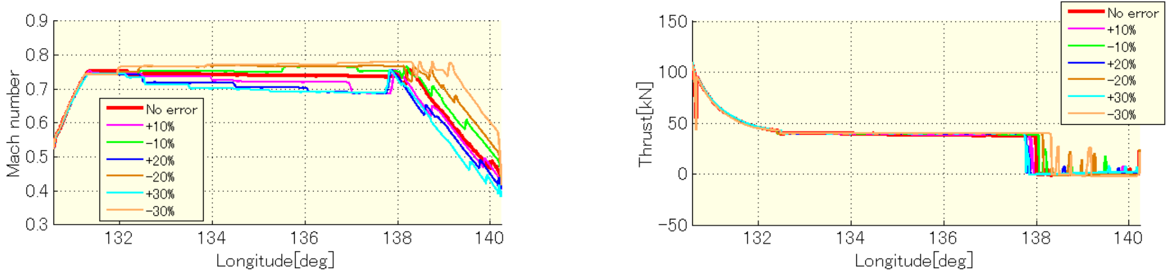
Fig. 9 Simulated wind conditions.

Table 2 Results of arrival time error at the target waypoint ADDUM (ATA, actual time of arrival).

Wind error	Arrival time error ATA−RTA[sec]	CDU output
No error	9	ON TIME
+10%	12	LATE 00:12
–10%	10	ON TIME
+20%	1	ON TIME
-20%	0	ON TIME
+30%	4	ON TIME
-30%	3	ON TIME



(a) Altitude (b) Calibrated air speed

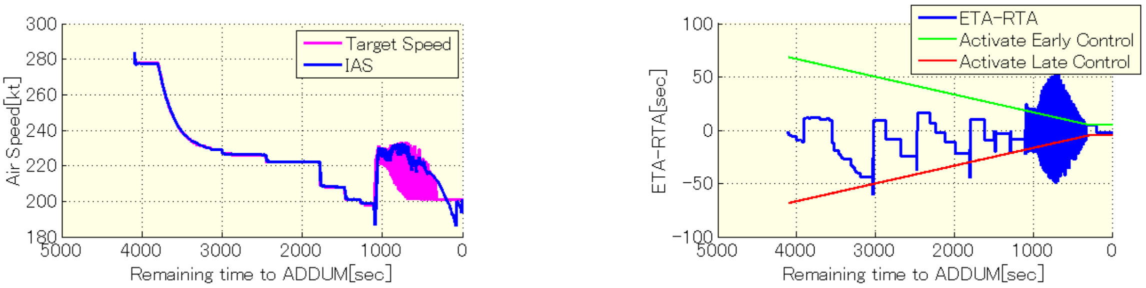


(c) Mach (d) Thrust

Fig. 10 Responses to wind error of RTA.

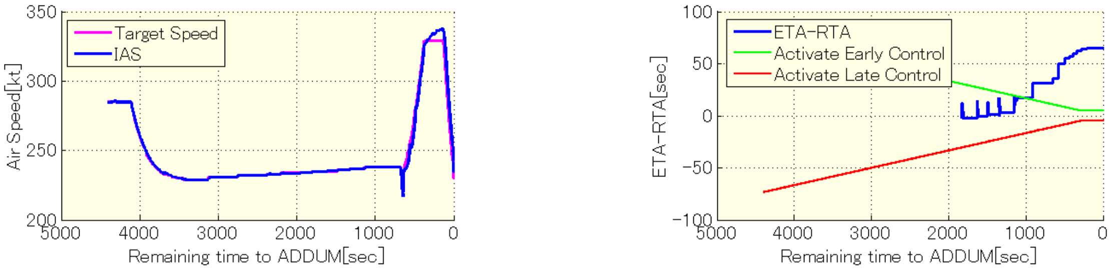
Table 3 Wind profiles studied for RTA function and simulation results.

CASE	Wind condition simulated[kt] （Wind direction 270 degrees） 45000-30000ft	 30000-20000ft	 20000-10000ft	 10000-0 ft	Input to FMS[kt]	ATA-RTA [sec]	TIME ERROR
1-1	40				0	0	ON TIME
1-2	-40				0	58	LATE 1:05
2-1	0	40	0	0	0	9	ON TIME
2-2	0	-40	0	0	0	-6	ON TIME
2-3	0	0	40	0	0	-6	ON TIME
2-4	0	0	-40	0	0	4	ON TIME



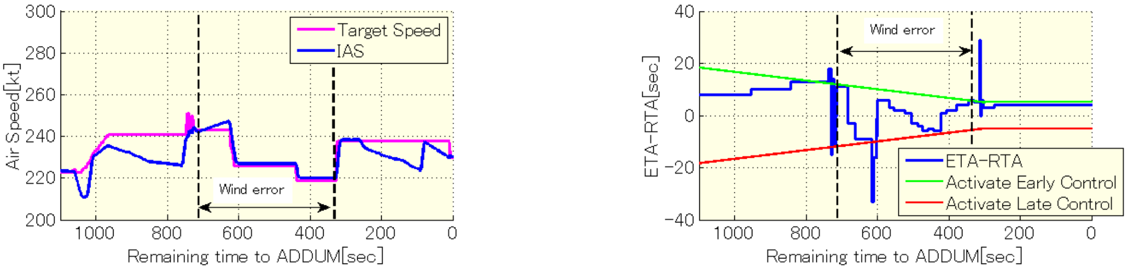
(a) CAS (b) ETA-RTA

Fig. 11 Response of CAS and ETA-RTA (CASE 1-1).



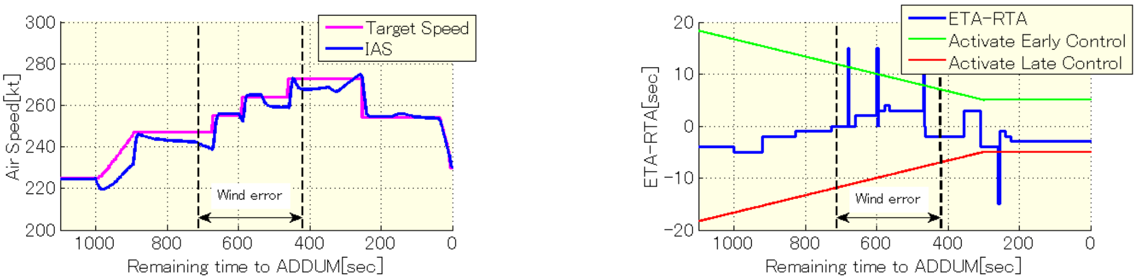
(a) CAS (b) ETA-RTA

Fig. 12 Response of CAS and ETA-RTA (CASE 1-2).



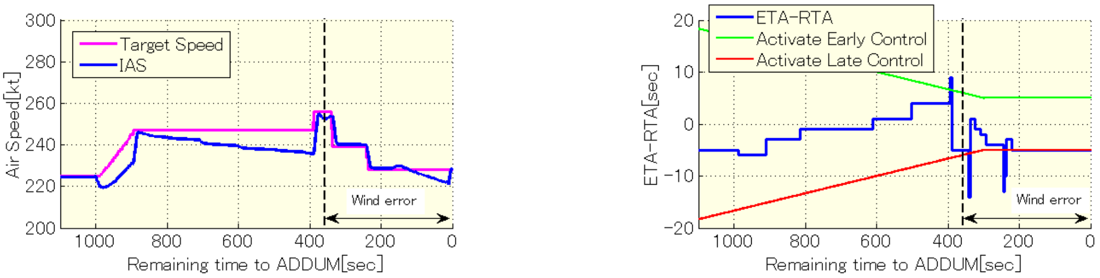
(a) CAS (b) ETA-RTA

Fig. 13 Response of CAS and ETA-RTA (CASE 2-1).



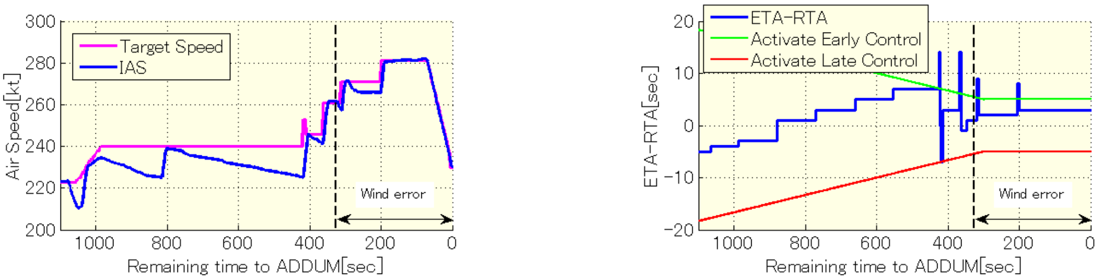
(a) CAS (b) ETA-RTA

Fig. 14 Response of CAS and ETA-RTA (CASE 2-2).



(a) CAS (b) ETA-RTA

Fig. 15 Response of CAS and ETA-RTA (CASE 2-3).



(a) CAS (b) ETA-RTA

Fig. 16 Response of CAS and ETA-RTA (CASE 2-4).

The control strategy identified from the simulation results was evaluated by comparing it with those from trajectory optimization using the same control logic (shown in Fig. 17). Figs. 18 and 19 show an example of the time histories of the off-line optimal trajectories. It reveals that wind error compensation is effective to reduce the RTA error, even though some sort of further studies are necessary.

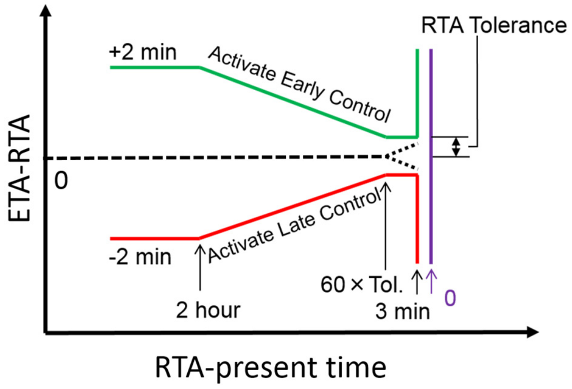
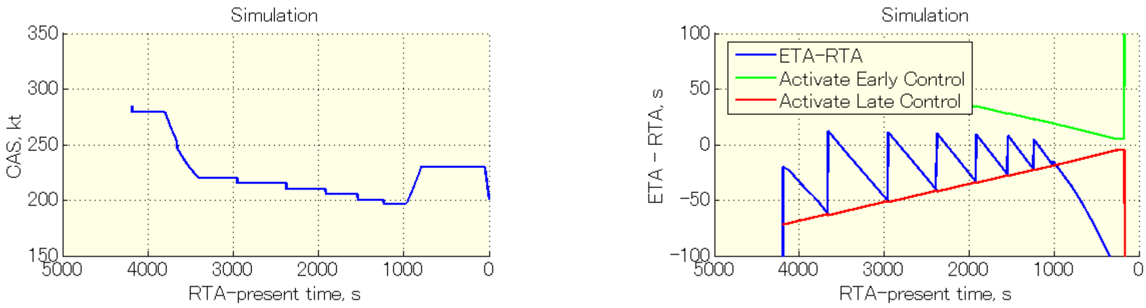
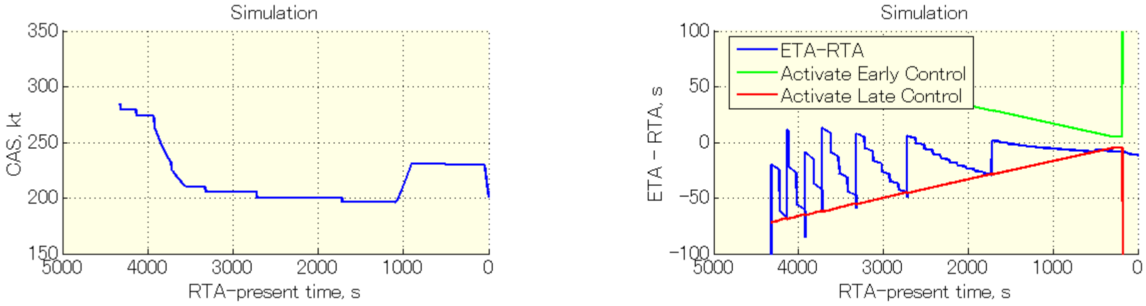


Fig. 17 Control dead-band of recalculation for RTA.



(a) CAS (b) ETA-RTA

Fig. 18 RTA control by off-line optimal trajectory without a wind error compensator (Case 1-1).



(a) CAS (b) ETA-RTA

Fig. 19 RTA control by off-line optimal trajectory with a wind error compensator (Case 1-1).

Although the simulation results from the FMW are encouraging for arrival time control, it should be taken into account that the tested simulation was a fast time simulation in which aircraft dynamics were not taken into account accurately. Evaluation by a training flight simulator or actual flight test using currently operational RTA functions of FMSs is necessary.

3.2 RTA control by ground controller

As has been discussed, arrival sequencing and time separation are currently controlled by the en-route ground controller's vector control of multiple aircraft. Our previous research showed that there would be advantages in replacing this procedure by speed control, which is calculated from the assigned arrival time without lateral navigation.

For aircraft not equipped with all-phase RTA functions, a practical method of arrival time control should be explored, such as velocity assignment by the ground controller during the cruise and descent phases through voice communication using a conventional system. The accuracy of the arrival time should be evaluated against wind prediction errors for this approach as in the previous section for all-phase RTA functions of onboard FMSs. A four-dimensional trajectory estimation of the ground-generated trajectory is expected to be more accurate because it uses more precise wind prediction data than onboard FMSs. The voice communication necessary for arrival time control is expected to be so limited that it could significantly reduce the workload of air traffic controllers and pilots. Although the research is in progress, the performance of the currently operational FMS all-phase RTA functions is still the key to future system developments. Ideally, a best-equipped and best-served environment could accelerate the installation of the function.

4. Concluding remarks

This paper studies the feasibility of the RTA function of onboard FMSs to be used as part of an arrival management system for Tokyo International Airport. The all-phase RTA function is evaluated by an FMW, which can simulate FMS-in-the-loop automatic flights under pre-assigned wind conditions. The optimal trajectory that corresponds to the simulation condition is calculated using the BADA performance model and the corresponding wind conditions to evaluate the result.

The simulation reveals that

- FMS optimizes its trajectory to minimize the fuel burn and flight time for a given weighting parameter CI.
- When the RTA function is active, FMS optimizes its trajectory to minimize the fuel burn with a constraint of arrival time by adjusting CI to let the ETA equal the RTA.
- Wind error generates a dynamic change of ETAs, which causes the differences between ETAs and RTAs, but the FMS recalculate new trajectories to change the ETA when the difference exceeds a threshold depending on the time distance to a meter fix. As a result of the feedback control, arrival time error is very

limited in almost all cases, except that the necessary control exceeds the speed limitation in the case of large head-wind errors.

Although the simulation result is encouraging for the use of all-phase RTA functions as part of time-based arrival management systems, this simulation neglects dynamics errors; therefore, future work will focus on evaluating the process with more accurate simulations.

Acknowledgement

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