Point Merge System and Arrival Metering Synergy Effect Estimation of Inbound Flight Efficiency at Tokyo International (Haneda) Airport

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Abstract

As air traffic increases, certain airspaces are becoming more crowded than the controllers can handle. Despite the current plunge due to Covid-19, demand for air travel is expected to recover and increase in the future, so efficient traffic handling will be essential. Ground delay programs (GDPs) have been introduced to balance demand and capacity, and excessive demand not managed by GDP is handled by speed control and vectoring in the terminal area of the arrival airport. In order to decrease air traffic controller (ATC) workload and provide more orderly flow, the point merge system (PMS) was introduced at Haneda Airport in 2019. Compared to conventional vectoring, PMS can absorb more delay in a more predictive manner because the path stretching is done following pre-defined arc-shaped paths. When the delay to be absorbed cannot be managed within the PMS area only, additional flow control is necessary in the airspace prior to PMS. This research evaluates the potential effects of time management for cruising aircraft and PMS on the airspace prior to PMS area. The metrics chosen for analysis are 1) distance flown, 2) number of headings (to describe vectoring) and 3) fuel consumption. Results show that the introduction of time management for cruising aircraft and PMS leads to a decrease in distance flown, number of headings and fuel consumption in the airspace prior to PMS, which leads to efficient flights and less ATC workload.

Keywords: Air Traffic Management, Vectoring, Tokyo International Airport, Point Merge System

1. Introduction

Covid-19 has caused a plunge in air travel demand, but forecasts show that in a couple of years the industry will not only recover to its pre-Covid-19 levels, but also continue its growth [1]. To cope with the increase in demand, improvement of air traffic management is required. In fact, some hub airports and the airspace around them are often used at their maximum capacity. Furthermore, from the viewpoint of sustainable aviation, air traffic management should be not only safe, but also efficient and environmentally-friendly. To address these challenges and balance supply and demand at peak times, various Air Traffic Flow Management (ATFM) initiatives have been considered [2].

Some typical methods of ATFM are ground holding [3] and Time-Based Flow Management (TBFM), including metering [4]. Ground holding is executed as part of a ground delay program (GDP) already implemented in many flight regions worldwide, including Japan [5][6]. Ground holding is in general cheaper than airborne holding and enables large delay absorptions [7], so its effect on traffic flow is substantial. However, ground holding also poses some issues, including inequity in delay distribution due to only domestic aircraft being part of the GDP program, and inability to compensate for uncertainties in aircraft departure time and runway capacity prediction, for example. Therefore, TBFM is necessary to absorb such uncertainties and to improve air traffic flow. The efficiency of TBFM relies on future forecasts such as traffic demand and acceptance rates at destination airports. When forecasted demand exceeds predicted capacity, some flights can be instructed to cross the control metering points near the arrival airport later than originally planned, for example. TBFM can be efficient to handle departure time errors, as well. Assigning too long a delay through TBFM would lead to lost runway throughput. However, perfect flight time prediction is impossible due to wind forecast errors, for example, so if one wants to avoid throughput loss, they need to make sure there are sufficient number of aircraft to land at any given time in congested periods. Currently, this inbound flight pool is achieved by vectoring, i.e. setting some delay buffer which usually results in vectored flights near the arrival airport. Vectoring reduces throughput loss but causes unnecessary extra fuel burn and ATC workload.

Currently, Point Merge System (PMS) [8] is a new arrival flow integration technique which is meant to keep the inbound flight pool necessary for throughput loss minimization while reducing vectoring and creating a more orderly and thus predictable flow. PMS provides a predefined procedure which allows controllers to stretch the path by controlling the flight over predefined arc-shaped legs. PMS procedure substitutes tactical vectoring and thus reduces controller's workload, increases predictability and safety, and eventually results in increased number of inbound flights handled per unit time.

There are numerous past researchers investigating PMS at Haneda Airport [9][10][11]. These studies mainly focus on the PMS airspace. However, as mentioned above, considering that the introduction of PMS replaces the inconsistent tactical vectoring before the PMS route with a more systematic vectoring, and since not all delay can be absorbed by PMS, the improvement of the flight route before PMS path also should be analyzed. This study considers the introduction of TBFM and PMS at Tokyo International (Haneda) Airport and investigates potential effect on traffic flow and ATC workload, focusing on the airspace prior to PMS feeding points (closer to the enroute portion of the flight). We used the flight distance, the number of heading changes (used to measure air traffic controllers' workload to an extend) and fuel consumption to quantitatively measure the TBFM and PMS effect. In the previous studies [12], we conducted a detailed evaluation about the number of heading changes and estimated the effect of time management to cruising aircraft such as TBFM. This study differs from the previous study in that the analysis is performed using wind condition data in addition to the actual track data used in the previous study. Considering the wind conditions makes two things possible. The first is the calculation of fuel consumption. By using the actual track data and the wind condition data, the airspeed required for calculating the fuel consumption can be obtained. The second thing is an increase in the number of target flights for analysis. In the previous study, the analysis was performed on the assumption that there was no significant change in wind conditions throughout one day. Therefore, we performed an analysis using only the data of the same day. In this study, it is possible to perform analysis using a data group including data on different days by considering the wind conditions, and it is possible to increase the number of data samples. This means that the number of target flights can be secured even when only the data of the same aircraft type is used for analysis, and as a result, the analysis using the fuel consumption, which depends on the aircraft type, can be performed.

Here is an overview of the study methodology. First, we set a target area extending further from the PMS, around 170 nm from Haneda Airport, which is the airport with PMS introduction, and use pre-PMS actual radar data to analyze the traffic flow in the target area. Next, based on the adjustment time (potential absorbed delay) that can be achieved by TBFM and PMS, we adjust the flight time in the target area. Flight trajectories with such post-TBFM and PMS adjustment times are simulated using actual past data to achieve high fidelity simulation. Next, the changes in flight path due to the time adjustment are analyzed. The metrics used are 1) flight distance, 2) number of heading changes (used as an indicator of ATC workload) and 3) fuel consumption. Examining the changes in these three metrics allows us to evaluate the effects of TBFM and PMS on air traffic flow. Note that no data after the PMS introduction is available, so the proposed analysis uses flight track data prior to the PMS. It is true that comparing pre-PMS data and post-PMS data is a straightforward method to analyze the PMS. However, post-PMS data can be only obtained after PMS is introduced. When considering the potential introduction of PMS, it is important to analyze the effect of PMS using only pre-PMS data and simulating the new arrival control initiative. Therefore, this study proposes a method for pre-introduction PMS analysis which can help decision-makers to evaluate potential benefits and limitations. This study is not focused on the PMS structure itself, but rather on the overall effect PMS will have on the arrival traffic flow. Therefore, we do not perform detailed analysis of PMS path and airspace around the PMS area, but investigate the flight time that can be adjusted by the PMS route.

The rest of the paper is organized as follows. In Section 2, we show more detail about PMS. Section 3 discusses the research methodology and data used in the analysis. The next Section 4 explain the simulation model, and section 5 presents the results and discussions. The paper is summarized in Section 6.

2. Current Air Traffic Control - Point Merge System (PMS)

Point Merge System (PMS) is an inbound flight flow control method developed by the EUROCONTROL Experimental Centre (EEC) in 2006 [8]. Details about PMS are explained with reference to Figure 1.

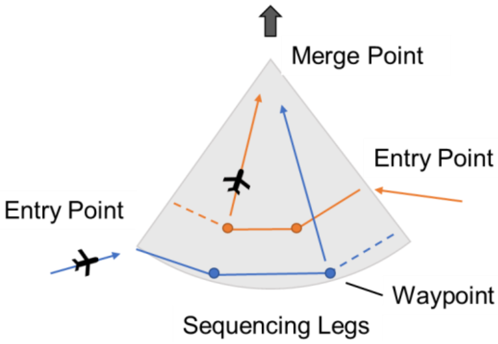


Figure 1 – PMS conceptual operations.

PMS is a control operation method that uses a predetermined arc-shaped routes. Aircraft entering from the entry point fly on an arc-shaped path called Sequence Legs. While flying the sequence legs, flights change their heading and proceed to the merge point from one of the waypoints set on the sequence legs when the separation from the previous aircraft is secured. In this way, PMS enables systematic control using a fixed route. The controller does not have to give the heading change instruction as frequently as they used to with tactical vectoring, but only needs to instruct which waypoint to start the diversion to the merge point, which is expected to reduce the burden on both the controllers and the pilots.

3. Research Methodology

3.1 Flight Data

CARATS Open Data is used in this analysis. CARATS Open Data is actual flight track data provided by the Civil Aviation Bureau, consisting of pseudo flight number, aircraft type, latitude, longitude and altitude data recorded every 10 seconds, on average. Note that this data is available at least two years after it is recorded. Therefore, although PMS was already introduced at Haneda Airport in 2019, the data cannot be used at the time of writing this paper, so the analysis is performed using the data before 2019, i.e. no-PMS data. More detail about CARATS Open Data is shown in Ref [13].

3.2 Target Flights

This research focuses on Haneda Airport, one of the busiest airports worldwide [14], which introduced PMS in 2019. About 70% of all Haneda arrivals come from the west or south, and most of these are frequently vectored. Therefore, we focus the analysis on west arrivals. As shown in Figure 2, Haneda airport has four runways, operated differently depending on the wind conditions [15]. Under general operation, arrival aircraft use runways 34L and 34R in north wind conditions, with aircraft coming from west and south being mainly assigned to RWY34L. Therefore, we limit the target flights of this study to flights departing from Fukuoka Airport and landing at Haneda Airport RWY34L. Fukuoka-Haneda route is one of the busiest routes in Japan, and flights there are frequently vectored. In addition, we limit the investigation scope to one aircraft type of twin-aisle airliner. There are two reasons why we limit the investigation scope. First, this increases the fidelity of route replacement. If there are differences in flight altitude and cruising speed selection for each aircraft type, the fidelity of route replacement will be reduced by replacing routes among different aircraft types. The second reason is to enable fuel consumption evaluation. Fuel consumption depends on the performance of the aircraft. To evaluate the fuel consumption before and after the route replacement, the same aircraft should be targeted. In addition, only flights that pass the waypoint ARLON when approaching the runway are selected. The number of target flights is 117, and their trajectories are shown in Figure 3.

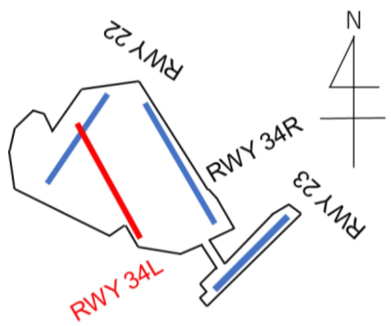


Figure 2 – Four runways at Haneda Airport.

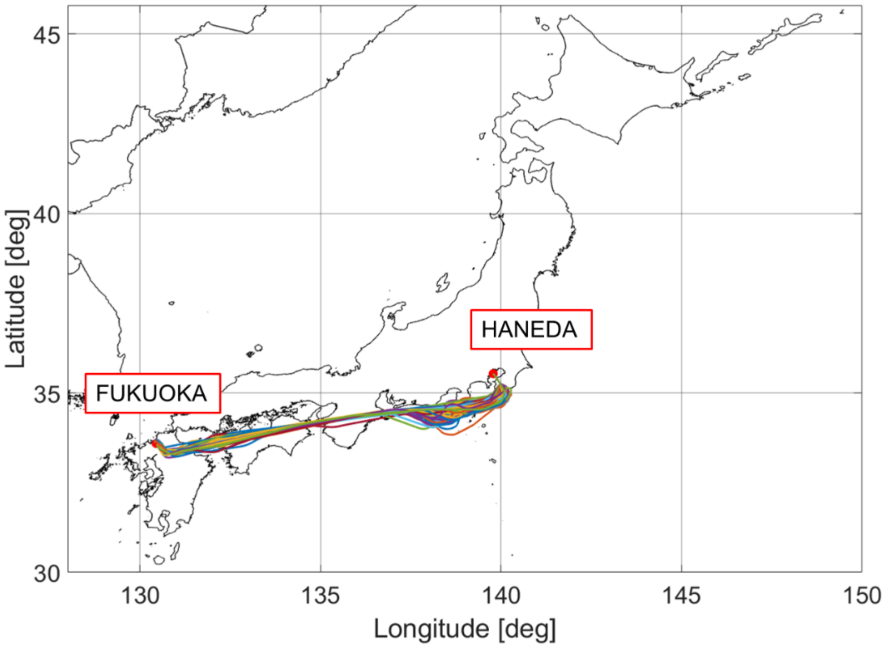


Figure 3 – The trajectories of Fukuoka - Haneda target flights.

3.3 Target Analysis Days

The target flights in this research depart from Fukuoka Airport and land on Haneda Airport RWY34L. Since RWY34L is mainly used by inbound flights in north wind condition, we chose days when north wind was predominant throughout the day as analysis target day of this study.

Among CARATS Open Data days, the days used in this study are as follows, and contain 29763 flights in total. The value written in parentheses is the number of target flights on each day.

2015/11/13 (24), 2015/11/14 (25), 2016/1/11 (15),

2016/1/13 (6), 2016/3/11 (17), 2016/3/12 (14),

2016/3/13 (16).

3.4 Target Area

In this study, we defined target area. The target area is defined to assess the effect of time adjustments on the flight path. As discussed in Section 3.2, west and south inbound flights are vectored frequently. Our research focuses on this vectoring, so defining target area correctly is important. We defined two circles centered on waypoint ARLON which is often used by RWY34L arrivals. The first circle has a radius of 170 nm and the other has a radius of 43 nm, defined by the distance from ARLON to OSHIMA. Here, OSHIMA is the waypoint which can be considered as feeding (entry) waypoint to arrival route to RWY34L. The donut-shaped area defined by these two circles is the target area for our analysis (referred below as V area). Here, the value of 170 nm is set so that vectored trajectories of flights from Fukuoka Airport are included in the V area. The V area is shown in Figure 4.

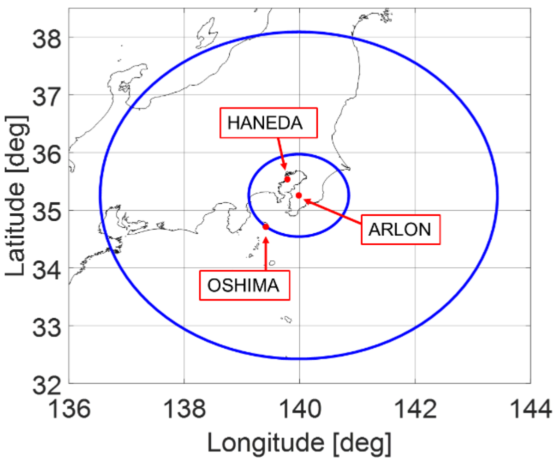


Figure 4 – Target airspace is the donut-shaped airspace defined by both blue circles.

3.5 Meteorological Data

For incorporating the effect of wind conditions on flight, we used Meso Scale Model (MSM) provided by Japan Meteorological Agency. The MSM data[1] is a numerical weather prediction data published every three hours, and the data consists of atmospheric properties such as east-west wind, north-south wind, altitude and temperature on three-dimensional grid. The covering region is from 22.4N to 47.6N and 120E to 150E, and the resolution is 0.1 in latitude direction and 0.125 in longitude direction. The atmospheric properties are published at barometric altitude 1000, 975, 950, 925, 900, 850, 800, 700, 600, 500, 400, 300, 250, 200, 150 and 100hPa for each lateral grid. We can calculate the airspeed from CARATS Open Data and MSM data.

3.6 Aircraft Performance Model

Base of Aircraft Data (BADA) model Family 3.15 is used to calculate the fuel consumption. BADA is the aircraft performance model developed by EUROCONTROL [16]. It consists of various information related to the operation of almost all types of aircraft, such as atmospheric model, total-energy model and concrete parameters necessary for calculating aircraft performance.

3.7 Parameters

3.7.1 Flight Distance

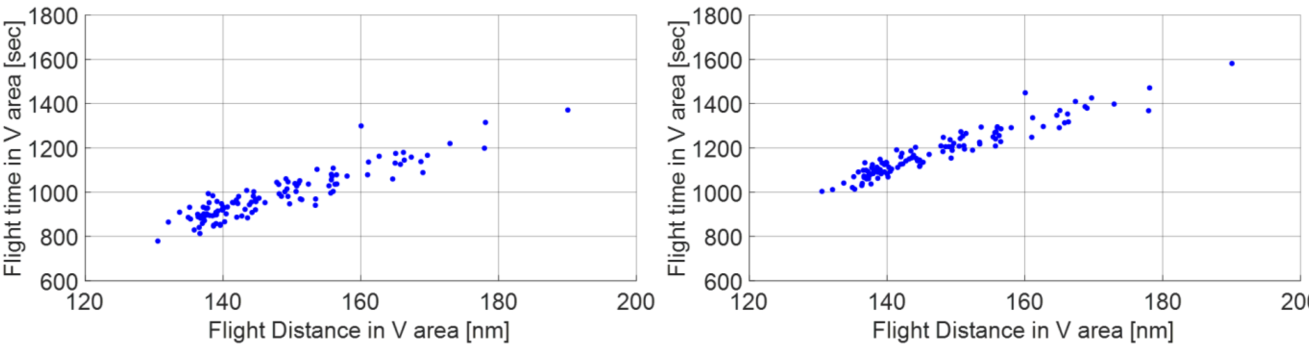
Flight distance is used as a metric to evaluate the effect of TBFM and PMS on the flight path. In this study, we evaluate the lateral (latitude and longitude) flight distance. That is, the change in altitude is not included in the flight distance.

3.7.2 Flight Time

In this study, we used two kind of flight time, flight time in V area and PMS path flight time. The definition of each flight time is explained below.

- Flight time in V area.

  This flight time is used as a key-parameter to replace the trajectories in V area after time adjustment, and is calculated based on the time of entry into V area and the time at which the flight left V area. To increase the fidelity of trajectory replacement among different dates, we calculated flight time considering the wind speed, which means that this flight time is the time excluding the effects of wind, which varies depending on the time or date. From the CARATS Open Data, the ground speed between each recorded plot can be calculated. The airspeed is calculated from the obtained ground speed and the wind speed which can be obtained from MSM data. The flight time without the effects of wind differences is calculated by dividing the distance between the plots recorded in the CARATS Open Data by the obtained airspeed. The differences in flight time before and after considering wind condition is shown in Figure 5. The value written in parentheses is correlation coefficient. From Figure 5, the correlation coefficient between flight distance and flight time change to high by considering wind condition. This means that the validity of route replacement based on flight time is increased.



(a) Without considering wind. (0.919) (b) Considering Wind. (0.956)

Figure 5 – The relationship between flight distance and flight time in V area.

[1]These data were collected and distributed by Research Institute for Sustainable Humanosphere, Kyoto University (http://database.rish.kyoto-u.ac.jp/index-e.html).

- Reference flight time when flying the PMS path.

  This flight time is a reference time assuming when flying the PMS path described in Aeronautical Information Publication (AIP), and is calculated from the speed and path shown on the standard arrival chart in the AIP. In this research, we used a part of OSHIMA 1A ARRIVAL as PMS path. The target part of OSHIMA 1A ARRIVAL and the information of it is shown in Figure 6 and Table 1, respectively. Please note that unlike the flight time in V area, actual flight data is not used. Although the flight time in V area is calculated by considering the wind condition of each target days, this flight time is calculated without considering wind condition. Here, the speed described in AIP is Indicated Airspeed (IAS). The True Airspeed (TAS) required to calculate the flight time is calculated using the CAS/TAS conversion formula described in the BADA model, and assumed no-wind standard atmosphere. Differences between IAS and CAS values are ignored. More detailed analysis considering wind condition is future work.

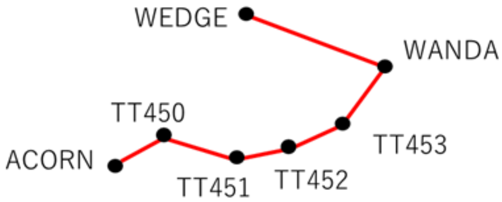


Figure 6 – A part of OSHIMA 1A ARRIVAL.

Table 1 – The Information of a part of OSHIMA 1A ARRIVAL.

Waypoint	Location	Altitude [ft]	Speed [KIAS]
ACORN	345028.2N / 1394146.7E	13000	230
TT450	345254.0N / 1394706.0E	-	-
TT451	345016.8N / 1395734.3E	-	-
TT452	345113.2N / 1400600.1E	-	-
TT453	345438.5N / 1401325.9E	-	-
WANDA	350155.3N / 1401954.1E	13000	230
WEDGE	350900.4N / 1395846.5E	8000	-

3.7.3 Heading Changes

The potential effects of TFBM and PMS are not only in reduced flight time and flight distance but also in reduced ATC workload. ATC workload evaluation is complicated and depends on the number of instructions given to the aircraft by the controller. Instructions include altitude change, speed change, heading change, and information provision [17]. In this study, we focus on the number of heading changes, based on the feedback of a veteran pilot, who advised on correlation between the number of ATC heading change instructions and the number of heading changes observed in flight track data. Although the number of heading changes is not sufficient to totally assess the controller's workload, it is a necessary parameter. More metrics will be added in future research. The method to calculate the number of heading changes is as follows.

1) Conduct a 7-point moving average smooth to remove position errors and fluctuations in the original CARATS Open Data.
2) Calculate the 10-second rate of change of the angle from each 10 seconds plots of data by inner product.
3) Extract the starting and ending points of heading changes.
   The extraction conditions are as follows.
   i. The 10-sedonds rate of change in angle crosses $\pm$0.5 degree.
   ii. The sign of the 10-seconds rate of changes in angle crosses in angle changes.
4) Sum the 10-second rate of change of the angle from starting to ending point to get the total degree of each heading changes.
5) Define the number of heading changes as the number of times that a given threshold, which is $\pm$8 degree in this study, is exceeded.

An example of heading changes count is shown in Figure 7 and Figure 8, and suggests that heading changes can be effectively detected. In addition, the relationship between the number of heading changes, flight time and flight distance is shown in Figure 9. Note that the difference in flight time used in Figure 9 means the difference in flight time between the shortest flight time and each flight time. Figure 9 shows that as the flight time and flight distance increase, the number of heading tends to increase.

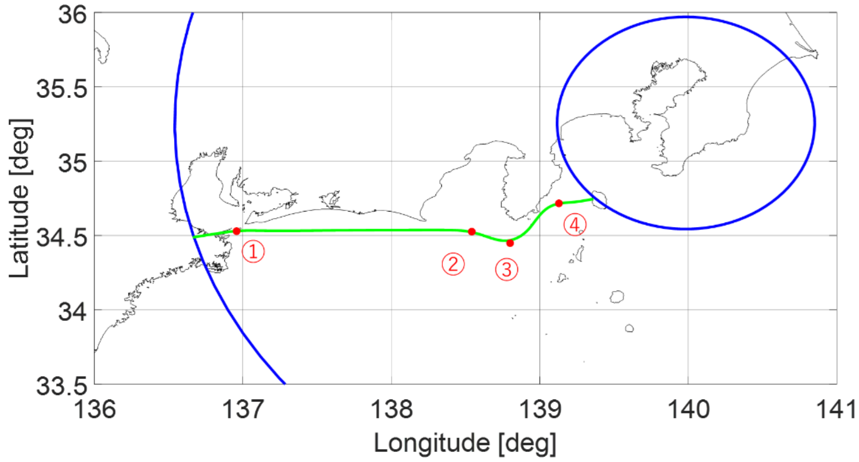
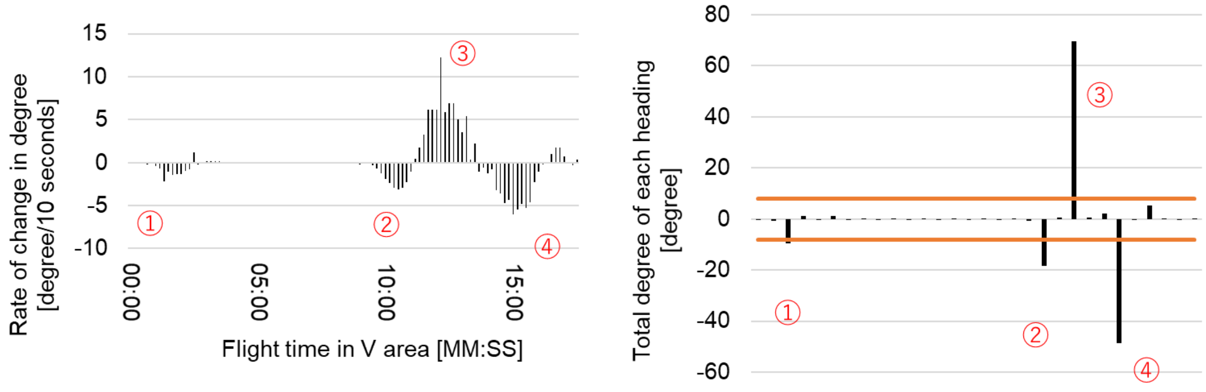


Figure 7 – Plot of CARATS Open Data.



(a) Rate of changes in degree. (b) Toral degree of each heading

Figure 8 – The example of calculation of degree.

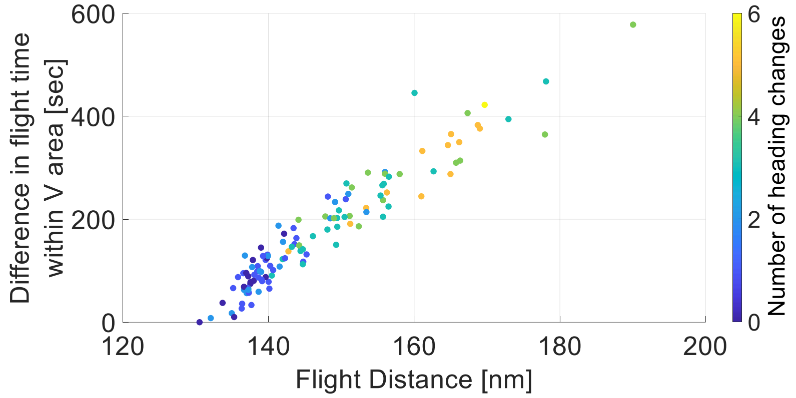


Figure 9 – The relationship between flight distance, flight time and number of heading changes.

3.7.4 Fuel consumption

Figure 10 shows true airspeed and the parameters involved in the movement of the aircraft.

In Figure 10, Thr is thrust; L is lift; D is drag; V_{TAS} is the true airspeed; and Mg_0 is the gravity applied to the aircraft. From the relationship of energy, the following equation is obtained:

$$(Thr - D)V_{TAS} = Mg_0 \frac{dh}{dt} + MV_{TAS} \frac{dV_{TAS}}{dt} \quad (1)$$

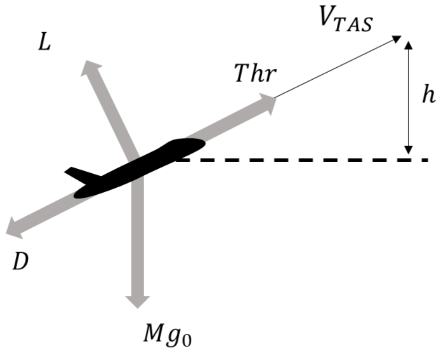


Figure 10 – Thrust, lift, drag, gravity and true airspeed.

D can be calculated from the equation written in BADA model. V_{TAS} can be obtained from CARATS Open Data and MSM data. Therefore, Thr can obtained from (1). From the Thr and equations written in BADA, fuel consumption can be obtained. The BADA model defines the formulas and values for each flight phase, which is the takeoff, cruising, and landing. In this study, these phases are defined only from the altitude changes of CARATS Open Data. The example of extraction of the change point in each phase is shown in Figure 11. In Figure 11, the red vertical line means the start and end point of cruise, and the blue vertical line means the boundary of V area. In calculation, whether flaps were used or not and the bank angle are ignored. Furthermore, we used 18-point moving average to V_{TAS} to smoothen the data. Although the fuel consumption is calculated from the first recorded point in radar data to the outflow point from V area, the fuel consumption used for analysis is the value only in the V area.

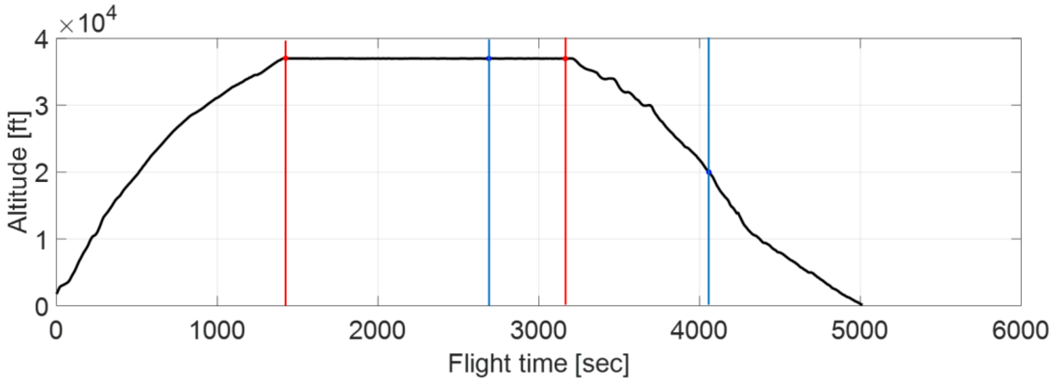
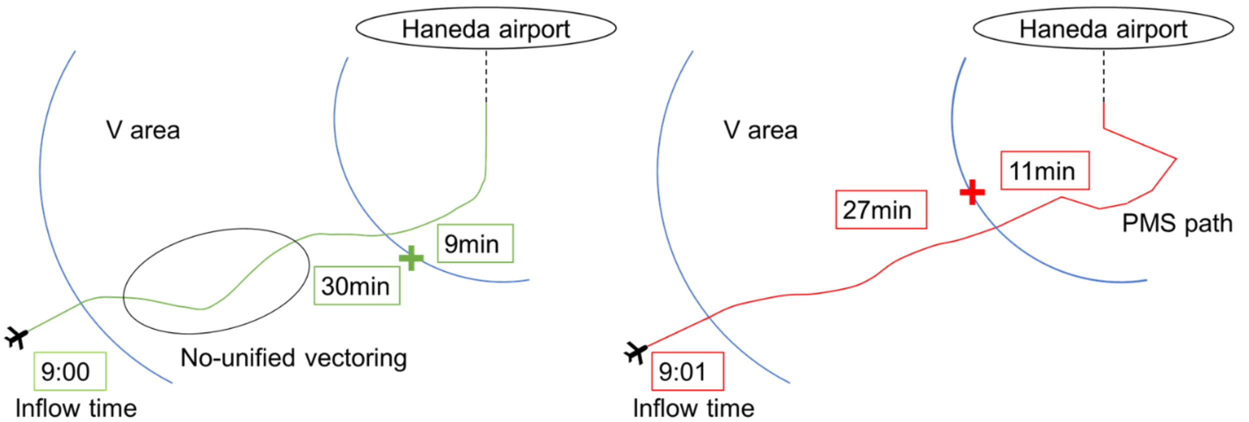


Figure 11 – Example of extraction of start and end of cruise phase.

4. Simulation Model

In this analysis, we performed a simulation to evaluate the potential benefits of time-based flow management (TBFM) and point merge system (PMS).

4.1 The concept of time adjustment assuming TBFM and PMS



(a) Trajectory example under no time adjustment (b) Trajectory example under time adjustment

Figure 12 – Time adjustment by TBFM and PMS.

As shown in Figure 7, the target flights of this study are time-adjusted by vectoring in V area. Effective execution of TBFM and PMS can lead to replace a part of adjustment time by tactical vectoring, which was previously performed by the controller, to adjustment time by velocity control before V area and procedural path-extension over the PMS path, as shown in Figure 12. Note that the value written in Figure 12 is not actual flight time but is shown to illustrate the concept only.

4.2 Time Adjustment

4.2.1 Adjustable Time by TBFM

The adjustable flight time during cruising may vary depending on the flight distance of the flight. When the flight distance is long, it is possible to issue time adjustment instructions at an early timing. According to references [18], in Japan air space (Fukuoka Flight Information Region), for most flights the maximum achievable delay is 2-3 minutes. Since the target flights of this study is the domestic flight and the adjustable flight time must be the value adjustable before entering the V area, we defined adjustable flight time by TBFM $\Delta T_{TBFM} \leq 100$ [sec].

4.2.2 Adjustment Time by PMS

The estimated flight time assuming when aircraft pass the PMS path is shown in Table 2. The calculation method is explained in section 3.7.2 and the name of waypoint in each PMS route is shown in Figure 6. From this result, we can say that the OSHIMA 1A ARRIVAL can adjust the time up to about 420 seconds. However, this value cannot be used as an adjustable flight time by PMS. As shown in Figure 13, there are routes close to the PMS path in the current operation. This means that the additional adjustable time for the current flights by PMS is expected to be less than 420 [sec]. Therefore, in this study, we assumed that the time adjustment by PMS is performed only route number k to k+1, that is, the flight time that can be adjusted by PMS ΔT_{PMS} is defined as $T_{k+1} - T_k$ for all aircraft. Since the average value of $T_{k+1} - T_k$ obtained from Table 2 is about 100 [sec], we defined the adjustment time ΔT_{PMS} = 100 [sec] for all aircraft. It is necessary to consider the influence of wind for more detailed analysis of the adjustable time by the PMS and for calculation of the adjustment time that differs for each flight. More detailed analysis is future work.

Table 2 – PMS path and the estimated flight time.

Route number k	Route	Estimated flight time T_k [sec]
1	ACORN TT450 WEDGE	317.3
2	ACORN TT450 TT451 WEDGE	434.3
3	ACORN TT450 TT451 TT452 WEDGE	525.0
4	ACORN TT450 TT451 TT452 TT453 WEDGE	615.4
5	ACORN TT450 TT451 TT452 TT453 WANDA WEDGE	731.9

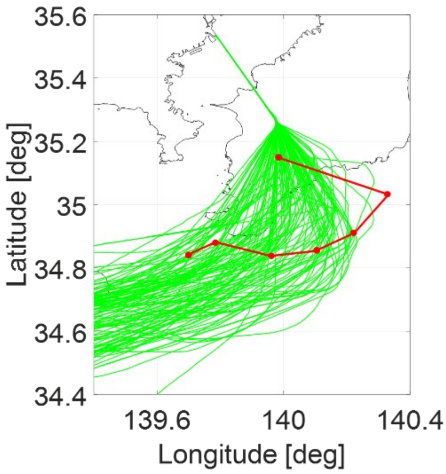


Figure 13 – A pat of OSHIMA 1A ARRIVAL and the trajectories of target flights.

4.2.3 Total adjustment time

The total adjustment time ΔT_{total} is defined from $\Delta T_{TBFM} + \Delta T_{PMS} \leq 200$ [sec]. In this research, we used three total adjustment time 60, 120 and 180 [sec].

4.3 Trajectory Definition After Time Adjustment

To evaluate the reduction of heading changes due to trajectory changes before and after time adjustment, it is necessary to define trajectories after time adjustment, i.e. TBFM-PMS trajectories. In this research, we defined TBFM-PMS trajectories by replacement among actual trajectories. The way of replacement is as follows. Note that the flight time shown below are the flight time calculated considering wind.

1) Calculate the flight time within V area T_i by summing the flight time, which is calculated considering the wind speed, between each plot of radar data from entering the V area to exiting. The minimum value of the flight time within V area is defined as T_{min}.
2) Subtract ΔT_{total} as the temporary adjustment time due to TBFM and PMS from the flight time in the V area.
3) Calculate the flight time within V area after the temporary time adjustment, $T_i^{'}$.

$$T_i^{'} = \begin{cases} T_i - \Delta T_{total} & (if\ T_i - \Delta T_{total} \geq T_{min}) \\ T_{min} & (if\ T_i - \Delta T_{total} \leq T_{min}) \end{cases}. \quad (2)$$

From T_i and T_i', actual adjusted time ΔT_i can be calculated.

4) Calculate the difference between the adjustment flight time and other airplane's original flight time.

$$|T_i^{'} - T_j| (j = 1,2 \dots i-1, i+1 \dots N) \quad (3)$$

For example, when we search the trajectory of Flight No.1 after time adjustment, we calculate as follows:

$$|T_1^{'} - T_j| \quad (j = 2,3 \dots N). \quad (4)$$

5) The trajectory of flight number i is replaced by the path of subscription j that gives the minimum value of $|T_i^{'} - T_j|$.

By using the method of replacing flight paths, it is possible to define routes that require vectoring even after time adjustment. The example when the adjustment time is 180 seconds is shown in Figure 14. In Figure 14, the green dotted line is an original path and the red line is a path after replacement.

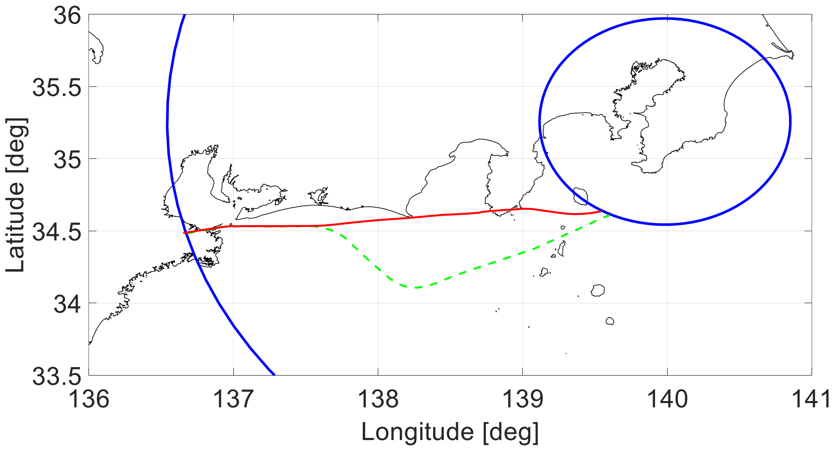
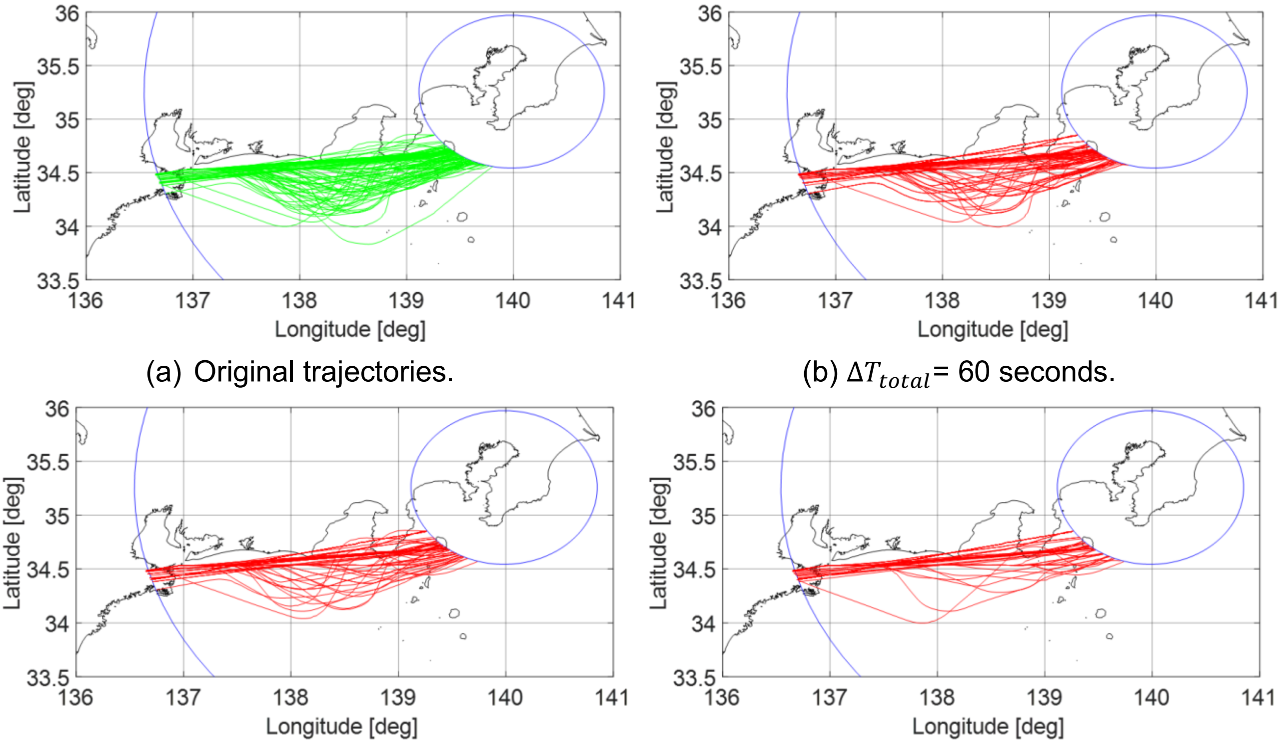


Figure 14 – Sample trajectory replacement.

5. Results

5.1 Trajectories

Figure 15 shows the result of trajectories replacement before and after time adjustment by TBFM and PMS.



(a) Original trajectories. (b) ΔT_{total}= 60 seconds.

(c) ΔT_{total}= 120 seconds. (d) ΔT_{total}= 180 seconds.

Figure 15 – The trajectories after time adjustment.

From Figure 15 (a) and (d), it can be said that the trajectories are significantly straightened, i.e. the number of heading changes and tactical vectoring have both been significantly reduced. This means that the value of adjustment time, 180 seconds, has a huge effect on flight time in V area. However, in (d), there are still some that are not replaced with the route with the shortest flight time. This means that if the aircraft flies at actual operating speed, it will be difficult to eliminate all vectoring with a 180 seconds adjustment time.

5.2 Flight Distance

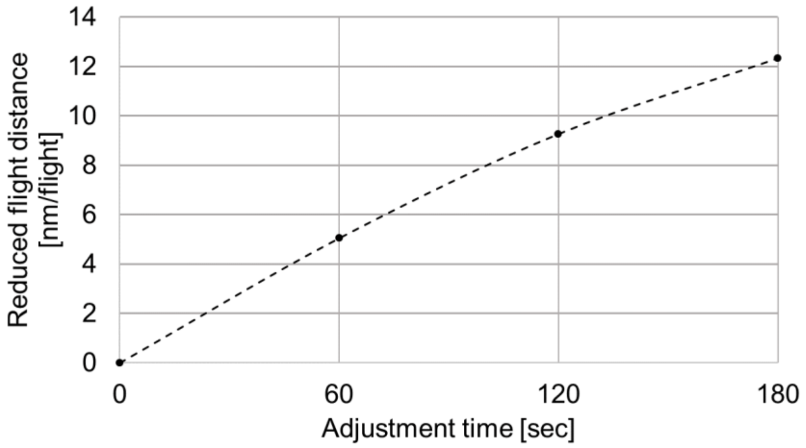


Figure 16 – Reduced flight distance.

Figure 16 shows the result of the reduced flight distance of each flight after time adjustment of TBFM and PMS. From Figure 16, the flight distance in V area can be reduced due to time adjustment. This result is seen as plausible judging from the flight path changes shown in Figure 15.

5.3 Heading Changes

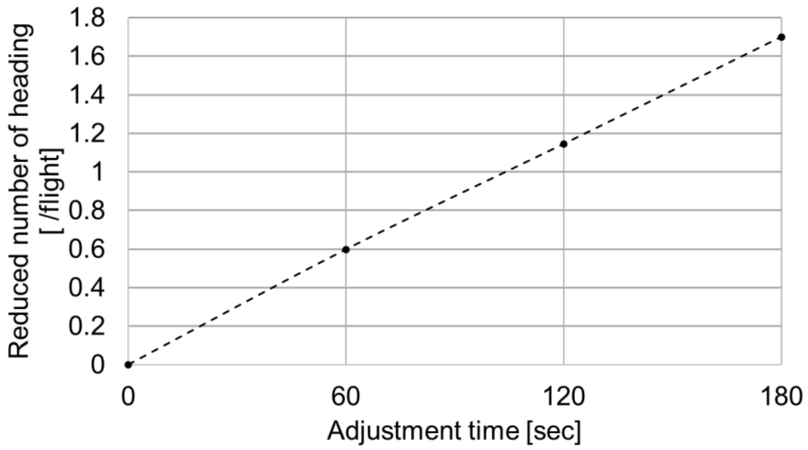


Figure 17 – Reduced number of heading changes.

The reduced number of heading changes is shown in Figure 17. The result shows that the number of heading changes can be reduced when time adjustment is conducted. This result is also supported by the relationship between the flight time, flight distance and the number of heading changes shown in Figure 9 and the profiles of trajectories changes shown in Figure 15. As stated in past research [17], among the control instructions related to the maneuver of the aircraft, the heading change instruction causes relatively high ATC workload. Although the number of heading changes is only one factor, it can be concluded that ATC workload can be potentially reduced due to time adjustment operations from this result.

5.4 Fuel Consumption

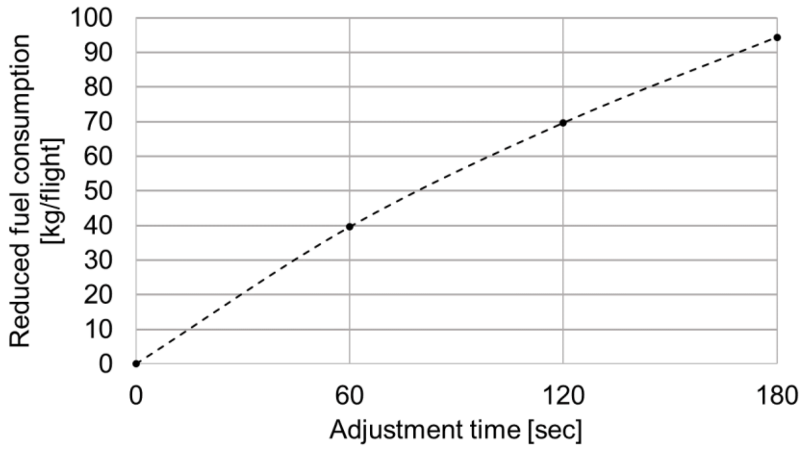


Figure 18 – Reduced fuel consumption.

Figure 18 shows the reduced fuel consumption before and after time adjustment. The result is that fuel consumption decreases as well as the flight distance and the number of heading changes. In this study, the fuel consumption was calculated using the route and speed obtained from the actual flight data. Therefore, the results obtained from this analysis are considered to be a more consideration of actual operations. In addition, by defining the flight path after time adjustment by replacement, it was possible to perform analysis including the path having vectoring and to wider length of flight time.

6. Concluding Remarks

In this study, the number of heading changes was used as an metric to quantitatively evaluate the heading instructions which relate to ATC workload. In addition, the time was adjusted assuming TBFM and PMS, and the route after time adjustment was defined by replacing the route. As a result, the flight distance, the number of heading changes and the fuel consumption within the target area decreased due to the time adjustment. The route replacement method used in this study can be used to verify the effect of time adjustment not only on the linear optimum trajectory but also on the trajectory with vectoring that is performed in actual operation. In terms of being able to do it, it can be said that the method will lead to a wider time range of analysis. In addition, the number of heading changes used in this analysis can become useful as a first stage for proposing a method for quantitatively evaluating the burden on the controller from the actual route. On the other hand, it is difficult to evaluate all the workload of the controller only from the index of the number of heading changes, and it is necessary to revise the evaluation index. Also, regarding the time adjustment by PMS, it is necessary to consider the wind of the target day and perform a more appropriate analysis by minimizing the difference between the analysis assumption and the environment of actual operation. The flight data under the PMS operation after 2019 will be published after 2021. By using the flight data as a reference data, the effect of introducing PMS can be estimated more accurately from the data before the introduction of PMS.

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