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Feasibility Study of Free routing Airspace Operation over the North Pacific Airspace

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Abstract— **A fast-time simulation study was conducted to examine the expansion of flexible track operations into the area occupied by the five NOPAC (North PACific) Air Traffic Service (ATS) routes, an area of high traffic demand. In this study, User-preferred routes (UPR) were created in a proposed NOPAC Free Route Airspace (FRA) area, in which airspace users (AU) may design routes with few constraints, and compared with current fixed NOPAC route structure by fast-time simulation. To reflect the effect of daily and seasonal wind variations, a clustering analysis approach was applied to select representative wind conditions for flight route generation. Fuel burn was used to evaluate the effect of the NOPAC FRA on the efficiency of flight operations, and Potential Loss of Separation (PLOS) was examined for three minimum lateral separations to evaluate the effects of Communication, Navigation and Surveillance (CNS) performance on airspace capacity and Air Traffic Control (ATC) workload. The simulation results show a trend of increased efficiency of individual NOPAC FRA flight routes and reduced overall PLOS time. This indicates that a NOPAC FRA could improve capacity and efficiency while maintaining or increasing safety.**

Keywords- free route airspace; flexible tracks; oceanic air traffic control; airspace design; air traffic management; machine learning; clustering

I. INTRODUCTION

The demand for air transportation between Asia and other regions has been increasing rapidly as a result of economic growth. As traffic increases, it is important to expand air traffic management (ATM) system capacity to avoid delay while promoting efficient traffic flows to mitigate environmental impact and maintaining an acceptable level of safety. North Pacific oceanic airspace includes five parallel Air Traffic Service (ATS) routes called NOPAC (North PACific) that connect the Anchorage Oceanic Flight Information Region (FIR) and Fukuoka FIR. These high-demand routes for flights between Asia and North America were established in the 1980s, and while the composition of the routes has not changed significantly since then, the applicable separation standards and traffic demand have changed. Traffic forecasts for the Asia-Pacific region predict high demand [1], and so more flights are expected to use the NOPAC airspace. Although air traffic declined sharply in 2020 due to the COVID-19 pandemic (which is still ongoing), and the International Air Transport Association (IATA) forecasts that for international passenger flights in particular, recovery will be slower than for domestic flights [2], the demand for cargo flights was not as badly affected [3] and the NOPAC airspace is especially utilized by cargo flights between the Anchorage cargo hub and Asia. The Asia-Pacific region also has a high proportion of the world's passenger flights, accounting for 34.6% of the global total (converted using RPKs: revenue passenger kilometres) in May of 2020 [4]. In view of these trends, it should be assumed that air traffic demand will recover to the same levels as before COVID-19 or increase still further, and airspace should be strategically designed to increase capacity and efficiency leveraging improvements in the performance of Communication, Navigation and Surveillance/Air Traffic Management (CNS/ATM).

To achieve this, the International Civil Aviation Organization (ICAO) has indicated the introduction of ATM system upgrades supported by technologies such as satellite-based CNS/ATM [5]. The introduction of Automatic Dependent Surveillance-Contract (ADS-C) using satellite navigation and communication has dramatically improved the frequency and accuracy of aircraft position reports in areas outside VHF voice communication and radar surveillance coverage. In addition, satellite-based positioning has made area navigation (RNAV) more common and improved the navigation accuracy of individual aircraft. Increased CNS performance enables the required separation between aircraft in non-radar airspaces to be reduced [6 - 8], and further reductions in separation, potentially to similar to that in a radar-controlled environment, may be possible by increasing surveillance update rates from minutes to seconds by means such as space-based ADS-Broadcast (ADS-B) [9, 10]. Moreover, increased CNS performance gives greater potential for user-preferred route (UPR) operation. In airspace with poor CNS performance, aircraft are largely confined to fixed airways or to flexible tracks designed to ensure safe separation using procedural control methods. Improved CNS performance can reduce the need for such ATM constraints, allowing operators to plan routes more freely.

We have been researching the introduction of the concept of Free Route Airspace (FRA) developed by EUROCONTROL [11] into the Asia/Pacific region [12]. In this paper, we examine the potential of NOPAC FRA operation and greater CNS performance in oceanic airspace by simulating traffic flows to estimate their effects on capacity, efficiency and safety, and to clarify problems that introducing them will entail.

Since flight plan routes in oceanic airspace are affected by daily and seasonal wind variations, it is necessary to take these variations into account. However, simulating all wind patterns over the course of a year or several years would be laborious. In previous studies, e.g. [12], we have attempted to select a small number of representative days from a year but this may not be sufficient to reflect the range of wind conditions typically encountered in operations. In this study, we selected representative wind cases by applying a clustering analysis method to 7 years of historical PACOTS (Pacific Organized Track System) [13] track data, which reflect the underlying winds aloft at typical cruise flight levels.

ATM system changes should be evaluated from the standpoints of benefit to airspace users (AU) and impact on air navigation service providers (ANSPs), and appropriate metrics selected. For metrics, we referred to studies conducted upon the introduction of FRAs in Europe. The introduction of FRAs in Europe was motivated by the desire to reduce the waste caused by discrepancies between planned and actual flown trajectories as revealed by EUROCONTROL's 2002 study [14]. Although this motive differs from that of our NOPAC FRA proposal, the processes of evaluation through fast-time simulation and real-time simulation [15, 16] used are valid for our study. As a measure of AU benefit, we focused on overall fuel consumption. This was calculated by fast-time simulations of wind-optimal flight routes created from a traffic demand scenario in both the current airspace/route configuration and the proposed NOPAC FRA. Regarding ANSP metrics we are concerned primarily with airspace safety (which affects capacity) and efficiency, and we adopted Potential of Loss of Separation (PLOS), which has been used a metric of airspace safety in a European FRA evaluation [17]. In fast-time simulations, we assume that each PLOS instance will require an intervention that increases air traffic controller workload and can therefore be correlated with airspace capacity. Because the target airspace is non-radar-controlled and several performance-based separation standards [6, 7] are applied depending on aircraft CNS performance, we calculated not only the number of PLOSs but also the time of persistence of subsequent separation losses (e.g. due to slowly converting or diverging tracks) as PLOS time. PLOS can also be considered as an AU metric related to flight efficiency. In non-radar-controlled airspace, level changes are frequently used for conflict resolution when a PLOS occurs. For long-haul flights, the planned cruising altitude is selected for greatest flight efficiency, so a long PLOS time means a need to fly at non-optimal altitude for long period.

The structure of this paper is as follows. Section 2 gives an overview of the traffic flow in the target airspace, and the simulation method. Section 3 describes the results of the simulation. We discuss the results in section 4 and conclude the paper in section 5.

II. TRAFFIC FLOW OUTLINE AND SIMULATION METHODS

A. *Study Objectives, Design and Limitations*

This fast-time simulation study compares flight efficiency and airspace safety metrics of traffic flows between a baseline scenario that reflects the current NOPAC ATS route structure and a proposed NOPAC FRA in which the ATS routes are eliminated, to evaluate NOPAC FRA effectiveness. In addition, the effect of different levels of CNS performance on airspace capacity is examined.

Table I shows the simulation variables and levels. Two airspace/route configurations were evaluated: a configuration with the current NOPAC ATS routes (baseline) and a configuration with the NOPAC routes deleted and free routing extended from the Central Pacific (CENPAC) area to the NOPAC area (NOPAC FRA). A traffic demand model (flight schedule) of flights through the target airspace was created based on actual flight plans on a high demand day. To reflect daily and season wind variations, *N* representative wind patterns were selected using a clustering analysis. For each airspace configuration and wind pattern (plus a no-wind condition), minimum time flight routes were generated from the flight schedule. Fast-time simulation was then used to create flight trajectories unconstrained by ATM or Air Traffic Control (ATC) interventions. To reduce dependency of the results on the demand model, the departure times in the model were perturbed randomly to create 5 additional scenarios in the fast-time simulation.

Performance-based separation standards are applied in the North Pacific oceanic airspaces of Fukuoka FIR, Oakland Oceanic FIR and Anchorage Oceanic FIR [6, 7]. The horizontal separation standard applied between a pair of aircraft varies depending on their CNS capabilities. In this study, we considered 50 NM and 30 NM as these are the most common separations currently applied in the North Pacific Ocean airspace, reflecting separations between pairs of FANS-1/A (Future Air Navigation System-1/A) RNAV10-capable aircraft and PBCS (Performance-Based Communication and Surveillance)-capable aircraft, respectively. A lateral separation of 15 NM was also considered assuming further reduction of horizontal separation due to the introduction of space-based ADS-B in the future.

TABLE I. STUDY VARIABLES AND LEVELS

Variable	No. of levels	Levels
Airspace configuration	2	Baseline (current NOPAC ATS routes) NOPAC FRA (free route design based on a regular lat/lon waypoint grid)
Wind condition	1 + *N*	No wind Wind conditions reflecting daily/seasonal variation, *N* was determined by clustering.
Traffic scenario (departure time)	6	Baseline scenario: All flights depart on schedule 5 random perturbations of flight departure time
Minimum applicable horizontal separation	3	50NM (ADS-C, RNAV10) 30NM (PBCS) 15NM (Space-based ADS-B)

B. *Flight Operations in North Pacific Airspace*

Fig. 1 shows a simplified map of the North Pacific Ocean area of interest in this analysis. The airspace consists of CENPAC airspace, in which the PACOTS flexible track system is in operation, and NOPAC airspace with five parallel ATS routes. The PACOTS consists of flexible routes that are designed and published daily by the Federal Aviation Administration (FAA) and Japan Civil Aviation Bureau (JCAB) considering the winds aloft, and there are no fixed ATS routes between Asia and North America in this region. The PACOTS tracks are designed to connect "gateway points" on the Fukuoka FIR side and Oakland Oceanic FIR side, and may partially overlap with NOPAC ATS routes.

In this paper, we define the "NOPAC area" as the area of non-radar-controlled airspace occupied by the five parallel NOPAC ATS routes, with the Russian Federation airspace boundary (parallel to R220) and east of the southmost NOPAC route (G344) including a buffer space, as its lateral bounds. This is a narrow airspace compared to CENPAC, but has high demand, with nearly half of all North America-Asia traffic flying through it. Its demand is relatively high throughout the year despite the variations in flight plan routes caused by day-to-day and seasonal changes in wind conditions. Table II shows total numbers of flights through the NOPAC and CENPAC areas in 2019, based on flight plans through the Fukuoka FIR and targeting trans-North Pacific flights to and from North America (i.e. flights between Asia and aerodrome ICAO designators with the prefixes PA (Alaska), C (Canada), K (Contiguous United States: CONUS), M (Mexico), and PH (Hawaii)). Cargo flights between Anchorage and Asia form a significant proportion of NOPAC traffic (33% of NOPAC flights in the 2019 were from / to Anchorage). Depending on the wind conditions, some westbound traffic operates north of the NOPAC airspace through the Magadan West, Petropavlovsk-Kamchatski and Khabarovsk FIRs, but this traffic is outside the scope of this study, which targets only the NOPAC area.

C. *Traffic Demand Scenario*

A traffic demand scenario was created based on flight plans of scheduled and non-scheduled general air traffic between Asia and North America filed through Fukuoka FIR on a day with the highest traffic volume in Fukuoka FIR oceanic airspace. In the scenario, a total of 451 flights between 178 city pairs departed from their origin airports between 0500 UTC of day 1 and 1400 UTC of day 2 of the simulation (33 hours).

For departure times, we referred to the flight plan EOBTs (estimated off-block times). When EOBTs of multiple flights from the same airport coincided, five-minute delays were applied to ensure only one departure from each airport at a time, with delays propagated to successive flights if a delayed flight's revised EOBT overlapped another flight. Table III shows the number of flights in the scenario broken down by North American region. Fig. 2 shows the number of departures each hour (histogram of adjusted EOBTs in one-hour bins).

The cruising altitude of each flight was taken as the highest planned cruise altitude from item 15 of the flight plan; that is, when cruise altitude changes such as "step climb" were indicated along the route, the highest altitude was assigned as the flight's cruise level rather than the initial cruise altitude. Only level flight was used in the fast-time simulations.

D. *Route Network Creation*

To evaluate a new airspace or route structure design, it is necessary to generate flight plan routes that will be representative of those requested by airspace users. In Europe, the average flight length of intra-European flights was only 517 NM in 2017 [18] and its FRA areas are comparatively small compared to oceanic airspaces, so direct (Great Circle) routes between FRA entry and exit points are often used. In North Pacific oceanic airspace, flights are long range and the westerly Polar Jet Stream winds dominate flight planning, so minimum flight time tracks based on wind forecasts are used in the calculation of routes through the CENPAC area south of the NOPAC region.

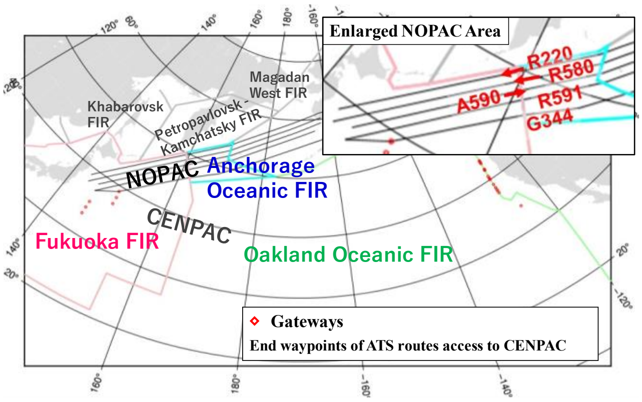


Figure 1. Simplified Map of the Study Area of Interest in the North Pacific Ocean Area

TABLE II. NUMBER OF NORTH AMERICAN FLIGHTS IN THE FUKUOKA FIR IN 2019

	NOPAC	CENPAC
Eastbound	33,453 (37%)	55,914 (63%)
Westbound	35,382 (63%)	20,958 (37%)
Total	68,835 (47%)	76,872 (53%)

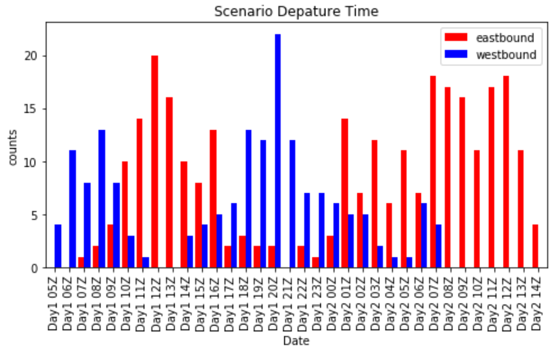


Figure 2. Traffic Numbers in the Scenario Based on Departure Time

TABLE III. NUMBER OF FLIGHTS IN THE SCENARIO DIVIDED ACROSS THE NORTH AMERICAN REGION

	Alaska	West	Central	East	Hawaii
Eastbound	35	136	16	47	48
Westbound	20	103	10	7	29

In order to generate such routes in the target airspace, a "network" of possible route segments was created for each airspace/route configuration and a graph search algorithm taking into consideration meteorological data was applied to create minimum flight time routes [12]. Fig. 3 shows the two networks used for the graph search, namely, [a] a baseline network reflecting the current airspace configuration with the NOPAC fixed ATS routes, and [b] a NOPAC FRA network in which a grid of nodes at intervals of 1° latitude and 5° longitude was created and each node was connected by edges to its east and west neighbours within a certain latitude range to form a mesh, allowing wind-optimal routes to be created. The NOPAC ATS routes were deleted in [b].

Fig. 4 shows an enlarged view of the NOPAC areas of the networks [a] and [b]. In the baseline network, the current NOPAC ATS routes with one-way route operations was applied — the northmost two routes R220 and R580 are westbound exclusive, the central NOPAC route A590 is eastbound exclusive, and the remaining routes R591 and G344 are bidirectional (see the enlarged inset in Fig. 1) — and traffic cannot fly between the NOPAC routes and CENPAC area. On the other hand, the NOPAC FRA network was designed without direction constraints and so that flights through NOPAC area could also freely join or leave the CENPAC flex track area by creating a mesh without the NOPAC ATS routes. Fixed ATS routes were retained in the Anchorage FIR radar airspace on the northeast side of the NOPAC area.

E. *Reflecting Winds Aloft*

The winds aloft that affect the planning of flight routes through oceanic airspace vary from day to day and seasonally. Capturing the effect of their variation by simulating all historical wind conditions over a year or more is prohibitively laborious, and in previous studies we have picked one or more "representative" wind conditions using a simple criterion (e.g. two days in winter and summer with no adverse weather), but this may not be sufficient to adequately reflect the range of wind conditions. To avoid such difficulties, we applied clustering to historical PACOTS track data to identify representative wind conditions automatically and objectively. PACOTS track data are used as a surrogate for the actual winds themselves since they are calculated reflecting winds aloft at a representative cruise altitude. This greatly reduces the volume of data that must be analysed and makes the problem tractable for clustering.

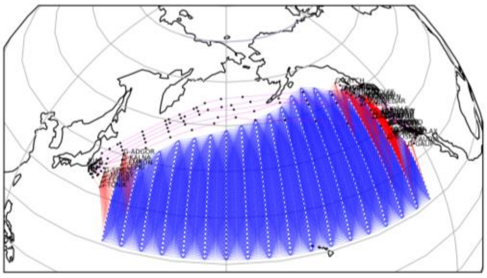
To apply clustering, a way to represent salient elements of the data as a *feature* must be designed. PACOTS tracks are created and published daily, assuming multiple city pairs. Fig. 5 shows an example of PACOTS tracks for a certain winter day. For clustering, tracks 1, 2, and 3 (eastbound) and tracks C, E, and F (westbound), which are created assuming city pairs connecting Japan and West Coast of North America, were used. Fig. 6 shows a plot of each daily PACOTS Track 2 over a period of 2,533 days (approximately 7 years). Their footprint has a spindle shape and is widely spread in the north-south direction. To reflect this characteristic, we define the feature of a single track k, F_k, as a tuple of three parameters:

$$F_k = \left(\varphi GW_{Japan}, \varphi 160W, \varphi GW_{US}\right)$$

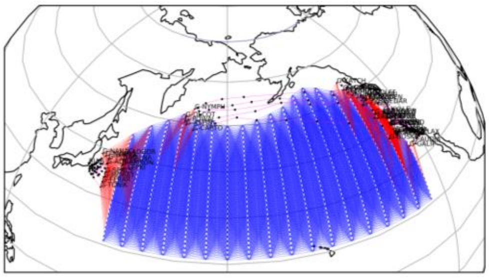
where k is the PACOTS track designator, φ denotes latitude, GW_{Japan} and GW_{US} are the positions of the track terminal points (i.e. the "gateways" between oceanic and radar-controlled airspaces) in Fukuoka FIR and Oakland Oceanic FIR respectively, and 160W is the position of the track's intersection with the 160W meridian, where the footprint of the tracks is widest (Fig. 6).

As the feature for a day, F_{day}, the feature parameters of westbound tracks C, E and F and eastbound tracks 1, 2 and 3 published on that day were concatenated to give:

$$F_{day} = [F_C, F_E, F_F, F_1, F_2, F_3]$$

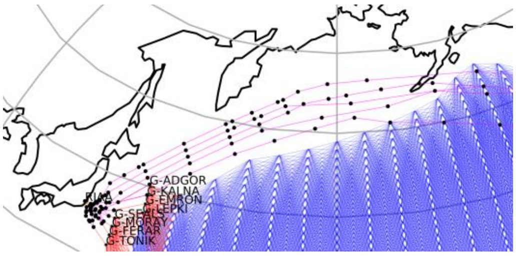


[a] Baseline network

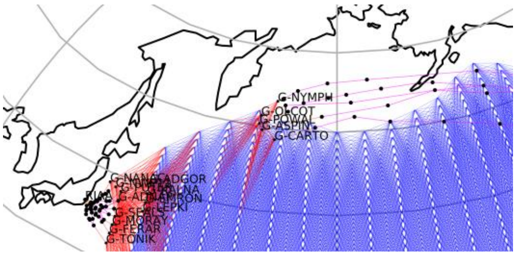


[b] NOPAC FRA network

Figure 3. Two Networks Composed with Fixed Route and Mesh used for the Graph Search



[a] Baseline network



[b] NOPAC FRA network

Figure 4. Enlarged Drawing of Networks [a] and [b]

With *k*-means clustering, the number of clusters *k* must be explicitly specified, so selection of a suitable value of *k* is an issue. To this end, the *X*-means clustering (an extension of *k*-means clustering [19]) routine was performed using the Python Pyclustring library on 2,533 datasets, covering approximately 7 years (2011–2017). Then, the value *k*=6 was chosen by applying minimum noiseless description length to the criteria for dividing into clusters [20].

To select wind conditions, it was thought necessary to consider long-term climate change trends as well as day-to-day and seasonal variations. Since current climate change trends due to global warming might make use of older historical wind data a less reliable indicator of future conditions, wind days for simulation were selected mainly from 2017. Once clustering was carried out, the number of days to select from each cluster for the simulations was determined by the condition that at least one day should be selected from the smallest cluster. Then, the number of days selected from each remaining cluster was determined by its proportionate size: 5 days were selected from C1 (46.5 %), 3 days from C3 (27.0 %), and 1 day was selected from each of C2 (6.1 %), C4 (9.0 %), and C5 (10.6 %), for a total of 11 days. The minimum number required to reflect the range of different wind conditions. Cluster C6 was considered an outlier due its small relative size of less than 1% of the total. Fig. 7 shows how the members of each cluster were distributed in 2017, with red arrows indicating the selected days. The clusters are not evenly distributed throughout the year, with C1 and C2 being more prevalent in winter and C4 and C5 being more prevalent in summer. To reflect this distribution, the middle days of runs of 3 or more consecutive days were selected in this study. Fig. 8 shows the winds at 00:00 UTC on the selected days at the 250 hPa pressure level (approximately 10,363 m, 34,000 ft).

F. Flight Plan Route Generation and Fast-time Simulation

Minimum time flight routes in each airspace route network for the flights in the baseline (unperturbed) traffic demand model were created for the winds on each of the 11 selected days using a tool developed at ENRI. The tool applies Dijkstra's shortest-path graph search, which from a single "source" node finds shortest paths from the source to all outer nodes of the graph, but minimises flight time instead of distance. Details are given in [12]. Based on the created flight routes, the AirTOp fast-time air traffic simulator [21] was then used to simulate flights in the NOPAC and CENPAC airspaces. To reduce the effect of the results on the demand model, an additional 5 traffic demand models were created by perturbing the flight departure times of the original model by a random amount with a standard deviation of 15 min. and a Gaussian distribution. And flight trajectories were output as time histories of position and altitude and also per-flight metrics such as fuel burn, flight time and flight distance.

The aircraft performance models used by both the route generation tool and AirTOp were derived from the Base of Aircraft Data (BADA) version 3 which is developed and maintained by the EUROCONTROL Validation Infrastructure Centre of Expertise (EEC) [22, 23] and has been evaluated and applied in many ATM studies [24 - 27]. Meteorological data used were Grid Point Value (GPV) data provided by the Japan Meteorological Agency's Global Spectral Model (GSM) numerical weather predictions [28], with interpolation between grid points in space and forecasts in time. The routes were

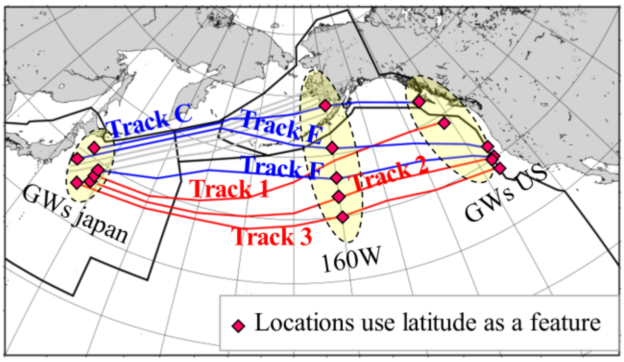


Figure 5. Example of PACOTS Tracks for a certain winter day

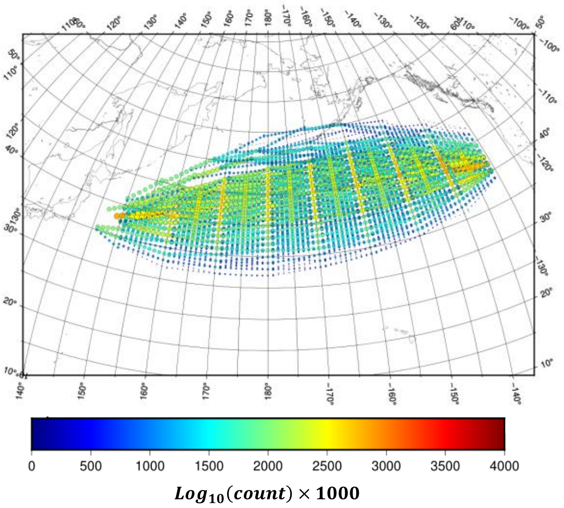


Figure 6. PACOTS Track 2 over a period of approximately 7 years (2011-2017)

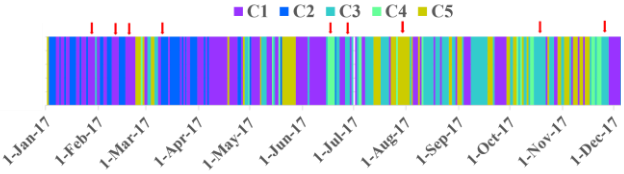


Figure 7. Clustering Groups of 2017

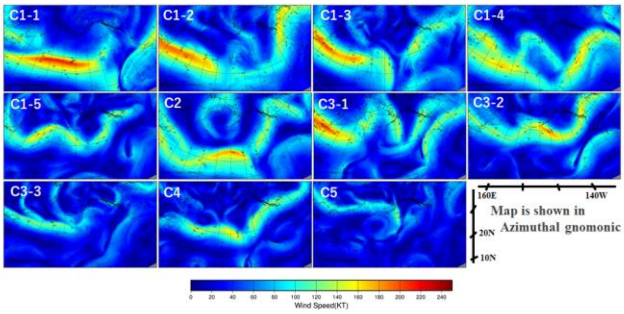


Figure 8. Wind Patterns for the Simulation

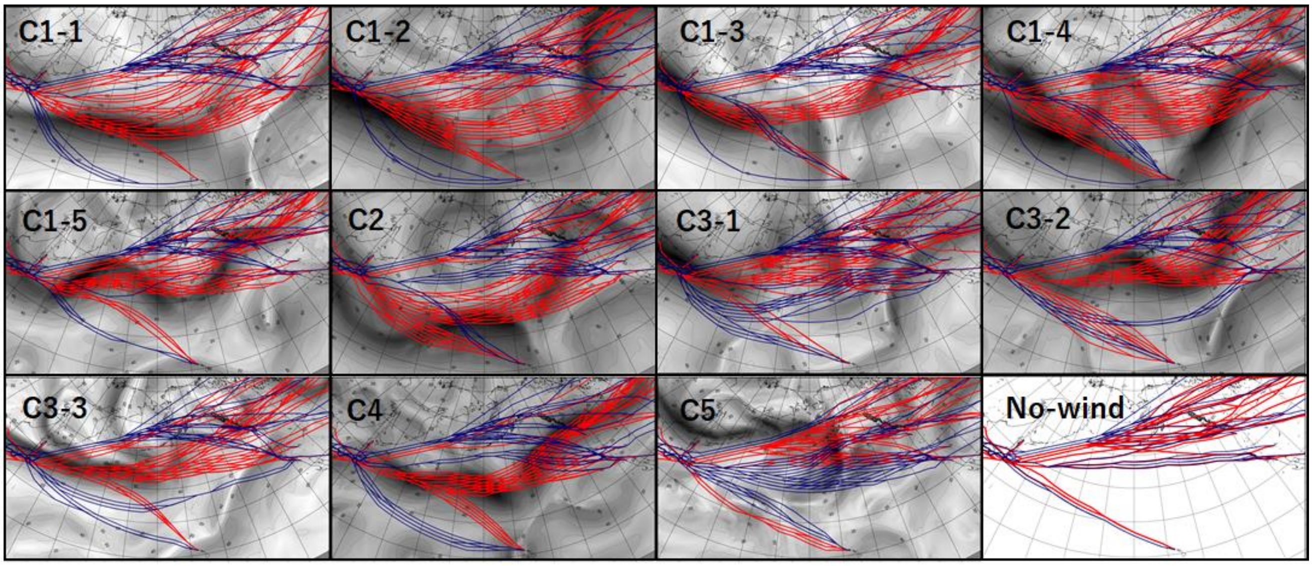
generated using the wind conditions at the time of flight in the traffic scenario.

III. RESULTS

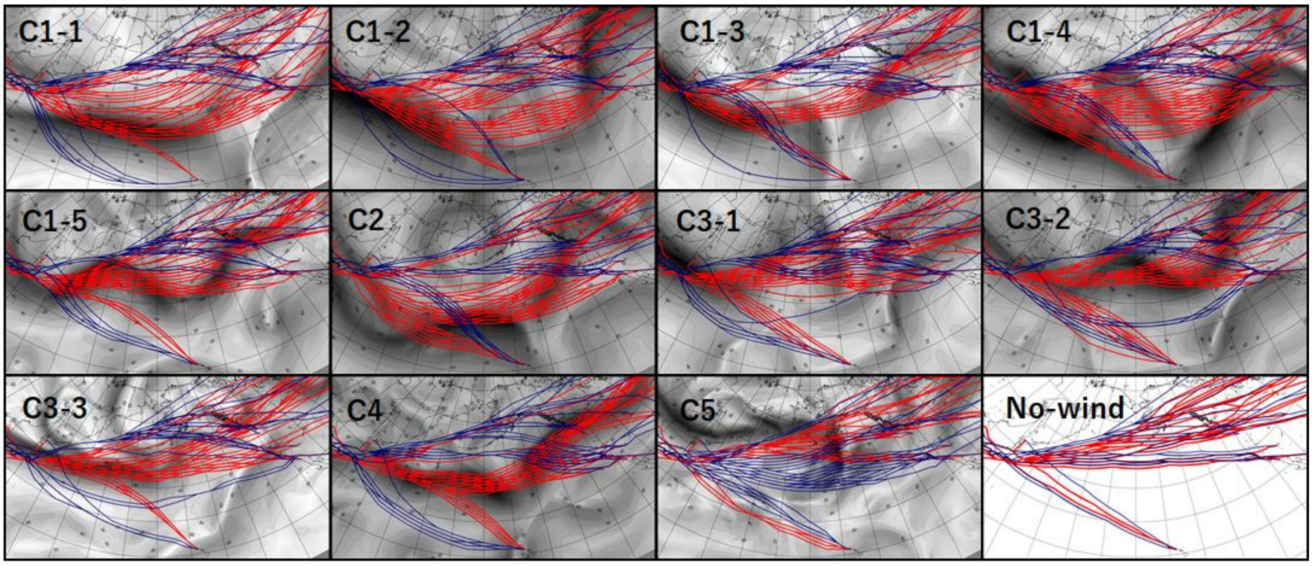
A. Flight Route Efficiency

Fig. 9 shows the calculated flight routes for the baseline airspace configuration [a] and the NOPAC FRA network [b] for each wind condition including no-wind (i.e. minimum distance) routes. The red lines represent eastbound flights and the blue lines represent westbound flights. The eastbound flights along the jet stream core diverged significantly from the minimum distance route when the jet stream was strong (C1, C2) to benefit from the tailwind, and tended to be closer the minimum distance route when the jet stream was weak (C4, C5). For the westbound flights, the routes avoided the jet stream headwind even in weak wind conditions. It can be inferred that the NOPAC area is likely to be used by westbound flights to avoid headwinds by flying to the north of the jet stream.

In order to measure the flight efficiency of the NOPAC FRA, flight distance fd, flight time ft, and fuel consumption fc were compared between flights in the baseline and NOPAC FRA airspace configurations ($fd_{baseline}$, $ft_{baseline}$, $fc_{baseline}$ and fd_{FRA}, ft_{FRA}, fc_{FRA} respectively) for all wind and departure time conditions. The effect of NOPAC FRA was evaluated by the differences of each metric, $\Delta fd = fd_{FRA} - fd_{baseline}$, $\Delta ft = ft_{FRA} - ft_{baseline}$, and $\Delta fc = fc_{FRA} - fc_{baseline}$, with negative values indicating a positive NOPAC FRA benefit. Table IV shows descriptive statistical values for each metric, and the mean values are all negative indicating that the NOPAC FRA airspace configuration has an overall benefit on flights, though some individual flights had positive values. Reasons for this are discussed in section IV.



[a] Baseline Network Flight Routes



[b] NOPAC FRA Network Flight Routes

Figure 9. Flight Routes of Baseline Network [a] and NOPAC FRA Network [b]

Regarding metrics of flight trajectory efficiency from an AU's perspective, *ft* and *fc* are more suitable than *fd*. Here, we analysed in detail the *fc* that has a significant impact on flight operating costs. Whether or not a flight operates in the NOPAC FRA airspace depends on the location of North American departure/arrival airport in addition to the winds aloft, so flights were categorised as Alaska flights (where all flights were expected to fly in the NOPAC area), Hawaii flights (of which only a small number were expected to fly in the NOPAC area), and other flights. Fig. 10 and Table V show the fuel consumption differences *Δfc* for each category. The boxes in Fig. 10 show the 25th – 75th percentile ranges (with the line in each box indicating the median), and the whiskers the 5th – 95th percentile ranges. Mean values are indicated by triangles.

For Alaska flights, the NOPAC FRA was particularly efficient for eastbound flights due to being able to operate within the southern side of the NOPAC area. For Hawaii flights, the most beneficial flight routes were ones running south-north across the NOPAC FRA. For North America flights, the effect of NOPAC FRA was high for westbound flights, because it gave more efficient route options to avoid the jet stream headwind.

TABLE IV. STATISTIC VALUES OF EACH METRICS BETWEEN BASELINE NETWORK FLIGHTS AND NOPAC FRA FLIGHTS

	Δfd [NM]		*Δft* [minutes]		*Δfc* [kg]	
	east	west	east	west	east	West
Max	239	261	23	31	2053	4119
75%	0	4	0	0	0	0
Median	0	0	0	-1	0	-154
25%	-3	-18	-2	-5	-194	-662
Min	-645	-663	-47	-120	-7362	-12136
Mean	-6.9	-14.3	-1.6	--3.6	-242.6	-468.5
SD	34.6	58.2	3.7	7.5	565.8	908.1

TABLE V. MEANS OF VALUES OF FUEL CONSUMPTION BETWEEN BASELINE NETWORK FLIGHTS AND NOPAC FRA FLIGHTS

	Alaska		North America		Hawaii	
	east	west	east	west	east	West
Mean [kg]	-849.2	-159.0	-176.2	-532.4	-75.6	-418.0
SD [kg]	784.9	260.7	487.4	739.1	365.4	1555.3

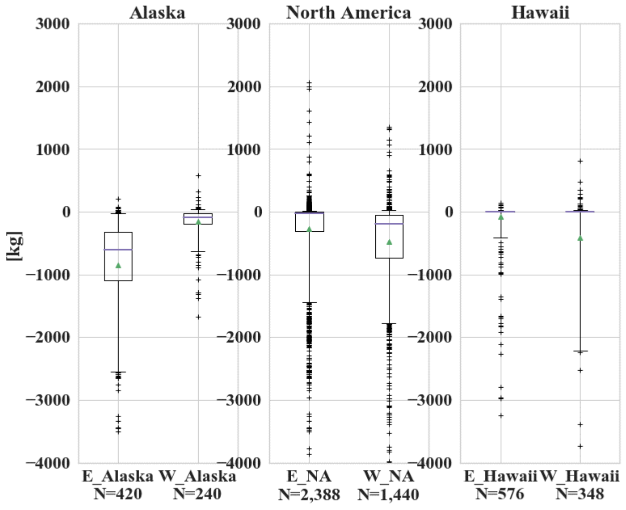
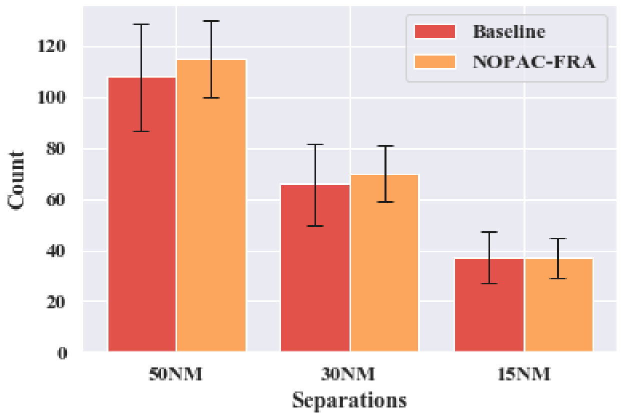


Figure 10. Comparison of Statistical Values of Fuel Consumption between Baseline Network Flights and NOPAC FRA Network Flights

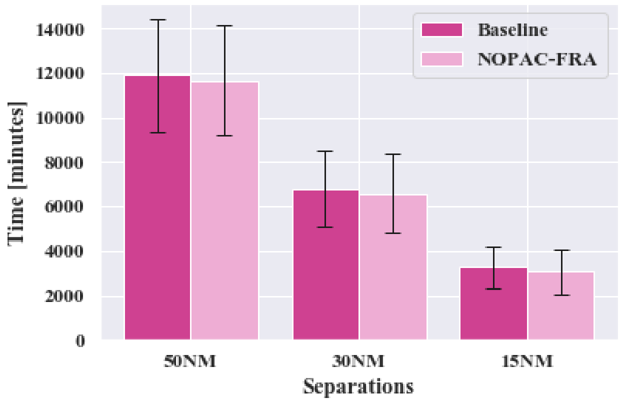
B. *Airspace Capacity and CNS Performance*

Flights enter the target airspace (the CENPAC and NOPAC areas) at their cruising altitudes and we did not consider altitude changes due to step climb or other operational reasons. Loss of vertical separation could therefore not occur and PLOS was evaluated based only on the horizontal distances between simulated trajectories at the same altitude. PLOS was calculated based on three horizontal separation criteria of 50 NM, 30 NM and 15 NM, and results were compared. Trajectories for an entire simulation day (from Day 1 15:00 UTC to Day 2 15:00 UTC) were extracted for PLOS calculations. To compute PLOS, pairs of aircraft with a potential loss of separation were detected at one-minute intervals. At each minute, the number of pairs (PLOS count) and the time of persistence of each PLOS between a pair (PLOS time) were calculated.

Fig. 11 shows the PLOS counts and PLOS times for each separation standard in for the baseline airspace and NOPAC FRA, respectively. The value for each PLOS is the mean of 72 simulations for each of the baseline airspace flights and NOPAC FRA flights, based on flight routes calculated from 12 sets of wind data (11 with wind and one with no wind) and six departure times (one unperturbed and 5 randomly perturbed). Overall, the NOPAC FRA flights had a higher PLOS count than the baseline



PLOS Count



PLOS Time

Figure 11. PLOS Count and PLOS Time

airspace flights (50 NM: +6.8%, 30 NM: +5.6%, 15 NM: +0.8%), but the PLOS time decreased (50 NM: –1.9%, 30 NM: –3.1%, 15 NM: –6.4%), with the decrease becoming larger as smaller minimum separation distances were applied. This suggests that if a smaller minimum separation standard can be applied, NOPAC FRA operation may be possible with no reduction in efficiency or safety as a result of PLOS.

IV. DISCUSSION

A. Fuel Benefit of NOPAC FRA versus Fixed ATS Routes

Wind-optimised flight routes in a free route environment have also been considered in simulation studies of trans-Atlantic flights, and shown to benefit to reduction of flight time compared to Great Circle routes [29, 30]. In this study, allowing free routing in the NOPAC airspace was also shown to increase the possibility of more efficient individual flight routes in terms of overall fuel consumption strongly related to the flight time. However, several flights had a greater fuel consumption in the FRA airspace compared to the fixed ATS route airspace, reflected in positive values of Δfc. Fig. 12 shows westbound routes for which Δfc was approximately +1,000 kg. In winter, it is typical for westbound flights to operate as far north as possible in the NOPAC area to avoid a strong jet stream headwind. In the baseline airspace, the R220 route allows a flight to operate with minimum distance from boundary with the Russian Federation FIR boundary on the north side of the NOPAC area. In the NOPAC FRA network in this study, however, the waypoints of the fixed ATS routes were eliminated, causing a gap to appear. As a result, under certain wind conditions, R220 could be more efficient than the best possible route using the mesh in the NOPAC FRA. For eastbound flights, although the number of flights that showed a higher *fc* when using the NOPAC FRA network was fewer, some flights via that used A590 in the baseline airspace had positive Δfc values.

On the other hand, many flight routes using the NOPAC FRA network showed high benefits. Fig. 13 shows some NOPAC FRA network routes that were particularly beneficial (routes with Δfc were –2,000 kg or below) for eastbound flights to the west and east regions of North America compared with NOPAC ATS routes. Currently, the NOPAC area is separated from the CENPAC airspace by a gap on the south side of airway G344, and in principle, flights do not cross between the NOPAC and CENPAC areas or between NOPAC routes (though a small number of flights do so in actual operations, when traffic levels permit). The NOPAC FRA removes those constraints. It can be said that NOPAC FRA is an airspace design that enables more efficient flight routes than the current route configurations, in particular to connect seamlessly the NOPAC area and the CENPAC airspace, and enabling flights that laterally traverse the NOPAC area.

The Informal Pacific ATC Coordinating Group (IPACG), which provides a forum for ANSPs and AUs to discuss for near-term ATC problems within Anchorage Oceanic, Oakland Oceanic and Fukuoka FIRs [31], is currently considering options to reorganise NOPAC airspace at the request of IATA to take advantage of PBCS capability to increase airspace capacity, e.g. proposals studied by the authors in [32]. More recent proposals are considering a phased approach of initially modifying existing one-way route constraints to give greatest benefit to PBCS-approved flights (e.g. route and/or altitude segregation), then progressively lifting the constraints while reducing the number of NOPAC ATS routes from five to three while narrowing the lateral separation between the routes. This will increase the airspace available for flex tracks. An element of the latest IPACG proposal that could be adopted in our NOPAC FRA design is to retain some of the existing NOPAC ATS route waypoints while deleting the routes themselves, to allow flights to operate parallel to the Russian Federation airspace boundary at minimum distance (i.e. along parts of the existing R220 route), which is of greatest benefit to westbound flights for avoiding headwinds without incurring air navigation service charges for Russian Federation airspace. Here, we conducted a simulation study on NOPAC FRA which completely eliminated the NOPAC ATS routes looking further ahead. We believe that the process presented here can be used in the study of realistic NOPAC route reorganisation in the near future.

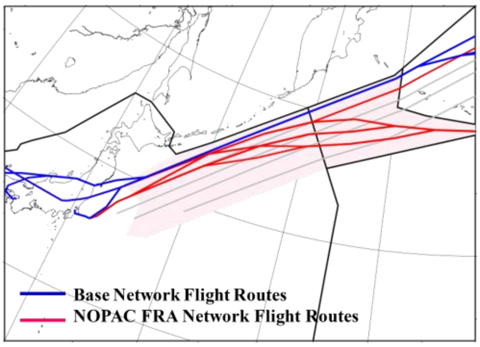


Figure 12. Westbound Flight Routes with $\Delta fc \approx +1{,}000$ kg

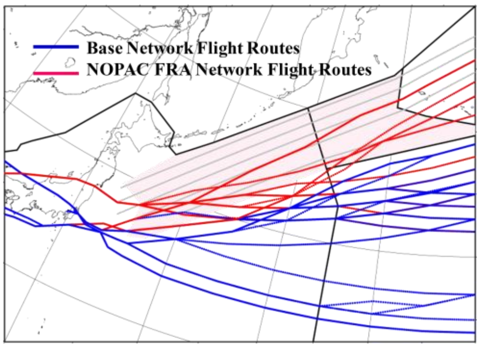


Figure 13. Beneficial NOPAC FRA Network Routes

TABLE VI SAME-ROUTE RATE FOR PLOS TIME

	50 NM	30 NM	15 NM
Baseline	74 %	75 %	76 %
NOPAC FRA	65 %	67 %	69 %

B. PLOS

Airspace changes require careful planning and verification of air traffic control practicality, airspace safety and capacity, and AU benefit. We applied PLOS as a surrogate metric of capacity and AU benefit. Since this was a fast-time simulation study, separation losses that are normally prevented by air traffic controller intervention occurred between aircraft trajectories. From pairs of simulated trajectories, the numbers of cases where a loss of separation began was tallied as a PLOS count, and the persistence of the loss of separation was summed as PLOS time. The results show that NOPAC FRA tended to have a higher

PLOS count compared to baseline NOPAC ATS route airspace, but PLOS times tended to be lower. This is because of the greater dispersion of routes allowed by FRA of flights between different city pairs. Table VI shows the proportion of “same route” conflict (when the bearings of a pair of aircraft in conflict differ by less than 5º) to total PLOS time for different lateral separation minima. In the NOPAC FRA airspace, even if PLOS occurred, the trajectories of the flights diverged after a while and as a result the PLOS time decreased compared to the fixed NOPAC track airspace. A reduced PLOS time means greater efficiency for the AU, but a greater PLOS count indicates an increased number of ATC interventions to resolve losses of separations, and those could possibly cause further PLOS, which may also increase PLOS time. This study showed that the risk, which PLOS number may have, was reduced if a smaller lateral separation standard could be applied. By applying a 15 NM separation, which it is assumed will be applicable in the near future using space-based ADS-B, it is possible to reduce the increase in the PLOS counts in the NOPAC FRA (see Fig. 11 top) to a similar level as in existing fixed-ATS route airspace.

This study assumed cruise at constant altitude, but step climb is typically used on long-haul flight operations. Step climb reduces the amount of traffic, and therefore potential interactions, at the previously occupied level, and increases it at the new level. We consider that this would tend to “balance out” the PLOS results at different levels, and the climb itself as transient, so step climbs would not greatly affect the results of our PLOS analysis. However, to confirm this assumption and quantify its effects, we plan to consider step climb as a next step.

Another concern with a higher PLOS count is increased airspace complexity. When flight plans are based on fixed ATS routes, PLOS events tend to be clustered around fixed locations (such as where ATS routes cross) which are predictable to air traffic controllers. In an FRA environment, PLOS events tend to be more dispersed due to the greater variability of flight trajectories, which might increase controller workload to detect PLOS. Dhief *et al.* also found that more conflicts could result from forecast wind uncertainty when using wind-optimal free routes compared to a wind-optimal track network [30]. However, increased automation and the higher predictability of a trajectory-based operations environment is expected to offset greater complexity. A trajectory-based oceanic air traffic control system (TOPS) recently introduced in Japan contains similar support functions, and verbal reports to the authors from oceanic controllers have indicated a reduction in workload. Airspace complexity metrics for NOPAC FRA evaluation and appropriate air traffic controller support for PLOS detection and resolution are issues to be considered in future work.

V. CONCLUSIONS

In order to evaluate the possible operator benefits and ATM impacts of replacing the NOPAC fixed ATS routes with a free route airspace permitting UPR, a NOPAC FRA environment was designed and fast-time simulations were conducted to compare it to the existing ATS route airspace configuration and to examine the effect of reducing lateral separation through better CNS capabilities. In order to reflect the daily and seasonal changes in winds aloft that affect North Pacific oceanic flight operations, we applied a clustering method to approximately 7 years of historical PACOTS track data to select a representative range of wind conditions in the simulation. This clustering method should give more robust results than the previous more ad hoc method of wind selection.

The results indicated that the NOPAC FRA network will be effective in increasing overall the efficiency of flight routes through the NOPAC area. In flight routes calculated for a traffic demand scenario of 451 flights over a period of 33 hours with 12 wind patterns, the NOPAC FRA flights had mean fuel savings of 243 kg for eastbound flights and 469 kg for westbound flights compared to flights using the baseline NOPAC ATS route airspace configurations.

As metrics of airspace capacity and efficiency, we detected potential losses of separation (PLOS) between aircraft pairs from the simulated flight trajectories applying different separation standards simulating current FANS-1/A/RNAV 10 (50 NM), PBCS (30 NM) and expected space-based ADS-B CNS capabilities (15 NM). PLOS count and PLOS time were calculated. NOPAC FRA increased the PLOS count over the fixed-ATS route airspace configuration, but the increment was reduced as the minimum separation distance decreased. The PLOS time was reduced in NOPAC FRA for all minimum separations, and the degree of reduction improved as minimum separation was decreased.

An intervention to resolve a PLOS might between an aircraft pair might cause a further PLOS with a different aircraft. We believe that the probability of such a “knock-on” conflict would increase when airspace complexity is higher as the case of an FRA compared to parallel ATS routes, so suppressing the PLOS count will be particularly important in the NOPAC FRA. These results suggest that NOPAC FRA could have greater capacity if reduced separation standards are applied in the future.

As a next step towards realising a NOPAC FRA, further consideration of the increased complexity of the airspace and the use of support tools to offset its impact on air traffic controller workload are necessary. We are also aiming to expand the FRA concept to the Asia-Pacific sub-region. Further, we will continue to the study and improve the method for selecting representative winds aloft.

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