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Airspace Design Proposal for Efficient Flight Operations in North Pacific Oceanic Airspace

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***Abstract*— Flights across the North Pacific remain in oceanic airspace for 7 hours or more, so increasing the efficiency of flights through this airspace may contribute significantly to reducing greenhouse gas emissions. One cause of loss of efficiency is flights being unable to operate at their requested cruise level due to conflicts with other traffic. Through fast time simulation of traffic between Japan and North America, this paper clarifies that the potential for conflicts increases in the vicinity of the oceanic gateway fixes in Fukuoka FIR, which are spaced approximately 60NM apart. We propose using advances in CNS/ATM performance to reduce the gateway interval to 30NM and create additional gateways between the existing ones, to disperse traffic and reduce conflicts. Simulation results show that the proposed gateway design concentrates westbound traffic at one or two gateways that coincide with the wind-optimal routes on each day, while eastbound traffic flows are dispersed.**

***Keywords-* fast-time simulation; oceanic air traffic control; airspace design; air traffic flow management**

LIST OF ABBREVIATIONS

ADS-B	automatic dependent surveillance–broadcast
ATC	air traffic control
ATFM	air traffic flow management
ATS	air traffic service
CNS	communication surveillance and navigation
FAA	Federal Aviation Administration
FANS-1/A	Future Air Navigation System-1/A
FIR	flight information region
FRA	free route airspace
FTS	fast-time simulator
GHG	greenhouse gas
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IPACG	informal Pacific ATC Coordinating Group
JCAB	Japan Civil Aviation Bureau
NOPAC	North Pacific. The term is used in this paper as a proper noun referring to the five parallel ATS routes between Fukuoka FIR and Anchorage Oceanic FIR.
PACOTS	Pacific organized track system
PBCS	Performance Based Communication and Surveillance
PLOS	potential loss of separation
RNP	Required Navigation Performance
UPR	user-preferred route

I. INTRODUCTION

The increase in GHG emissions including CO_2 accelerates global warming which causes many harmful effects such as sea-ice retreat, floods, droughts, and wildfires. Emissions from transportation account for 27% of GHG emissions in the United States [1] and 18% in Japan [2], with road vehicles accounting for the greater proportion of these emissions while aviation accounts for around 8% [3]. However, aviation has higher CO_2 emission per passenger kilometre than other modes of transport [4]. Hence, increasing the efficiency of each flight operation is desirable to reduce GHG emissions.

North Pacific oceanic airspace spanning the Fukuoka FIR, Oakland Oceanic FIR and Anchorage Oceanic FIR is in high demand by flights connecting Asia and North America, and is one of the regions where satellite-based CNS/ATM technologies were introduced at an early stage when the ICAO CNS/ATM concept [5] was created to increase capacity. Since flights spend typically 7 hours or more in this airspace, gains in average flight efficiency can give a significant benefit to each flight. We have therefore been studying airspace design improvements targeting the North Pacific Ocean to enable greater operator per-flight benefit as well as to further increase airspace capacity. In considering airspace design, fast-time simulation is invaluable to estimate the feasibility, benefits, and safety of new airspace concepts at a preliminary stage, and promising concepts then be further evaluated by detailed human-in-the-loop simulations to assess air traffic controller workload and operational factors [6]. Fast-time simulation can be used to evaluate statistically large numbers of scenarios [7–9], such as wind pattern and flight route variations, in a short period of time, and so is an appropriate tool for our studies.

In previous works, we have conducted simulation studies of oceanic airspace design to enable more efficient aircraft operations by allowing more operator-desired routes to be planned. We have shown that a per-flight reduction in fuel consumption could be achieved by applying the FRA concept in the area of the fixed ATS routes called NOPAC [10]. In addition, the target airspace is greatly affected by the powerful westerly jet stream [11], and the patterns of optimal flight routes change during a year with its seasonal variation. In order to evaluate the overall effect of proposed airspace or operations changes over a year, it is necessary to simulate operator-desired wind-optimal (minimum time or fuel) routes while taking seasonality into account, and this requires careful selection of the wind conditions to be reflected in simulations. We therefore studied the use of clustering to derive a set of wind conditions on a small number of days that will give fast-time simulations results representative of wind conditions throughout a year [12]. For a more realistic calculation of wind-optimal flight plans through oceanic airspace, we added a step climb calculation function to our optimal route generation tool, and in a study using this function we estimated that when a step climb is not feasible, for example due to the requested level being occupied by blocking traffic, the extra fuel consumption would be over 3,000 kg per flight on average, which equivalent to approximately 9,500 kg of CO_2 [13].

While the above studies have indicated potential benefits from free routing and reduced separations enabled by improved CNS performance, an inability to perform step climb as planned due to other traffic reduces some of these gains. If PLOS that block step climbs can be reduced, overall airspace efficiency will be increased. The present paper builds on the results of these studies and extends the previous works by identifying the areas of high PLOS occurrence that prevent cruise at requested levels, clarifying the factors contributing to PLOS, and proposing and evaluating an airspace design to reduce PLOS in oceanic airspace.

The structure of this paper is as follows. Firstly, the setup of the simulation experiment to clarify where PLOS occur is described in section 2, and section 3 reports the simulation results. Section 4 discusses new airspace design proposals that were considered based on the simulation results, and section 5 presents conclusions.

II. SIMULATION SETUP

A. Airspace Operations over the North Pacific

The target airspace of our study over the North Pacific (excluding the Polar region) considers the three FIRs shown in Fig. 1, in which ATS are provided by the FAA and the JCAB. Since there is no radar or VHF communication coverage, ATC surveillance and communications are mainly provided by FANS-1/A satellite-based data link services, with a small volume of HF voice position reporting for non-equipped aircraft. As CNS technology has improved, the applicable separation minima between aircraft have been reduced, and the most commonly used separations are currently 50 NM lateral (between RNP 10 aircraft), 50 NM longitudinal (between RNP 10 and PBCS aircraft), and 30 NM lateral and longitudinal (between RNP 4 and PBCS aircraft) [14]. The target airspace is greatly affected by the strong westerly jet stream winds, the core region of which coincides with jet aircraft cruise altitudes. The jet stream core axis has a sinusoidal shape, and it moves northward and weakens in summer and moves southward and strengthens in winter, when core speeds can exceed 70 m/s (approximately 136 knots) [11]. Eastbound flights across the oceanic airspace use the jet stream tailwind to reduce flight time, even though they may have to deviate from a great circle route to follow the jet stream core. Westbound flights tend to plan routes that avoid the strong jet stream headwind region,

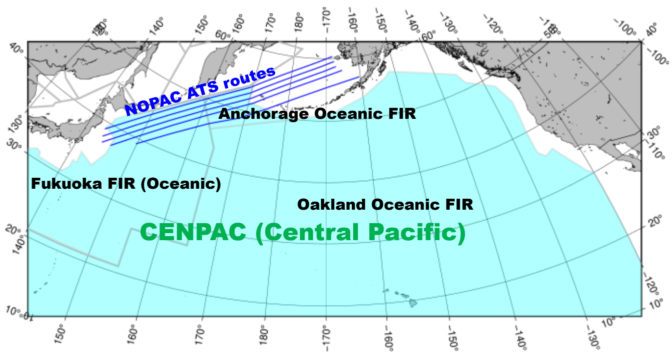


Figure 1. A target airspace is composed of three FIRs (areas shown in light blue; Fukuoka, Anchorage oceanic and Oakland oceanic FIRs) over the North Pacific Ocean where the majority of flights between Asia and North America are flown. The blue lines are high demand fixed ATS routes called NOPAC set up in the area between Japan and Anchorage.

In consideration of the daily and seasonally-varying wind patterns, within in a portion of the North Pacific airspace (labelled CENPAC in Figure 1), flight plans use either published flexible routes called PACOTS, which are generated daily by the FAA and the JCAB for certain city pairs, or UPR which are planned by the aircraft operator [16][17]. On the other hand, the NOPAC airspace between Alaska and Japan tends to be highly congested at peak times due to high demand by cargo flights between Anchorage and Asian cargo hubs, and also because part of the great circle routes between many airports in Asia and central and eastern North America pass through this airspace. To establish an orderly traffic flow to facilitate ATC handling, the NOPAC set of fixed parallel ATS routes spaced at approximately 50NM intervals was established in the 1980s. However, these have remained essentially unchanged since then, while CNS technology has advanced and separation minima between aircraft have been reduced. A redesign of NOPAC airspace to exploit the reduced separation minima based enabled by PBCS was requested by aircraft operators and IATA via the IPACG meeting [17], and a phased restructuring of the routes is currently being implemented.

As described above, flight operations over the Pacific Ocean have three major characteristics that differ from many other airspaces: minimum separations between aircraft are determined based on airspace and aircraft CNS performances, the most efficient flight routes are wind-optimized routes that consider the jet stream, and due to limitations of CNS performance, clearances into oceanic airspace are regulated such that flights will remain deconflicted for long periods of time. However, it should be noted that no all flights are at desired cruise altitude. Our research is examining airspace design to allow operators to plan and execute routes that are as close as possible to wind-optimal, assuming the possibility of further reducing separations by using new technological innovations such as space-based ADS-B [18, 19]. In this study, simulations considering step climbs, which are typically planned for oceanic flights to achieve greater fuel efficiency, were conducted assuming a NOPAC FRA (that is, the NOPAC ATS routes were eliminated and NOPAC airspace were assumed to be FRA), which is a step further ahead than the NOPAC redesign currently being considered at the IPACG, and 15 NM separation [19] was considered in view of a future possibility of using space-based ADS-B for ATC surveillance of oceanic airspace.

B. Step-Climb Operations

Our previous study examined the benefit to individual flights in terms of flight time and fuel burn reduction as well as the potential effect on ATC in terms of overall airspace PLOS trends that would result from extending the UPR operations airspace into the area currently occupied by the NOPAC ATS tracks. Flight plan routes were calculated assuming cruise at a constant altitude in [10], but in actual operations, one or more en-route step climbs are typically planned for oceanic and other long-durations flights to reduce fuel burn. Subsequently, a step-climb function was developed and added to the wind-optimal flight route calculation program developed by the authors for earlier studies [10, 12, 13], and validation by comparing calculated trajectories with actual trajectories obtained from FlightRadar24 [20] showed that the calculated step-climb trajectories were acceptable for use in airspace design evaluation in North Pacific airspace [13].

In actual operations, during flight planning, operators plan step climbs to be executed at flight plan waypoints based on the forecast departure weight and weather conditions. During flight, if the pilot determines that step climb is possible from an aircraft performance perspective (typically based on the real-time FMS calculation of optimum cruise altitude), he or she will transmit a climb request to ATC. Based on the traffic situation, ATC will generally approve the request if the climb will not cause conflicts with other traffic, otherwise the request will be denied with an "unable" response. An analysis of pilot-controller communication records (CPDLC and HF voice) in Fukuoka FIR oceanic airspace found that the initial response to an altitude change request was "unable" in nearly 30% of cases [21]. Changes to the ATM system that will increase step climb approvals will lead to more efficient flight operations. In this study, we use trajectory calculations that take into account step-climb to explore ways to increase step climb approvals.

C. Simulation Design

We designed a fast-time simulation experiment in order to identify “hotspot” areas where PLOS events occur more frequently. A traffic demand schedule of trans-Pacific commercial services in a 24-hour period was created based on actual flight plans, and minimum fuel flight plan routes including step climbs were then calculated for each flight in the schedule for a variety of wind conditions (different days in the year) chosen to reflect seasonal wind variations. Each “day” of flight plans was then executed by a FTS to produce flight trajectories, which were used to calculate PLOS. It should be noted that the FTS executed step climbs at the flight planned waypoints rather than between waypoints, which is possible in real-world operations.

Departure mass (initial mass) and departure time were varied since these affect the vertical trajectory profile (location of step climbs) and the relative positions of different flights. The simulation variables are listed in Table I. It should be noted that to reduce the overall simulation time and volume of data to be processed, there was only a single case for variable initial mass (i.e. only a single set of variable initial masses for each aircraft type was trialled), so the experiment design did not explore of all possible combinations of the variables. Although this reduces the statistical significance of the results, we believe that the overall trends revealed by the simulation study will still be valid.

The design of the experiment is explained in more detail below.

1) Trajectory Optimizer

A trajectory optimizer based on a shortest path graph search has been developed to study efficient airspace operations in North Pacific oceanic airspace [22]. A node-link network of possible flight paths (flight route legs) is first prepared for each city pair in the target airspace. The tool then calculates the “shortest” path through the network between the city pair using Dijkstra’s algorithm, using fuel burn or flight time as the metric along each link of the network instead of physical distance, taking into account the winds and aircraft performance. The aircraft performance calculation is based on the aircraft kinematic model and performance parameters published in the EUROCONTROL EEC BADA Family 3 database [23]. As atmospheric conditions, horizontal wind velocities and temperatures were obtained from Grid Point Value (GPV) numerical weather forecasts, interpolated between grid points and pressure levels in space and between forecasts in time. The step-climb function added to the trajectory optimizer for this research uses additional performance tables for each aircraft type computed using the BADA4 database [24].

2) Flight Schedules and Wind Conditions

The 24-hour traffic schedule was created based on flight plans of scheduled airline services that operated in Fukuoka FIR on a day in 2019. The schedule covered flights between airports in Asia and North America, with the latter classified as having ICAO designator prefixes of C (Canada), K (contiguous United States), M (Central America, in fact only Mexico), PA (Alaska) or PH (Hawaiian islands). Each service was defined by its origin and destination aerodrome, aircraft type, initial cruise altitude, initial mass, and departure time. The schedule contained a total of 451 flight services (282 eastbound and 169 westbound) operated by 11 aircraft types.

TABLE I. VARIABLES OF SIMULATION FOR PLOS CLARIFICATION.

A total of 132 simulations were performed.

Airspace model	1	NOPAC FRA
Initial mass conditions	2	***const*:** BADA PTF reference mass, ***var*:** randomly assigned with BADA PTF file as the mean and 34 % of the difference between the maximum mass and reference mass as variance
Wind conditions	11	Wind days to reflect seasonal wind trends result in [12] as follows 2017/01/28, 2017/03/28, 2017/06/05, 2017/06/24, 2017/09/23, 2017/10/17, 2017/10/25, 2017/11/02, 2017/11/12, 2017/12/10, 2017/12/22
Departure time shift	6	randomly-shifted departure times within a range of ±1 hour sampled from a normal distribution centered on the schedule departure time with a 1-σ value of 20 minutes.

The numbers and locations of planned step climbs is highly dependent on the initial mass [13], so this information is necessary to calculate realistic step climb trajectories. Routes and trajectories were calculated for two initial mass conditions: the fixed BADA reference mass of the aircraft type (condition *const*) and variable mass (condition *var*). The latter condition should ideally use actual initial mass distributions but since aircraft weights are not contained in flight plans, this information was not available. Instead, variations in cargo payload, passenger load factor and fuel were represented tentatively by sampling initial mass from a normal distribution with the reference mass of the aircraft type in the BADA PTF file as the mean and 34% of the difference between the maximum mass and reference mass as the standard deviation.

As historical meteorological data, the Japan Meteorological Agency's Global Spectrum Model (GSM) "nowcast" forecasts were used in the calculations of routes and trajectories. To reflect seasonal wind trends, the results of a previous study on representative wind selection using clustering [12] were used to select the 11 wind days shown by year/month/date in Table I that gave wind-optimal route trends close to those of 365 day-average.

3) Airspace Conditions

For each city pair, a search network was constructed that assumes a future "NOPAC FRA" airspace design that allows operators to plan UPR through the NOPAC area using a latitude/longitude grid of waypoints, removing the constraint of using the fixed ATS routes. (However, the ATS route waypoints were not retained in this design, which resulted in loss of efficiency due to a "gap" emerging between plannable routes and the northern FIR boundary of the target airspace. This is further discussed later in this paper.) An example of graph for a route search is shown in Fig. 2.

4) Trajectory Generation by FTS and Calculation of PLOS

The schedule departure time, aircraft type, flight plan route including step climbs, and weather conditions were input to the AirTOp fast-time simulator [25] to generate trajectories for all flights on each wind day for each initial mass condition. Since the timing and location of PLOS events between aircraft pairs depends on the aircraft departure timing, departure times were randomly varied to reduce the dependence of the study results on the schedule departure times. Fast-time simulation runs of each wind day and initial mass case were executed with randomly-shifted departure times within a range of ±1 hour sampled from a normal distribution centered on the schedule departure time with a 1-σ value of 20 minutes.

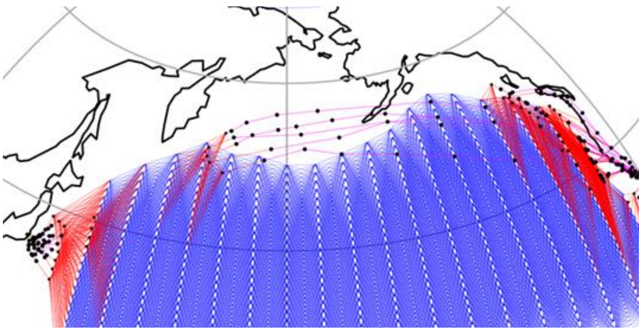


Figure 2. Examples of a graph of possible route segments created for searching optimal flight routes between Narita International Air-port and San Francisco International Airport.

As shown in Table I, a total of 132 simulation runs were executed. From the outputs of each simulation run, PLOS events were calculated between each pair of trajectories from the instantaneous aircraft positions and altitudes at each minute in time. PLOS events are reported as two metrics: "PLOS count", which is the number of individual aircraft involved in a PLOS event (a single PLOS event involves two aircraft), and "PLOS time", which is the duration of a PLOS event (how long a pair of aircraft remains in PLOS state). PLOS was calculated for horizontal separation distances of 15 NM.

III. RESULTS

A. Overall Trends in PLOS events

Since the route trends of eastbound and westbound traffic differ due to the prevailing westerly jet stream, PLOS count and PLOS time were examined separately for eastbound and westbound flights. Average PLOS counts and PLOS times for the constant and variable initial mass cases (n = 66, 11 winds and 6 departure times for each case) are shown in Fig. 3. Both PLOS count and PLOS time tended to be lower when the initial mass was varied than when a constant mass was used for each aircraft type, the difference between the two being more pronounced for PLOS time. This indicates that comparing *var* and *const* might provide insight into the factors contributing to

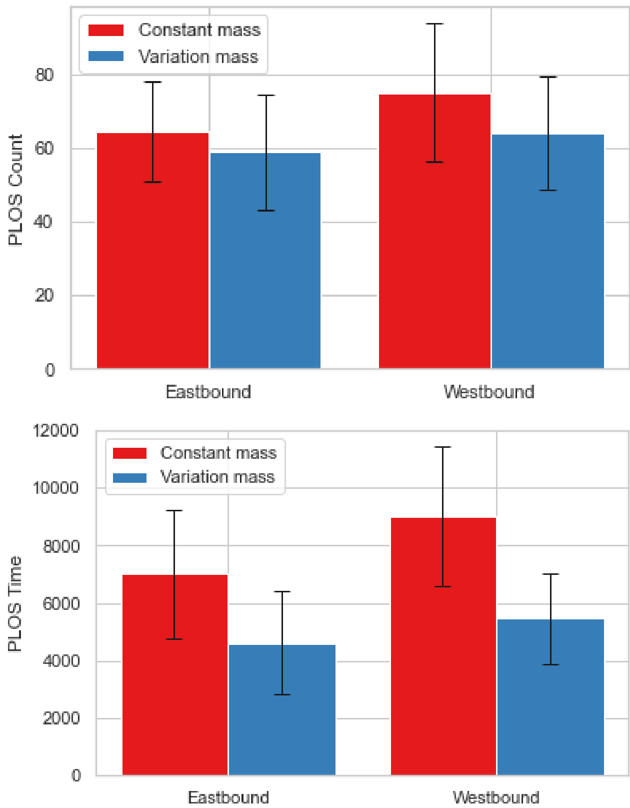


Figure 3. Average of PLOS count (above figure) and PLOS time (below figure) comparison of constant initial mass and randomly varied initial mass, shown eastbound westbound flow separately.

PLOS events. It should be noted that both the PLOS count and PLOS time trends between *const* and *var* were both significantly different ($p < 0.05$) in the *T*-test.

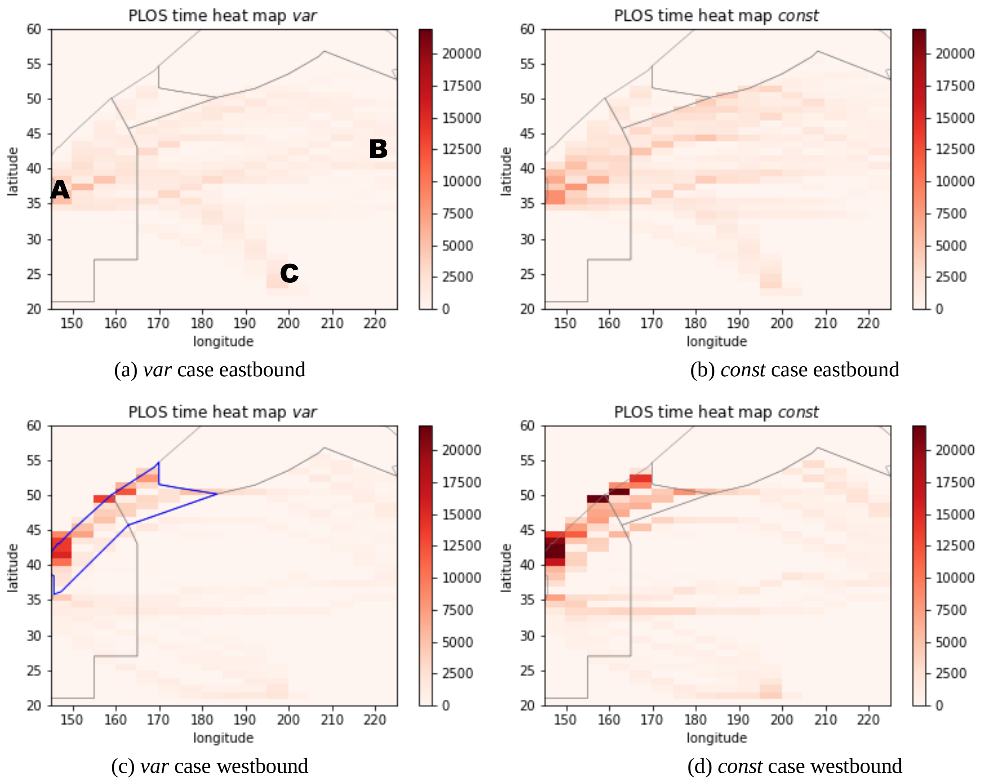
B. *PLOS Hot-Spot*

If the causes of PLOS events can be clarified, it may be possible to mitigate them and increase conformance of the actual flown trajectory to the operator's plan. We therefore explored the causes of PLOS by comparing the *var* and *const* cases, which tended to have low and high PLOS times respectively.

First, PLOS "hotspots", i.e. the areas in which PLOS events occurred more frequently, were examined. Fig. 4 shows heat maps of PLOS time summed in 5° longitude x 1° latitude cells over all wind and departure time conditions. The Fukuoka, Oakland oceanic and Anchorage oceanic FIR boundaries are overlaid as grey lines. Point "A" in Fig. 4(a) is the Fukuoka FIR oceanic airspace entry/exit area for flights to and from Japan and other Asian countries, "B" is the North American west coast oceanic airspace entry/exit area for flights to and from continental North America, and the Hawaiian Islands are located at "C". Although the PLOS hotspot locations are not significantly different between the *var* and *const* cases, their frequencies (heatmap intensities) are different. For both eastbound and westbound flights, PLOS hotspots are found between 145°E and 180°E (145°E 160°W/200°E in the eastbound *const* case). The causes of these hotspots are as follows.

- For eastbound flights, there is a PLOS hotspot around 145°E between 34°N~40°N, near the Fukuoka FIR oceanic entry/exit area, that is the boundary between oceanic and radar-controlled airspace. Flights to/from the city pairs in the scenario pass through this area where gateways are spread over a narrow north-south range compared to the North America side. Oceanic airspace entry and exit gateway waypoints are established near the boundary at approximately 60 NM (~1°) intervals between 30°N~40°N, and routes in oceanic airspace originate and terminate at these points. Although there are multiple gateway points, the most fuel-efficient routes through oceanic airspace on a given day tend to select a small number of gateways, causing traffic concentration.
- For westbound flights, there is less concentration at particular oceanic entry points on the North America side, partly due to the greater geographical dispersal of the airports of the target city pairs. Optimal routes that avoid the jet stream headwind area tend to concentrate in the NOPAC area shown enclosed by a blue line in Fig. 4(c), causing the observed PLOS hotspots.

PLOS occurs when both the lateral and vertical separations between a pair of aircraft at a given moment are less than specified values. As can be seen from the heatmap in Fig. 4, there is almost no difference in the route trends between *var* and *const*, so the reason for the observed difference in PLOS frequency is likely to be the result of differences in vertical flight profiles, that is, the location (timing) of step-climb maneuvers.



(a) *var* case eastbound

(b) *const* case eastbound

(c) *var* case westbound

(d) *const* case westbound

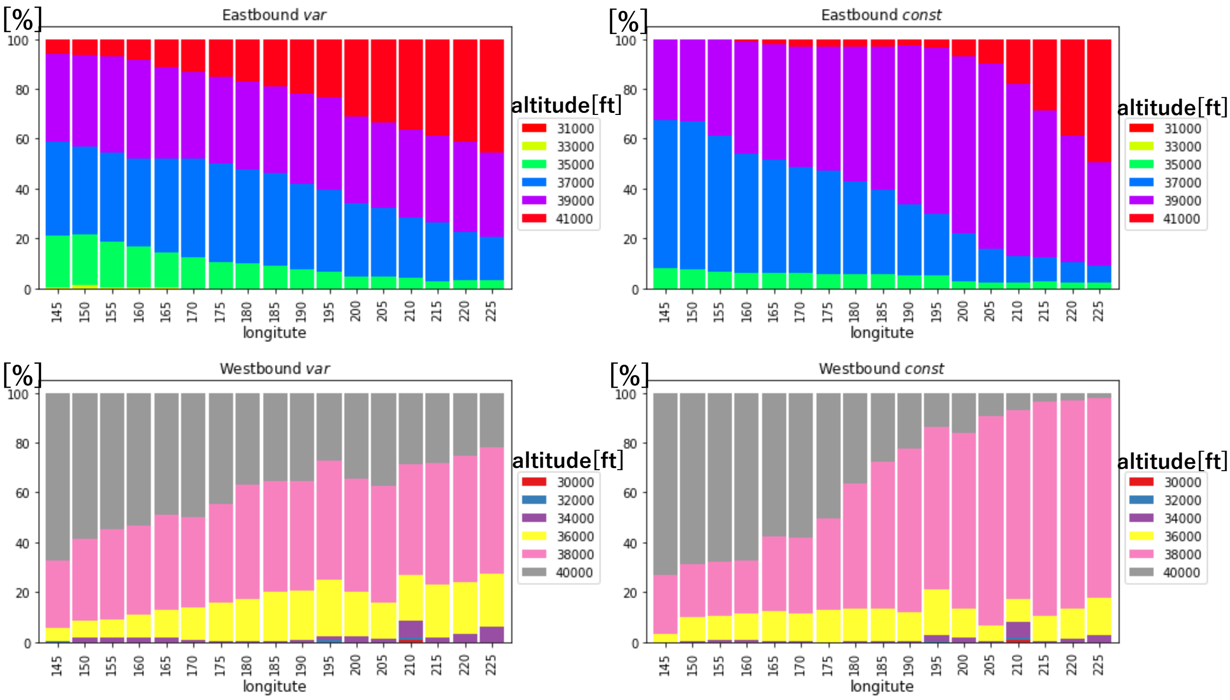
Figure 4. Heat map of PLOS time. Colour scale indicated PLOS time (sec.) accumulated in each 5°x1° cell over 66 simulations.

To investigate this, Fig. 5 shows the altitude distribution of flights crossing each meridian at 5° intervals. Overall, flights in the *var* case have a wider range of cruise altitudes compared to *const*. It can be said that the variation of initial weight results in a dispersion of climb position and a decrease in PLOS events. Looking in more detail, in the *const* cases, the fixed departure mass caused flights to concentrate at a relatively small number of altitudes after departure and during the first part of the flight over oceanic airspace (140°E to 190°E for eastbound flights, 140°W to 180°W for westbound flights). However, eastbound flights pass through only a few gateway locations in Fukuoka FIR from which they "fan out", causing hot spots around the gateway area, while for westbound flights, the greater north-south dispersion of origin aerodromes causes dispersal of routes entering oceanic airspace and so fewer hotspots over the eastern Pacific, even if flights are concentrated at a few cruise altitudes.

IV. Discussion

The above analysis revealed PLOS hotspots resulting from traffic concentration near the oceanic gateways in Fukuoka FIR. The greater the number and duration of PLOS events, the fewer the flights that are able to execute step climb maneuvers as planned, thus increasing flight duration at less efficient altitudes. We therefore considered airspace design modifications aimed at reducing PLOS events and increasing efficiency. As mentioned above, the Fukuoka FIR oceanic gateway points are currently spaced at approximately 60 NM intervals. However, the proportion of flights to which 30 NM lateral separation can be applied is expected to grow, 23 NM lateral is available in the regulations [25], and there is a possibility of reduction to 15 NM in the future from new technologies such as space-based ADS-B. One proposal is therefore to create additional gateway points between the existing ones, giving gateways at 30 NM intervals, and to distribute traffic between them. Fig. 6 shows the proposed airspace design. Current gateway points are shown in black, and proposed additional points are shown in red. The hotspot area for eastbound flights (around 145°E between 34°N~40°N) is shown in light green. The change in the gateway configuration will affect not only traffic in oceanic airspace, but also in the radar-controlled airspace on the west side of the boundary, so further simulations were conducted to verify the feasibility of this concept.

The concept was evaluated by comparing PLOS count, PLOS time, and traffic numbers passing through each gateway of three airspace configurations described below. The experiment variables are shown in Table II. The overall simulation design and setup are based on the PLOS experiment described in section II with some modifications. The flight schedules in the traffic scenario were based on flight plans of a different day to the scenario in section II to allow sharing of data and results with another research project. Since the gateway changes affect traffic not only in oceanic airspace but also in Fukuoka FIR radar-controlled airspace, it was necessary to extend the wind optimal route calculation time span to include the expanded areas. The traffic schedule consisted of all flights that passed through the oceanic gateways during a 24-hour period in May 2019, a total of 749 flight services (426 eastbound and 323 westbound flights between Asia and North America). The simulation time period was set to generate the complete trajectories of all of these flights from start to finish. The initial mass of each aircraft type was set randomly as in section II, and



Above figures: eastbound flight, below figures: westbound flight, left figures: *var* case, right figures: *const* case

Figure 5. Proportions of flights at each altitude at each 5° longitude waypoint.

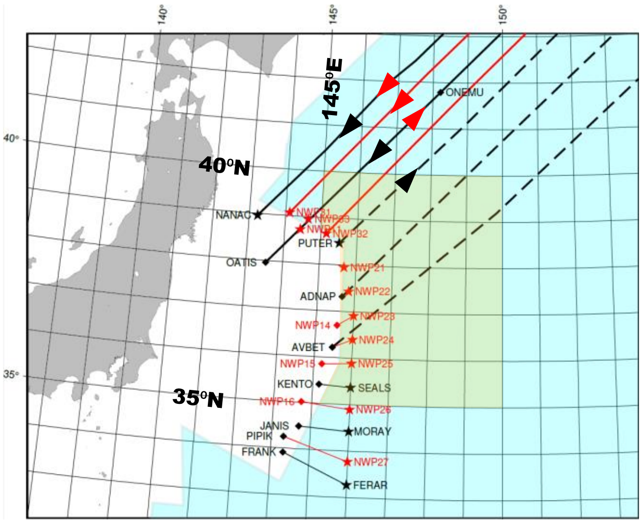


Figure 6. Proposed oceanic gateway points between Fukuoka domestic airspace and oceanic airspace. The area shown in light blue is the oceanic airspace. Black lines are the current NOPAC routes and *dct* case assumes this NOPAC routes. In NOPAC redesign phase 3, the dashed line routes are eliminated and new red line routes are set. New gateways shown in red are added in this study as *new* case. The *fra* case is a design that excludes all routes in the NOPAC area (bold line routes). Gateways are shown in star shape. The black and red arrows represent the route directions for the *dct* and *new* cases, respectively.

the same wind conditions and departure time shift method were used.

Three NOPAC area airspace configurations were prepared: the current airspace design with five parallel ATS routes at roughly 50 NM intervals (*dct*), the planned phase 3 of the NOPAC restructuring, with four routes at 25 NM intervals that will be PBCS/RNP4-exclusive at jet cruising altitudes (*new*) [27], and a NOPAC FRA design based on our previous study [10] but including the waypoints of the both the current and phase 3 NOPAC ATS routes to allow flight parallel to the northern FIR boundary (*fra*) of the target airspace. In Fig. 6, black lines are the current NOPAC (*dct*). In *new* case, red lines are added and the dashed lines are deleted. In *fra* case, all ATS routes in NOPAC area are deleted, although the routes from radar airspace to the gateways are retained. Some of the routes in the NOPAC area are one-way in the *dct* and *new* cases: black arrows indicate route directions for the *dct* case and red arrows

TABLE II. VARIABLES OF FURTHER SIMULATIONS FOR PROPOSED GATEWAY POINTS CONFIGURATION.

A total of 198 simulations were performed.

Airspace model	3	***dct***: the current airspace design with five parallel ATS routes at roughly 50 NM intervals ***new***: the planned phase 3 of the NOPAC restructuring, with four routes at 25 NM intervals ***fra***: NOPAC FRA
Initial mass conditions	1	Same as ***"var"*** condition in section II
Wind conditions	11	Same wind days in section II
Departure time shift	6	Same shift method in section II

for the *new* case. In each case, the two northernmost routes are dedicated to westbound traffic, while the third route from the north is eastbound. For the Fukuoka FIR radar-controlled airspace adjacent to the oceanic gateways, it was assumed that the currently ongoing division into upper and lower airspaces at FL335 will have been completed and will allow overflights to route directly between the oceanic gateways and the FIR boundary on the west side of Fukuoka FIR radar airspace. To capture the effect of seasonal wind variation on oceanic routes, the same 11 wind days as described in section II *C 2)* were used, and the results for each airspace case were aggregated over all the wind days.

Fig. 7 shows for each airspace configuration the total number of flights passing through each gateway summed over the 11 wind days, with eastbound traffic in red and westbound traffic in light blue. The gateways are ordered along the horizontal axes from north to south. We now discuss the trends for eastbound and westbound traffic.

For westbound flights, increasing the number of gateways and reducing their interval causes a tendency for traffic to concentrate at a certain gateway (NWP 21 and NWP31 in the *new* and *fra* cases respectively). Westbound wind optimal trajectories generally bypass the jet stream core area to the north or to the south and converge on the gateway area. The *fra* model is the least constrained and its simulation result indicates that NWP31 is the gateway closest to the ideal oceanic airspace exit point. However, the parallel ATS route structure in the *dct* and *new* cases constrains westbound traffic that enters the NOPAC area from the east, since such traffic generally cannot cross the eastbound ATS route to join the westbound ATS route connected to the ideal exit gateway. Consequently, such traffic would tend to exit oceanic airspace through gateways south of the eastbound traffic entry gateway. Further analysis is a future work.

On the other hand, eastbound flights tended to become more distributed between the gateways, and removing the NOPAC ATS routes gives the greatest dispersion of traffic.

Regarding the effect of the new gateway configuration (*new* and *fra* cases) on PLOS, Table III shows the average PLOS counts and PLOS times. Considering PLOS count, this increases for westbound flights as the degree of flexibility in route selection increases (i.e., *dct* < *new* < *fra*). For eastbound flights, *new* case results in the lowest PLOS count, and the PLOS count of the *fra* airspace design, which allows crossing the NOPAC area, is similar to the *dct* case. For PLOS time, the new gateway design gives higher PLOS times for westbound traffic and lower PLOS times for eastbound traffic. Overall, westbound traffic converges at the gateways and tends to concentrate at specific gateway points. Although adding gateway points gives more possibilities, both PLOS counts and times are increased. Eastbound traffic tends to diverge from the gateways, and adding further gateways does not increase PLOS events.

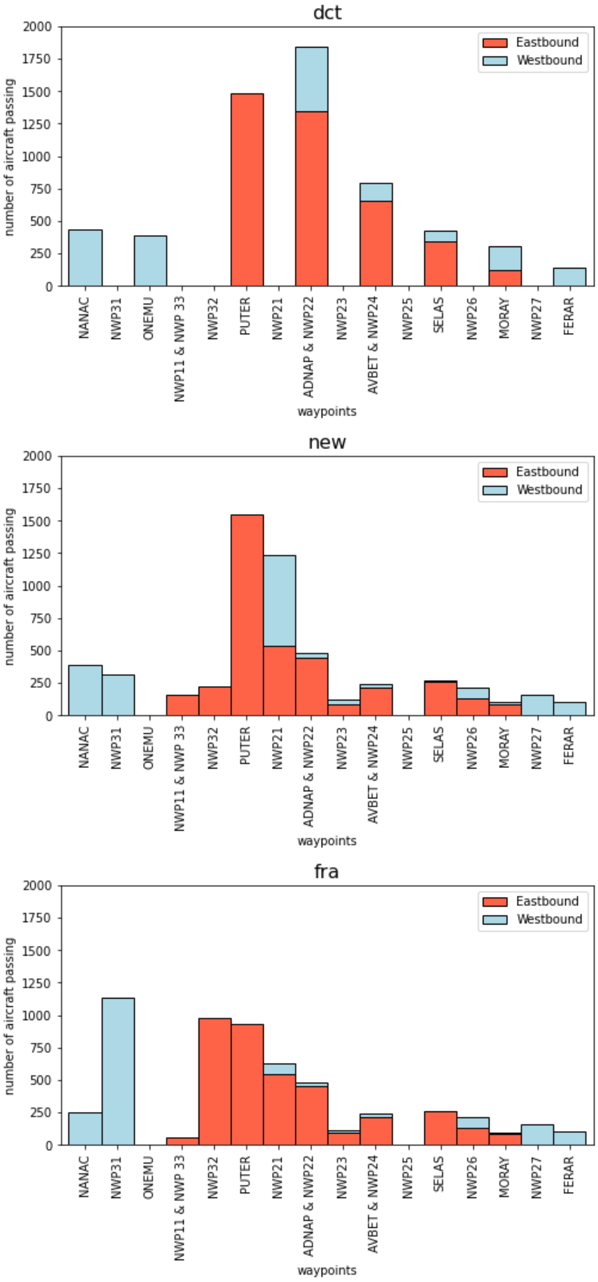


Figure 7. Total number of flights passing through each gateway for the 11 wind days

Increasing the number of oceanic gateways in Fukuoka FIR and reducing their spacing gives greater flexibility to plan flight routes that are closer to optimal. The result disperses eastbound traffic and reduces its PLOS events, since eastbound traffic originates from geographically close airports and the optimal routes fan out to dispersed destinations, but results in a concentration of westbound traffic at specific gateways, since it has the opposite characteristic and optimal routes converge. It might be said the proposed gateway alignment has improved eastbound traffic flow, although the issue of how much flexibility in routing to allow in the airspace after passing the gateways remains.

TABLE III. PLOS COUNT AND PLOS TIME PER FLIGHT IN EACH AIRSPACE CONFIGURATION

	PLOS count		**PLOS time (minutes)**	
	E	W	E	W
dct	0.15	0.12	11.4	10.2
new	0.14	0.12	10.7	11.2
fra	0.14	0.16	10.1	11.0

E; eastbound, W; westbound

V. CONCLUSION

Airspace design that enables the realization of more operator desired routes over the North Pacific Ocean was studied. One cause of loss of oceanic airspace efficiency is that flights may be prevented from cruising at their planned altitudes by other traffic, either due to congestion at oceanic airspace entry gateways, or due to a planned step climb inside oceanic airspace being delayed by other traffic occupying the requested higher level or head-on traffic at an intermediate level, possibly for an extended period of time.

To investigate this, a step-climb calculation function was added to an optimal trajectory generation program which was used to calculate wind optimal flight routes for a schedule of flight services between Asia and North America, with multiple wind conditions used to reflect seasonal variation of the jet stream. Fast-time simulations were then executed to clarify the PLOS hotspots. The results show that PLOS hotspots occurred on the Japan side of the North Pacific oceanic airspace, where westbound traffic flows converge and eastbound traffic diverges. Higher PLOS results in fewer opportunities to reach planned altitudes as described above, and reduces flight efficiency.

We then considered airspace design to enable operators to achieve their planned flight trajectories more closely. Additional oceanic gateway points were added at half the existing interval between Fukuoka FIR radar-controlled and oceanic airspaces and route design freedom in the NOPAC area was increased. Additional simulations to examine their effect showed that the proposed gateway configuration resulted in a greater dispersion of diverging traffic and reduced PLOS events for eastbound flights, while westbound traffic became concentrated on converging optimal routes. We suppose that the reason why westbound flights concentrated at certain gateways is due to the route configuration of the NOPAC area. Establishing a one-way eastbound route in the NOPAC area creates a barrier that divides the area lengthways. The FRA configuration removes such a constraint and so increases the route flexibility for traffic approaching from the east, possibly allowing entry into radar-controlled airspace at a more optimal gateway. This requires further analysis.

In the absence of further improvements in airspace design, and it will be necessary in the future to introduce ATFM measures at oceanic gateways to mitigate the concentration of traffic flow. Assignment of gateways and/or gateway crossing times by air traffic control or an ATFM unit might be used to reduce conflicts and alleviate congestion, particularly for westbound traffic. Although trajectory modification by ATFM this will result in some flights having a higher fuel burn than on operator-requested trajectories, on the other hand the resulting alleviation of PLOS might increase step climb opportunities and offset the fuel penalty by allowing more flights to operate at optimum altitude, as well as alleviating congestion. These are topics for future study.

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