国際交通流に関するフリールート空域概念と予測精度

航空交通管理領域　ブラウン　マーク，※村田　暁紀，平林　博子，
ビクラマシンハ　ナヴィンダ，虎谷　大地，井無田　貴

1 Introduction

The volume of air traffic in the Fukuoka Flight Information Region (FIR) is resuming the upward trend that existed prior to the SARS-CoV-2 pandemic. While domestic (intra-Japan) traffic will remain largely constant, international traffic (between Japan and overseas) and overflight traffic are expected to increase. Responding to this demand will require increasing airspace capacity, alleviating the effects of congestion by better management of delay through international air traffic flow management (ATFM), and increasing flight efficiency to offset the climate change impact.

In March 2025, we completed a four-year research project aimed at creating smoother and more efficient international air traffic flows. We explored using the Free Route Airspace (FRA) concept to increase the flexibility of flight planning and thereby flight efficiency. We also examined use of trajectory-based operations (TBO) concepts for international air traffic flow management (ATFM), and considered ways to improve their effectiveness.

In this paper, section 2 outlines a simulation-based study that demonstrates the potential to increase the efficiency of flights between North America and Asia by introducing the FRA concept into oceanic NOPAC airspace. In section 3, we introduce time-based management concepts for distributed international ATFM in the Asia-Pacific region, and present the results of a case study that applied machine learning to improve the accuracy of trajectory prediction. In section 4 we propose exploiting the increased trajectory predictability and information sharing gained from TBO by coordinating ATFM measures further ahead of time with operators using Collaborative Decision Making (CDM).

2 NOPAC Free Route Airspace Concept

Much of the air traffic between Asia and North America traffic passes through the Fukuoka FIR, and the oceanic airspace known as NOPAC, over the Pacific Rim east of the Kurile Islands and Kamchatka that carries traffic between Japan and Alaska, is particularly highly demanded.

Wind conditions over the North Pacific are dominated by the westerly jet stream, which strengthens and moves to northerly latitudes in winter and weakens and moves to southerly latitudes in summer. The routes of eastbound flights are planned to exploit the strong tailwind in the jet stream core area, while westbound flights avoid the strong headwind area over the North Pacific, often by skirting the Pacific rim. Accordingly, traffic between Asia and North America across the North Pacific Ocean uses flexible tracks that are planned according to the winds aloft. The NOPAC area, however, is structured with a set of parallel fixed airways in order to handle the traffic demand. Although it is on the Pacific margin and flight planning through NOPAC is less affected by the jet stream, our studies showed that the currently ongoing NOPAC airspace restructuring that reduces the lateral spacing of the routes [1, 2] will allow more flights to benefit from flexible tracks and so increase efficiency [3].

These studies prompted us to explore the effect of removing the NOPAC fixed routes entirely; effectively, turning the NOPAC airspace into a free route area, while exploiting greater automation support for air traffic control (ATC) and improved communication, navigation and surveillance (CNS) performance to manage the expected increase in traffic complexity. We carried out simulation experiments to study this issue with two questions: (i) what would be the gain in flight efficiency from free routing in the NOPAC relative to fixed airways, and (ii) how would a NOPAC FRA affect airspace capacity; that is, would the airspace be manageable. The study is reported in detail in ref. [4].

2.1 NOPAC FRA Design

NOPAC airspace is being restructured taking advantage of CNS improvements in oceanic airspace. As a further future step, we propose a free route airspace that removes the NOPAC fixed routes and increases the number and density of oceanic gateway points. The configuration studied is shown in figure 1. Air traffic passes between oceanic airspace and radar-controlled airspace via fixed gateway points. At present, the gateways on the Japan side of oceanic airspace are at intervals of approximately 60NM. As well as expanding the flexible track area to include the NOPAC region, we propose to reduce the interval between gateways to approximately 30NM to allow more flexible flight planning and dispersal of traffic concentrations.

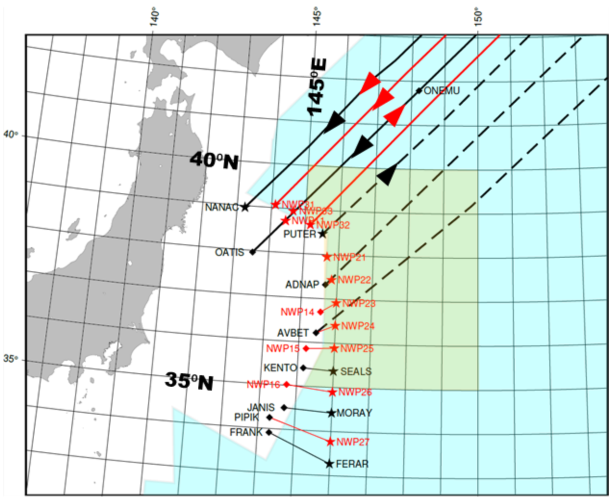

Figure 1. Proposed oceanic gateway points between Fukuoka FIR radar-controlled airspace and oceanic airspace (blue). Black lines indicate the current NOPAC airways. Arrows indicate the directions of one-way routes. In NOPAC redesign phase 3, the dashed line routes are removed and new red line routes are set. Gateways shown as red stars are newly added in this study.

2.2 Experiment

We compared the airspace configurations of the proposed NOPAC FRA and gateways (configuration M3) with the original NOPAC routes (M1) and an intermediate NOPAC restructuring (M2) by fast-time simulation, looking at the effects on individual flight routes and performance, and on changes in air traffic complexity.

We created a traffic demand scenario based on a schedule of flights between existing city pairs in Asia and North America in 2019. Since flight routes vary depending on wind patterns that change over a year, the experiment used wind conditions on multiple days selected to represent seasonal trends [5, 6]. For each wind condition, wind-optimal (minimum flight time) routes for each flight were calculated using a tool developed for this research [7] extended to calculate optimal step-climb points [8]. The fuel burn and flight time of each flight were calculated given forecast wind and temperature conditions. Trajectories for each flight were generated by the AirTOp fast-time simulator and checked against each other for Potential Loss of Separation (PLOS). For each trajectory pair that came into conflict, the number of times that the distance between the aircraft became less than prescribed separation minima were tallied (PLOS count) and the durations of each loss of separation were summed as PLOS time.

Because separations between trajectories vary according to departure time, and step climb positions and aircraft performances vary with aircraft mass, simulations for each traffic demand schedule and wind condition were repeated with randomly perturbed weights and departure times, and the results were averaged.

2.3 Results

Figure 2 compares the original NOPAC airspace design with the intermediate NOPAC restructuring and the proposed NOPAC FRA (M1, M2 and M3 respectively) for eastbound flights (left graph) and westbound flights (right graph). The left bars in each graph (labelled 2D effect) show fuel benefit. Each step to improve the NOPAC airspace gives a reduction in fuel burn and flight distance. Increases in PLOS (omitted for brevity) could be offset by further reducing separation minima, for example by using near real-time surveillance (e.g. space-based

ADS-B [9]).

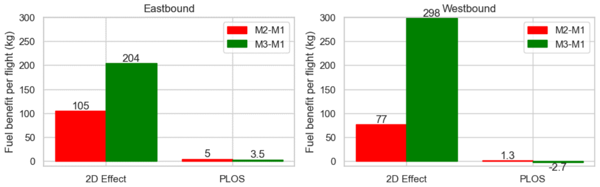

Figure 2. Fuel consumption benefit ("2D Effect") and changes in fuel consumption due to PLOS resolution (PLOS) comparing airspace configurations M2 with M1, and M3 with M1.

The removal of the fixed routes through NOPAC had an effect on westbound traffic flow, shown in fig. 3. The optimal flight routes of westbound flights through the NOPAC area trend towards the western edge of the area, parallel to the boundary with Russian Federation airspace (green dotted line). However, flights are prohibited from crossing opposite-direction NOPAC routes (pink line), so flights that enter the NOPAC airspace through its eastern boundary are prevented from reaching the western boundary of the NOPAC area but must enter Fukuoka FIR radar-controlled airspace through a gateway that is further east than optimal (solid green line). Removing the NOPAC routes enables such flights to reach the western edge of the NOPAC and causes a higher concentration of traffic at the western-most gateway as well as increasing airspace complexity due to crossing traffic.

Figure 3. Route trends of westbound flights from North America to Japan and South Korea. Dashed green line indicates the ideal route that avoids jet stream core area (shaded) and is available in NOPAC FRA. With fixed NOPAC routes, flights cannot cross the NOPAC eastbound fixed airway (pink line) and hence must use the solid green line route.

We investigated the trade-off between the fuel benefit of being able to plan more efficient routes and increased traffic complexity by assuming that each PLOS event could be resolved by one flight of a conflicting pair descending to a lower, less fuel-efficient altitude for the PLOS duration. The changes in fuel consumption due to PLOS resolution are shown in the right-hand bars in the graphs of fig. 2. It was found that even with this penalty, there was a net reduction in fuel burn from allowing flights to cross the NOPAC area as shown in fig. 3. Further analysis of whether this is manageable from ATC workload and operational perspectives is a future work.

3 ATFM and Trajectory Prediction

3.1 Distributed International ATFM

ATFM addresses imbalances that arise between the demand for airspace and airport resources and their capacities. When the demand is predicted to exceed capacity (which often occurs at congested airports at peak times), it must be reduced to within available capacity by either delaying or diverting flights. In Europe, ATFM is carried out across multiple FIRs by a centralised air traffic flow management unit. However, in the Asia-Pacific region, there is no centralised regional ATFM function and so international (cross-border) ATFM must be distributed between the FIRs.

We investigated international ATFM in the Asia-Pacific region in joint research with Korea Aerospace University, the Korea Aerospace Research Institute (KARI), and Nanjing University of Aeronautics and Astronautics (NUAA) [10]. There are two distributed international ATFM mechanisms in the Asia region; APAC Cross-Border Multi-Nodal ATFM Collaboration (AMNAC, previously called Multi-Nodal ATFM) that operates between countries mainly in southeast Asia, and the North Asia Regional ATFM Harmonization Group (NARAHG) that operates between China, Korea and Japan. Both use time-based ATFM mechanisms that leverage TBO. With TBO, flights are managed using trajectory information that is shared between stakeholders involved in the flight. Trajectories include not only lateral route and vertical profile, but also time at each point, and allow a more precise expression of a flight's path (planned, predicted, or flown) than a current ICAO flight plan.

Prior to TBO, there was limited cross-boundary information sharing and traffic flow was controlled using minutes-in-trail or miles-in-trail restrictions applied at the FIR boundary (e.g. 10-minute intervals between flights with destination ZBAA at AVAGO). TBO enables precisely targeted ATFM measures, allocating delay to individual flights by imposing a time constraint. With AMNAC, a congested airport may delay an inbound flight that has not yet departed by assigning a Calculated Take-Off Time (CTOT) from the departure airport. With NARAHG, an FIR with a capacity constraint may delay flights by assigning a Calculated Time Over (CTO) at the FIR boundary, and the departure FIR calculates a corresponding CTOT. A simulation case study by KARI demonstrated that CTO/CTOT is more effective than MIT/MINIT and can achieve a more equitable allocation of delay [10].

3.2 Improving Prediction Accuracy with Machine Learning

With time-based ATFM, flights are effectively assigned a target time slot. Flights that fail to meet their time slot reduce the effectiveness of the ATFM and create additional ATC and ATFM workloads, so a margin is required to ensure that the probability of a missed slot is reasonably low. Too large a time buffer, however, also reduces efficiency. The effectiveness and efficiency of ATFM therefore depend on the predictability of the trajectory.

One approach to flight trajectory prediction is physical modelling; each flight is modelled using a simplified physical aircraft model, typically a point mass model, and a set of performance and operating parameters, typically dependent on aircraft type and flight phase, for example the Base of Aircraft Data (BADA) model and database developed by EUROCONTROL [11]. Given a flight plan route and cruise altitude, and a set of initial conditions and forecast weather, it is possible to calculate when the aircraft will reach each point along its planned route by essentially a fast-time simulation. However, apart from being time-consuming, this method does not address factors that may influence a flight but are difficult to incorporate into a physical model, including delays that might be expected due to traffic and weather. Moreover, not all of the performance parameters might be available, such as departure weight and the cost index (tradeoff between flight time and fuel consumption) used by the aircraft operator.

As an alternative, statistical modelling based on historical data has been receiving attention, particularly since the development of machine learning (ML) techniques that can automatically infer relationships between significant parameters (features) and quantities that we wish to predict. As a case study to explore the potential of ML for improving trajectory prediction, we evaluated a ML regression model of flight time from take-off to reaching a point on a standard instrument departure (SID) at Narita International Airport (RJAA), described in more detail in ref. [12]. We used historical data obtained from radar surveillance records to train a gradient-boosting histogram regression model specifying features including temperature and winds at the airport, aircraft type, estimated en-route time (as a surrogate for trip fuel), and aircraft operator. We compared predictions by the regression model with simple average flight times.

Using average flight time as the predicted value, the mean prediction error of a large number of predictions will be zero, but there may be a larger than acceptable variance. For the TETRA8.ENPAR departure, the average flight time of 12,225 samples was 11.4 min. with a standard deviation of 0.93 min. Assuming a normal distribution, this would result around 68% of predictions having an absolute error of 1 minute or less.

Figure 4 shows the distribution and cumulative probability of flight time prediction error using average flight time (left) and the regression model (right). The prediction accuracy of the average is consistent with a normal distribution; that is, around 72% of predictions are within +/-1 min, while with the regression model the probability rises to around 88%. This demonstrates the potential of ML to improve trajectory prediction accuracy and contribute to more effective ATFM.

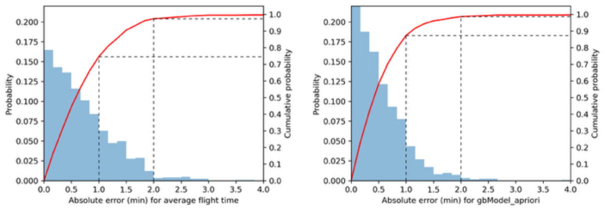

Figure 4. Distribution (bars) and cumulative probability (red line) of absolute error in flight time prediction of the TETRA8.ENPAR SID. Left graph shows the result using the average flight time value as the prediction, and right graph shows the result using prediction with a regression model. Dashed lines indicate probabilities of prediction accuracy within 1 and 2 minutes.

4 Trajectory-Based ATFM with CDM

Improved predictability from TBO will enable decisions about resource allocation to be made further ahead of time, rather than on a first-come first-served (FCFS) basis. This will give traffic managers flexibility to meet other objectives; for example, lowering greenhouse gas emissions across the ATM system as a whole, or achieving more equitable delay allocation. Making decisions ahead of time will also allow stakeholder preferences to be incorporated. However, this raises the question of how to balance the allocation of a limited resource between sometimes conflicting performance objectives and competing stakeholders.

This situation is similar to so-called Wicked Problems encountered in social planning and policy, in that there is no single “best” solution due to incomplete and conflicting requirements. Possible approaches to deal with such problems include Authoritative, where decision-making is entrusted to a small group, and Collaborative, which engages all stakeholders to find a mutually-acceptable “best” solution. In considering this, we drew on our previous research to proposed a concept for using ATFM incorporating CDM to allocate oceanic entry conditions between flights.

Our previous research studied tradeoffs of allocation of oceanic cruising level and oceanic airspace entry time to overflight traffic and departures from Japan, where the latter are disadvantaged under FCFS because overflights, which are already airborne, take precedence. For a set of traffic predicted to enter oceanic airspace within a given time period, we used a genetic algorithm to determine optimal conflict-free combinations of departure delay and flight level allocation at the gateways that could be used to give a more equitable distribution of delays and cruise altitudes [13]. We propose extending this work to allow collaborative selection of the set of Pareto-optimal oceanic airspace entry conditions through a CDM negotiation mechanism [14]. Challenges include the fact that prediction accuracy improves as the time forecast time decreases; the solutions presented must be robust against inaccurate prediction. We intend to elaborate the concept further in the future.

5 Conclusion

This paper has overviewed some of the main results from our research into improving international air traffic flows in Fukuoka FIR, in collaboration with other FIRs for ATFM and stakeholders via CDM. Our future research will continue some of these topics; in particular, the use of machine learning to improve ATFM, and our CDM concept for strategic resource allocation that gives flexibility to implement policy that balances performance objectives and stakeholder preferences.

Acknowledgements

The authors acknowledge the cooperation of the Japan Civil Aviation Bureau, including the provision of data.

References

[1] Blackwell, T., “NOPAC Route System Re-design Project,” https://ops.group/blog/wp-content/uploads/2023/05/NOPAC-ROUTE-SYSTEM-REDESIGN-PROJECT-final.pdf

(Retrieved May 2025).
[2] Thornton, S., and Blackwell, T., System Impact Report NOPAC ATS Route Structure Changes. Federal Aviation Administration (FAA) Memorandum, 24 November 2021. https://www.faa.gov/sites/faa.gov/files/2022-01/NOPAC-Route-Changes_SIR.pdf (Retrieved May 2025).
[3] Brown, M., and Hirabayashi H., "A Simulation Study of Alternative Route Structures for NOPAC Airspace Reconfiguration", 2019 Asia Pacific International Symposium on Aerospace Technology (APISAT2019), Dec. 2019, Gold Coast, Australia.
[4] Hirabayashi, H., Brown, M., and Takeichi, N., "Airspace Design Proposal for Efficient Flight Operations in North Pacific Oceanic Airspace," Fifteenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2023), Savannah, USA, March 2023.
[5] Hirabayashi, H., Brown, M., and Takeichi, N., "Study of a Representative Wind Selection Method using Track Data to Evaluate Pacific Flight Operations," Proc. 59th Aircraft Symposium, JSASS-2021-5041-1D04, 2021. (In Japanese.)
[6] Hirabayashi, H., Brown, M., and Takeichi, N., "Study of a representative wind selection method using track data to evaluate Pacific flight operations," J. of Air Transport Management Vol. 119, Article 102639, 2024. https://doi.org/10.1016/j.jairtraman.2024.102639
[7] Brown, M., Hirabayashi, H., and Wickramasinghe, N. K., "A Graph Search-Based Trajectory Optimiser for Practical Wind-Optimal Trajectories," Proc. 2018 Asia Pacific International Symposium on Aerospace Technology (APISAT2018), pp. 2201–2208, 2018. DOI: org/10.1007/978-981-13-3305-7_177.
[8] Hirabayashi, H., Brown, M., Wickramasinghe, N. K., Suizu, H., and Takeichi, N., "Effect of step-climb operation on long-haul flight over the Pacific Ocean," Proc. 2022 Asia Pacific International Symposium Aerospace Technology (APISAT2022), S22-3, 2022.
[9] Aireon, "Space-Based ADS-B via Low Earth Orbiting Satellites – Concept and benefits for use in oceanic and remote air traffic management environments," ICAO SAT/21 WP09 presentation, June 2016.
[10] Brown, M., Kim, H., Wang, Y., Lee, K., Hirabayashi, H., Wickramasinghe, N. K., Murata, A., Jeon D., Eun Y., Oh, E., Lee, S., and Gray, N. H., "International Air Traffic Flow Management in North and East Asia," 2022 Asia Pacific International Symposium Aerospace Technology (APISAT2022), Oct. 2022, Niigata, Japan.
[11] EUROCONTROL, "User Manual for the Base of Aircraft Data (BADA)-Revision 3.6," EEC Note No. 10/04, 2004.
[12] Brown, M., Murata, A., Hirabayashi, H., and Imuta, T., "Departure Flight Time Prediction at Narita International Airport using Machine Learning," 2024 Asia Pacific International Symposium on Aerospace Technology (APISAT2024), Oct. 2024, Adelaide, Australia.
[13] Murata, A., Takadama, K., Toratani, D., Hirabayashi H., and Brown, M., Benefit Balancing between Japan Departure Flights and Overflights in the North Pacific Route System. Trans. JSAS Aerospace Tech. Japan, Vol 20., pp.41–48, 2002. DOI:10.2322/tastj.20.41
[14] Brown, M., Murata, A., Hirabayashi H., and Imuta, T., "A Concept for Air Traffic Management Performance Balancing in Trajectory-Based Operations with Collaborative Decision Making," 2024 International Workshop on ATM/CNS (IWAC2024), Tokyo, Japan.