フリールート空域の設計、潜在便益、及び評価について

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1 Introduction

Area navigation (RNAV) removes the need for aircraft to fly between ground-based radio navigation aids, enabling "free route operations" that allow airspace users to plan routes that are closer to their ideal trajectories. Figure 1 shows the Free Route Airspace (FRA) concept. In conventional airspace, flights plan to fly between waypoints (triangles) along Air Traffic Service (ATS) routes (white). With Free Route Airspace, flights may plan a direct route between entry points (E) and exit points (X) at the edges of the airspace, or via one or more intermediate points (I), for example to avoid restricted airspaces or weather.

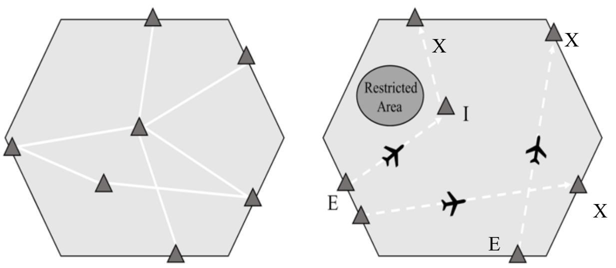

Figure 1 Conventional airspace (left) and Free Route Airspace (right).

FRA has been adopted by the International Civil Aviation Organization (ICAO) as an Aviation System Block Upgrade (ASBU), and implementation is being planned regionally. FRA has been implemented in much of European upper air space, as shown in Figure 2 [1], and greater benefits are obtained by creating FRA blocks that span Flight Information Region (FIR) boundaries (shown by red outlines in Figure 2). In Asia/Pacific, it has been identified in the regional Seamless ANS Plan as a Priority 2 implementation item, following Direct Routes, UPR, and Flexible Routing as intermediate steps [2], and the AFI region has produced a concept of operations [3].

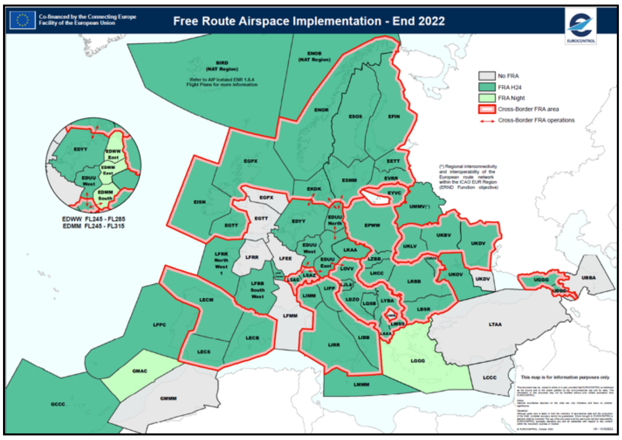

Figure 2 Free Route Airspace (FRA) Implementation in Europe at End 2022 [1].

ENRI and the Korea Aerospace University (KAU) have been collaborating in joint research, and have proposed introducing FRA into the Asia/Pacific region [4], developed a concept of operations [5, 6], and conducted airspace design studies [7, 8, 9]. In this paper, we summarise the results of these studies, discuss benefits, and identify topics for further research.

2 Free Route Airspace Concept in NE Asia

The ENRI/KAU concept for FRA proposed three maximally-sized blocks of FRA shown in Figure 3: the airspace of Incheon FIR (Incheon FRA), Fukuoka FIR radar-controlled airspace (Fukuoka Domestic FRA), and Fukuoka FIR oceanic airspace (Fukuoka Oceanic FRA). The base altitude of FRA was set at FL310 or higher based on an analysis of initial cruise altitudes of flights from Incheon airport to North America [6]. Following this concept proposal, ENRI then examined airspace design to implement FRA in Fukuoka FIR radar-controlled airspace and oceanic airspace. These studies were supported by development of a tool to create optimum user trajectories in a free route environment [10].

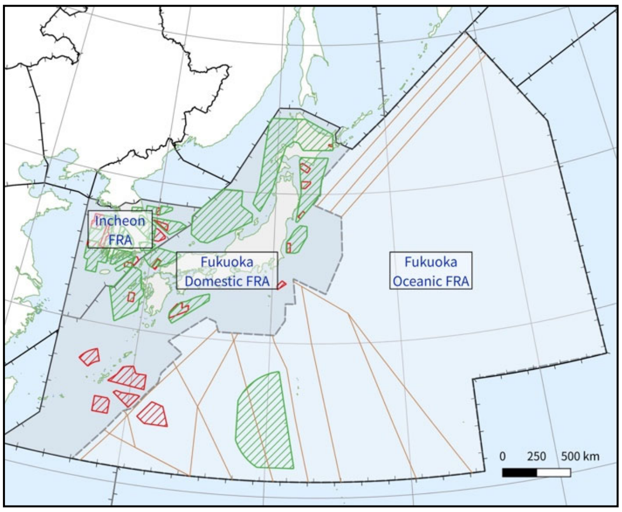

Figure 3 Initial proposed maximum-sized FRA blocks for Republic of Korea and Japan [5]. Hatched areas indicated restricted use airspaces at FL310 and above: green indicates training areas and red indicates military restricted areas. Brown lines in oceanic airspace indicate ATS routes retained in the initial proposal.

2.1 Radar-Controlled Airspace

Two cases were considered for FRA design in Fukuoka FIR radar-controlled airspace: domestic traffic (flights departing from and arriving at airports in Fukuoka FIR), and overflight traffic (flights crossing Fukuoka FIR). As case studies, we examined the 10 domestic city pairs with the greatest traffic [8], and overflights between Incheon FIR and oceanic airspace [7, 9]. The following were considered in FRA design:

(1) The maximum-size FRA block (i.e. covering the whole of radar-controlled airspace) was considered initially to avoid inefficiencies due to airspace fragmentation.

(2) For initial implementation, changes to existing airspace should be minimizsed, and the dimensions and availabilities of civil and military training airspaces were assumed as fixed.

(3) Horizontal entry and exit points are designated at the edges of the FRA, denoted as ‘E’ (entry), ‘X’ (exit) or ‘EX’ (entry and exit), determined by the directions of the existing ATS routes that pass through those points.

(4) Vertical entry and exit points are set around airports to allow traffic to transition between terminal airspace and FRA. These are denoted as ‘A’ for exit points (where A stands for arrival) or ‘D’ for entry points (where D stands for departure). This was achieved by analysis of radar tracks as well as the instrument departure and arrival procedures (SID and STAR) to determine at what points traffic would enter or leave FRA by ascent and descent.

(5) The most common restriction preventing flights from routing directly between FRA entry and exit points is the presence of restricted use airspaces (shown as red and green polygons in Figure 3). FRA intermediate points, denoted as ‘I’, were established around these airspaces to allow flights to plan to bypass them with minimum buffer distance when active. The buffer distance was set nominally at 10 nautical miles (NM), although the actual distance should be determined by a safety analysis. Where crossing the training airspace is permitted by a Conditional Route or fixed ATS route, those routes were retained but terminated by ‘I’ points at the minimum buffer distance from the airspace boundary.

To support airspace design, the most commonly-filed flight plan routes between the targeted airport pairs for domestic flights, and between radar-controlled airspace entry/exit points for overflight traffic, were analysed. Traffic and flight plan data were selected from 2019 to reflect traffic levels prior to the COVID-19 pandemic. The airspace designs were evaluated mainly in terms of changes in flight plan route distance; that is, the difference between the length of flight plan routes in the baseline airspace (with ATS routes) and in the FRA airspace.

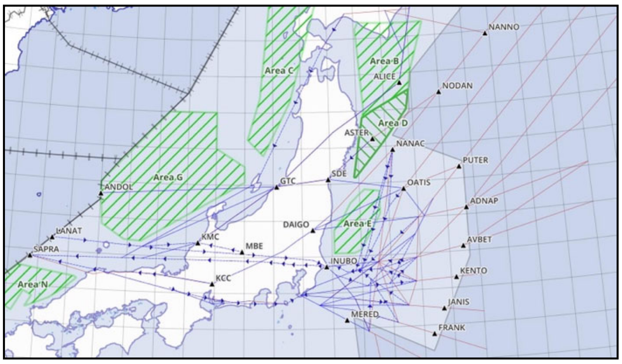

Figure 4 Simplified diagram of airspace across northern Honshu in mid-2019 showing RNAV ATS routes between Incheon FIR and oceanic airspace (blue) and conventional ATS routes (brown). Training areas are shown as green hatched polygons.

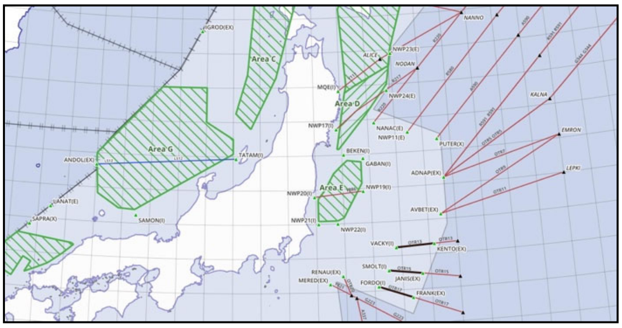

Figure 5 Example of FRA design of the airspace in Figure 4 considering traffic between Incheon FIR boundary and oceanic airspace.

As an example of airspace design, Figure 4 shows a simplified diagram of the airspace over northern Honshu in around mid-2019, and Figure 5 shows an FRA design of the airspace considering traffic between the Incheon FIR boundary and oceanic gateway points following the principles outlined above. The difference in flight plan distance for 2019 traffic following the most common flight plan routes between the Incheon FIR boundary and oceanic gateways via the ATS routes in Figure 4 and routes between the same entry and exit points planned through the FRA in Figure 5 is on the order of 150,000 NM per year. This is approximately equivalent to 300 hr flight time, 3,000,000 lb of fuel (assuming a twin-engined widebody aircraft consuming fuel at 10,000 lb/hr) or 4,300 tonnes CO_2 (assuming 3.16 kg CO_2 per 1 kg of fuel).

One design parameter that remain unresolved in the airspace design in Figure 5 was the FRA base altitude. En route radar-controlled air space is currently being restructured, with upper air space established at and above FL335. However, our studies indicate that approximately half the traffic originating from Seoul bound for North America via Fukuoka FIR enters at ANDOL and LANAT at FL310 or below. It may be desirable to consider different FRA floor altitudes in different airspace sectors depending on the traffic characteristics.

Figure 6 Flight tracks (grey lines: below FL310, red lines: above FL310) and most common flight plan route (dashed black line) of flights from Hiroshima airport (RJOA) and Tokyo Haneda airport (RJTT) during a week in 2019.

Regarding setting FRA(A) and FRA(D) points around airports, our study [6] showed cases where this may not so straightforward. Figure 6 shows radar tracks and the most commonly filed flight plan route of flights from Hiroshima airport (RJOA) to Tokyo Haneda (RJTT) airport during a week in May 2019. Departures from RJOA ascend above FL310 at MOMOT, which could therefore be designated as an FRA(D) point. However, the designation of a suitable FRA(A) point for RJTT for this traffic stream is less easy. Traffic descends below the FRA base altitude around SHOOT (changing from red to grey in Figure 6), but radar vectoring starts from around SHTLE during congested periods, and it is undesirable that vectoring should be handled in FRA, which is considered as en route airspace in our concept. Alternatively, setting the FRA(A) point at SHTLE or GAKKI could force traffic to be descended before its optimal top-of-descent point and reduce flight efficiency. In such cases, a cost-benefit analysis may be necessary, and a loss of flight efficiency due to vertical profile changes associated with FRA may be possible.

ATS routes are used to manage high volume traffic flows by imparting structure, and some fixed routes may be required to reduce traffic complexity in an FRA environment. In Japan and Korea, major bidirectional traffic flows are structured using pairs of opposite-direction ATS routes, and these routes give close to great circle flight distances between terminal areas for the highest demand city pairs while separating traffic in each direction and increasing ATC manageability. In FRA, a similar effect could be achieved without fixed routes by the design of the airspace geometry and the locations of entry and exit points considering the traffic demand. Structuring traffic flows by such means is less flexible or easy to change than by the use of mandatory routes or ATS routes, however.

Our study also raised a concern that free routing might reduce a degree of flexibility used by air traffic controllers (ATCOs) for control. In Figure 6 it is observed that departures from RJOA are often appear to be given a “direct to” towards SHTLE on the flight plan route leg between MOMOT and IKUNO, but the timing varies; in fact, in some cases, flights are required to extend the leg beyond IKUNO. This traffic flow crosses another traffic flow between MOMOT and SHTLE, and we speculate that ATCOs use flown distance along the MOMOT-IKUNO leg as a control to allow traffic to cross that flow without conflicts. In a simple FRA airspace, such flights would be able to fly direct from the FRA(D) point at MOMOT to the FRA(A) point for RJTT (SHOOT, GAKKI or SHTLE, as discussed previously), which might reduce this flexibility. The FRA sector controller would have to coordinate with the terminal controller if it was desired for a flight to maintain its present heading after MOMOT, which would increase coordination workload. On the other hand, a mandatory route could be added between MOMOT and IKUNO to allow short cuts.

2.2 Oceanic Airspace

Figure 7 shows North Pacific Oceanic airspaces. Flight planning is dominated by westerly jet stream winds, with the optimal routes between city pairs varying from day-to-day and having seasonal trends according to the winds. For flights across the central North Pacific area (CENPAC in Figure 7), PACOTS (Pacific Organized Track System) tracks are published daily that are designed to give minimum flight time between certain key city pairs considering forecast winds, adjusted for mutual separation. Airspace users may also plan User-Preferred Routes (UPR), which have restrictions based on the PACOTS tracks to avoid conflicts.

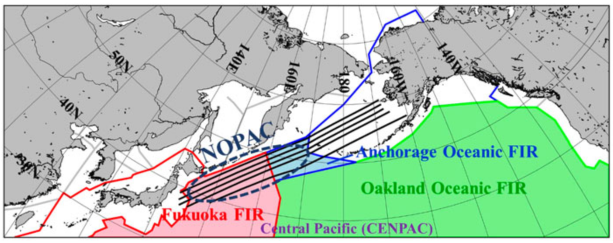

Figure 7 Oceanic airspaces over the North Pacific Ocean. Fukuoka FIR is bounded by the red line, with its oceanic airspace shown as a red shaded area. Anchorage Oceanic FIR is shown as the blue area, and Oakland Oceanic FIR is the green area. The NOPAC ATS routes are shown as black lines between Japan and Alaska.

There is a region of high traffic demand between Japan and Alaska parallel with Russian Federation FIR boundaries. Traffic from North America to Asia tends to select routes through this region to avoid strong headwinds, and the region is also crossed by routes between the North American central and east coast areas and Asia. There is also high demand by cargo traffic between Asian cargo hubs and Anchorage. To deal with this demand, a set of five approximately parallel ATS routes around 50 NM apart, called NOPAC (North Pacific), has been established. Other routes such as PACOTS and UPR may also partially overlap with NOPAC routes.

ATC in oceanic airspace is procedural due to communication, navigation and surveillance (CNS) performance limitations, and flights are admitted into oceanic airspace on trajectories that are conflict-free for several hours ahead. Oceanic operations have changed, however, as CNS performance has improved. Most aircraft that operate through Fukuoka FIR oceanic airspace have at least RNAV10 navigation performance and are equipped with FANS-1/A (Future Air Navigation System–1/A) avionics with satellite communication-enabled ADS-C (automatic dependent surveillance–contract) and CPDLC (controller-pilot data link communication), which enable 50 NM longitudinal separation and 50 NM lateral separation on parallel or non-intersecting tracks to be applied. These separation distances may be reduced to 23 NM between aircraft that meet RNP4, RCP240 and RSP180 requirements for navigation, communication and surveillance performance, respectively, in PBCS (Performance-Based Communications and Surveillance)-monitored airspace (see table 5-2 of PANS-ATM [11]). In Fukuoka FIR, 30 NM longitudinal separations have been applied in oceanic airspace between PBCS-compliant aircraft since 2018. Taking advantage of PBCS capabilities, over the next few years the NOPAC routes are being restructured to reduce their spacing to 25 NM and their number from five to three, increasing the area available for free routing. A study by ENRI to investigate NOPAC restructuring proposals has shown that enlarging the free route area will give a fuel reduction benefit to operators, particularly in summer when optimal routes are further north due to the position of the jet stream [12].

Looking beyond the current NOPAC restructuring plans, we have conducted a fast-time simulation study of the effect of removing the NOPAC ATS routes entirely, permitting free routing throughout the whole of North Pacific oceanic airspace [9]. The study included the effects of seasonal wind tendencies, and showed a potential average benefit of 849 kg reduction in fuel burn for eastbound flights and 532 kg for westbound flights. The effect on ATC workload was estimated by examining Potential Loss of Separation (PLOS) between the simulated flight trajectories. Removal of the NOPAC routes resulted in a tendency for PLOS to increase with current separation standards, but this was suppressed by further reducing minimum separation to 15 NM, as could be achieved by using space-based ADS-B.

While these studies have shown benefits of increasing flight planning flexibility through free routing and reduced separation distances, another cause of loss of efficiency is aircraft being unable to step climb to higher altitudes as planned due to conflicts with other traffic. Such conditions may persist for long periods of time in oceanic airspace because of the greater separation margins required and limitations of procedural control. ENRI has been analysing ATC rejection of step climb requests in Fukuoka FIR oceanic airspace due to traffic to determine their causes [13], and with Tokyo Metropolitan University has developed an algorithm that can automatically identify blocking traffic in such cases with performance comparable to that of a human expert [14]. It was found that traffic concentrations near the oceanic gateway points along the boundary between radar-controlled and oceanic airspace can block step climbs. We have proposed creating additional oceanic gateways between the existing gateways, reducing the interval from approximately 60 NM to approximately 30 NM as enabled by PBCS, and potentially using gateway assignment as an air traffic flow management (ATFM) measure to disperse traffic concentrations and deconflict traffic. Although this may result in slightly less than optimal routes for some traffic, it may allow more opportunities for step climb that increase overall airspace efficiency. We are continuing to study this proposal.

3 FRA Benefits and Metrics

We now briefly discuss FRA potential benefits and ways of evaluating it. Potential benefits of FRA can be viewed from the point of view of each stakeholder in the air traffic management (ATM) system: (1) is benefit to the operator, (2) concerns air traffic control and (3) concerns the ATM system as a whole.

3.1 Operator Benefit

For air transportation flights, the optimum route typically minimises a trade-off between flight time and fuel burn, and for flights of up to a few hours, is approximated by a direct route between the terminal exit and entry points of the departure and arrival airports most aligned with the great circle between those airports. As flight time exceeds perhaps 3-4 hours, however, the benefits of a wind-optimised route over a great circle may start to become significant, and calculating operator benefit for airspaces in which flight planning is dominated by winds aloft is not straightforward due to varying wind patterns, although ENRI has studied how to do this in a way that reduces bias [15].

Operator benefit of FRA is therefore often quantified in terms of reduced flight plan distance due to more direct routes being possible than with ATS routes. Concomitant benefits include reduced flight time and fuel burn, which translates to operating cost and environmental impact reductions, and reduction in planned fuel, which can allow a greater payload capacity or lower fuel burn. However, while reductions in theoretical flight plan route distance and associated benefits are relatively easy to calculate, they might overestimate the actual reduction gained in practice. One reason is that in radar-controlled airspace, ATCOs tend to offer “short cuts” when the air traffic situation and controller workload allow. The resulting trajectories may be close to direct routes, so the delivered benefit in terms of actual reduction of flown distance might therefore be less than the theoretical benefit.

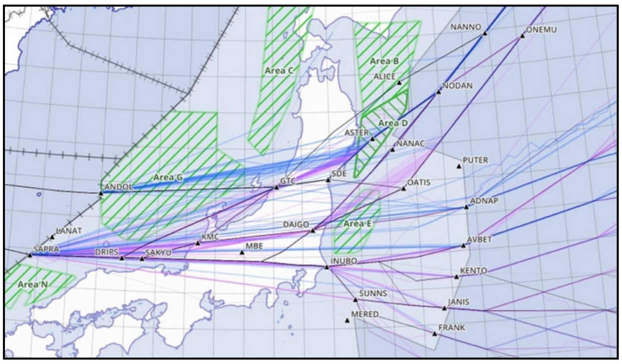

Figure 8 Radar tracks and flight plan routes of westbound flights between oceanic airspace and Incheon FIR during 20-26 May 2019. Blue lines indicate flights during the night period (crossing ANDOL or SAPRA between 00:00 and 07:00 local time), magenta lines indicate flights during the day (between 07:00 and 24:00 local time). Thin black lines indicate flight plan routes during 1-31 May 2019.

Figure 8 shows a sample of surveillance tracks of flights between oceanic airspace and Incheon FIR, with night tracks (crossing ANDOL and SAPRA between 00:00 and 07:00 local time) shown as blue lines and day tracks shown as magenta lines. Flight plan routes are shown as black lines and generally follow the ATS route structure shown in Figure 4. The effect of “short cuts” that bypass inflections in the planned routes is clearly seen, and some of the tracks are close to the direct routes that could be planned in the proposed FRA in Figure 5. Particularly at night, some flights fly directly between the radar airspace entry and exit points (e.g. ADNAP and AVBET to SAPRA), while during the day there is evidence of “direct to” via one intermediate waypoint (e.g. DAIGO or INUBO). Traffic across this area has to pass through multiple sectors, and at night when traffic and workload are low and sectors tend to be combined, a “direct to” from the entry point to the exit can be coordinated more easily than during the day. This implies that inter-sector coordination workload may be an issue in FRA implementation.

3.2 Air Traffic Control

Evidence for FRA benefit regarding ATC has been less concrete than those of potential operator benefit. This may be due to difficulties of defining, forecasting and measuring it. It could be said, however, that FRA implementation would not be so beneficial if it reduced airspace capacity. Airspace capacity is determined by the workload that ATCOs can sustain with an acceptable level of collision risk, and ATCO workload depends on the density and complexity of the traffic.

It has been claimed that FRA can lead to a better spread of conflicts [1] or fewer conflicts [17]. However, since initial FRA implementations tend to use existing significant points as entry and exit points, we consider that the fundamental traffic flow patterns through an airspace in which the majority of traffic is scheduled air transportation flights would remain essentially unchanged by the introduction of FRA, although the locations of conflict “hot spots”, for example due to intersecting traffic flows, might shift. Whether this would be “better” from an ATCO workload point of view, however, depends on for example where these hotspots occur relative to sector boundaries. It is therefore necessary to evaluate the capacity and safety of proposed FRA designs with realistic traffic demand scenarios by using fast-time simulation, modelling, and/or real-time human-in-the-loop simulation.

Since most airspace safety metrics are *post priori* and can only be obtained during actual operations, airspace studies using fast-time simulation or modelling tend to use simpler metrics that are correlated with workload. One method is potential loss of separation (PLOS) of the flight planned trajectories of the traffic demand, which we have used in our oceanic airspace studies. Another indicator is complexity, but there is a need to correlate complexity with actual ATCO workload. We have in previous work also created a novel index of air traffic control difficulty based on complexity [16], and are currently studying correlating airspace metrics used for sector capacity management, such as MMBB (modified Messer-schmitt-Bölkow-Blohm method), with workload measured using human-in-the-loop experiments and traffic analysis.

It has been claimed that FRA implementation has slightly reduced ATCO workload due to a decrease in R/T transmissions, monitoring and coordination [17], but it is noteworthy that FRA implementation has not included areas of high traffic density and complexity such as over the southern part of the United Kingdom and the Reims Area Control Centre which covers Paris. An exception is the airspace managed by Maastricht Upper Area Control Centre, which has continually developed and implemented advanced ATC support tools and systems. If FRA promotes flown trajectories that better conform to the planned trajectory, it should improve the performance of trajectory-based controller assistance tools that can reduce workload. However, such advanced tools change ATC working practices. It would not be clear how much ATCO workload reduction is due to traffic brought about by FRA itself, and how much is due to controller tools.

3.3 Uncertainty

FRA should theoretically increase conformance of the flown trajectory with the planned trajectory, partly by reducing the scope for ATC “short cuts”. This should in turn improve flight trajectory predictability, which should benefit the quality of air traffic flow management (ATFM) measures. A degree of uncertainty will remain, for example due to unplanned weather avoidance. In Fukuoka FIR, we speculate that even greater uncertainty may be caused on certain routes by short cuts across training airspaces, which cannot be planned but are coordinated between ATC and the user of the training airspace while the aircraft is in flight approaching the area. Concepts such as Flexible Use of Airspace (FUA) and improved coordination between ATC and training airspace users could reduce this uncertainty, allow more planned crossings of training airspace, and improve training airspace utilization by civil traffic as well as military users.

4 Discussion and Conclusions

In accordance with the Asia/Pacific Seamless ANS Plan [2], to increase airspace user flexibility to plan routes that are closer to their desired optimum trajectories, direct routes and UPR are now being implemented in the Asia/Pacific region (e.g. [18]) as an intermediate step towards FRA, which has been implemented in Europe but has yet to be deployed in Asia/Pacific. This paper has introduced the Free Route Airspace concept, summarized ENRI's research activities, and discussed its implementation and potential benefits based on its studies.

Regarding operator benefit, in radar-controlled airspace we consider that reduced flight plan route distance benefits may be obtained in some cases, but not in all cases due to the already highly optimized ATS route network in Japan. Metrics based on comparing planned flight route distances in ATS route and FRA airspaces risk overstating actual operator benefit due to ATC short cuts in an ATS route environment. Reduction of flight uncertainty is an expected benefit, but it is difficult to quantify what impact it would have on ATFM and operators' desires to adhere to schedule, which can override flight direct cost concerns. Oceanic airspace benefits are harder to quantify due to daily variations of the optimal routes with winds, but since strict adherence to the cleared route is required in oceanic airspace, may be more likely to be actually realized. High demand for wind-optimal routes causes traffic concentrations that may require ATFM measures to reduce blocking of step-climb, such as traffic dispersion via closer-spaced oceanic gateways enabled by improved CNS performance.

One identified issue regarding the location of vertical entry/exit points raises an issue of the management of upper airspace and lower airspace, if FRA is assumed to correspond to the former, as in this concept; e.g. whether arrival radar vectoring should be handled in upper or lower airspace. Forcing arrival traffic to descend prematurely for vectoring could lead to loss of efficiency, and suggests that trade-off studies are required when considering FRA(A) placement.

Optimising training airspaces, for example using Flexible Use of Airspace (FUA) concepts and more fine-grained allocation and usage to allow more planned access by civil flights, however, could lead to significant reductions in flight plan route distances, and should be pursued alongside free route initiatives.

Removal of ATS route constraints on flight planning may cause conflict hotspot areas to shift, which may affect sector coordination workload. PLOS and complexity may be used as surrogates for workload estimation in fast-time simulation and airspace modelling studies, but complexity metrics need to be correlated with workload. Although FRA has been implemented successfully in Europe, doubts linger regarding the application of FRA to the highest density and most complex airspaces without advanced controller automation support or traffic flow structuring.

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