An Analysis of Flight Routes and Considerations for Free Route Airspace Implementation in Fukuoka FIR

Mark Brown, Hiroko Hirabayashi, and Keumjin Lee

Abstract The Electronic Navigation Research Institute and Korea Aerospace University have proposed an initial Free Route Airspace (FRA) concept for the Fukuoka and Incheon Flight Information Regions (FIR) to improve air traffic flows and air traffic management in northeast Asia. We are now working to elaborate the concept, quantify benefits, and identify implementation issues. This paper examines two air traffic flows in Fukuoka FIR: (1) Japanese domestic flights between the highest traffic city pairs, and (2) overflight traffic between Korea and North America across radar-controlled airspace. From an analysis of operations based on flight plan and radar data for 2019, prior to the COVID-19 pandemic, FRA design and implementation issues are considered. Our analysis and findings are expected to contribute to the planning of FRA implementation in Northeast Asia.

Keywords Air traffic management · Free route airspace · Airspace design

1 Introduction

To handle predicted increases in air transportation demand in the Asia/Pacific region, the International Civil Aviation Organization (ICAO) Asia/Pacific region's Seamless ANS Plan [1] recommends the introduction of Direct Routes, Free Route Airspace (FRA) and Flexible Use of Airspace (FUA). The FRA concept was developed by EUROCONTROL to improve the environmental performance of the Air Traffic Management (ATM) system. Free Route Airspace is "*a specified volume of airspace in which users can freely plan a route between defined entry and exit points. Subject to airspace availability, routeing is possible* via *intermediate waypoints, without reference to the air traffic service (ATS) route network*" [7]. Benefits include shorter

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flight distances enabled by more direct routing, with concomitant flight time and fuel savings, and better trajectory predictability through higher correlation between the flight planned route and the actual flown track. Restricted airspaces that are reserved for training or military purposes can hinder direct routes, and the concept of Flexible Use of Airspace (FUA) seeks to improve the utilisation of such airspace resources through better coordination between military and civil users. An Air Navigation Service Provider (ANSP) may also make provision for use of Direct Routes within non-free route airspace in its Aeronautical Information Publication (AIP) to increase efficiency, which can be used as an interim step towards or as a supplement to FRA.

Most of Europe's upper airspace will have implemented FRA by the end of 2022 (*ibid.*), but the concept has yet to be applied in Asia. The Electronic Navigation Research Institute (ENRI) and Korea Aerospace University (KAU) are therefore studying the FRA concept [2]. Based on an analysis of air traffic between Seoul Incheon International Airport (RKSI[1]) and North America [3], we have proposed a preliminary FRA concept for Incheon Flight Information Region (FIR) (RKRR) and Fukuoka FIR (RJJJ) [4], and are now working to elaborate the concept by clarifying airspace design, considering performance indicators, forecasting changes to existing operations, identifying FRA implementation issues, and proposing solutions. This paper considers two traffic flows for the more detailed design of FRA implementation in Fukuoka FIR radar-controlled airspace: (a) Japanese domestic air traffic flows, and (b) overflight traffic between Korea and North America. For the former, we identify the highest frequency domestic city pairs and analyse the most commonly filed flight plan routes in 2019 and a sample of radar tracks. Based on EUROCONTROL airspace design guidance [5, 6], we suggest arrival and departure connecting routes between terminal manoeuvering areas (TMA) and FRA vertical entry/exit points. The latter extends our earlier preliminary traffic flow study [3] in scope and increases the traffic sample considered from one week to a year, and gives considerations for direct/free route airspace design between the RKRR and Khabarovsk FIR (UHHH) boundary.

This paper is based on 2019 data, but airspace restructuring in RJJJ[2] and the effects on air traffic of the COVID-19 pandemic mean that our analyses based on these data are not fully up-to-date. Although this affects some of our quantitative findings, the overall qualitative findings and our adopted methodology should not be affected. The work is intended to guide the design of a reasonable FRA model for further research and implementation; it is not intended to be a complete and detailed airspace design for operational purposes. Notwithstanding, it is expected to contribute to the implementation of direct routes and FRA in Fukuoka FIR, Incheon FIR and the wider northeast Asia region.

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[1] In this paper, aerodromes and FIRs are referred to by their four-letter ICAO designators to save space.

[2] Point Merge arrivals were introduced in the Tokyo TMA around July 2019, and an upper airspace region is being introduced at and above Flight Level 335 (FL335) in RJJJ radar-controlled en-route airspace over a five-year period from around 2020.

In the remainder of this paper, Sect. 2 explains the data and processing methods used. Section 3 analyses the RJJJ domestic traffic flows and gives some considerations for direct route and FRA design. Section 4 examines overflight traffic across the northern part of Fukuoka FIR radar-controlled airspace and presents airspace proposals for direct and free route traffic flows between the RKRR/RJJJ boundary and UHHH. Section 5 concludes the paper.

2 Data and Processing

Flight plan and operational data were obtained from “dayplan” records provided by the Japan Civil Aviation Bureau (JCAB) of all civil General Air Traffic flights that operated under Instrument Flight Rules in RJJJ during 2019. Dayplan records contain the ICAO flight plan data of each flight, a Segment Data Block (SDB) containing times and altitudes abeam significant points on the flown route within RJJJ, and information such as estimated off-block time, takeoff time, and landing times for aerodromes in RJJJ.

The planned route of a flight is given in Item 15 of the ICAO flight plan as a sequence of waypoint and Air Traffic Service (ATS) route segments. To obtain the planned two-dimensional trajectory, it is necessary to “expand” the ATS route segments into a sequence of waypoints, referencing a database of navigation information. Such navigation data are published in the AIP of each state and updated on a 28-day “AIRAC” cycle, but the information is not directly machine-readable and only limited historical data are available. For this research, we manually extracted information from the Japan AIP for the publication dates 20 June and 18 July 2019 (before and after airspace restructuring due to the introduction of Tokyo TMA Point Merge arrivals) and compiled databases that were used for route expansion of flight plans. Since manual data compilation is error-prone, there may be minor errors in the expanded routes, but they appear reasonable overall and correlate well with radar tracks.

Radar track data are also provided to ENRI by JCAB for research, approximately one week in each month of the year. ENRI performs processing such as combining data from different radar sites and conversion to latitude/longitude coordinates. Flight metadata associated with the tracks (origin and destination aerodromes, callsign, aircraft type and “computer number” identifier assigned by the data processing system) were used to associate tracks with flight information.

3 Japanese Domestic Air Traffic

We examined the traffic between Japanese city pairs to consider Direct Route and FRA design around and between major airports. We first analysed the overall characteristics of the domestic air traffic. We then identified the highest demand city pairs extracted their most commonly filed flight plan routes. Comparison with radar tracks revealed differences between actual executed and planned routes that served to inform FRA design.

Figure 1 shows histogram and cumulative frequency plots of (left) planned cruising altitude and (right) Estimated Elapsed Time (EET) of domestic flights in RJJJ in 2019. The sample size was $n = 853{,}987$ flights, giving an average of 2,340 flights per day. Upper airspace sectors are being implemented above FL335, and this therefore forms a reasonable floor altitude for an FRA block that comprises Fukuoka FIR radar-controlled airspace proposed in [4]. Around 50% of domestic flights cruised in upper airspace. Regarding flight durations, around 50% of flights had an EET of less than approximately 70 min., and 75% of flights were less than 85 min.

Table 1 shows the traffic between the highest ranked city pairs in terms of number of flights. The 'Roundtrip/day' column is simply the number of flights over the

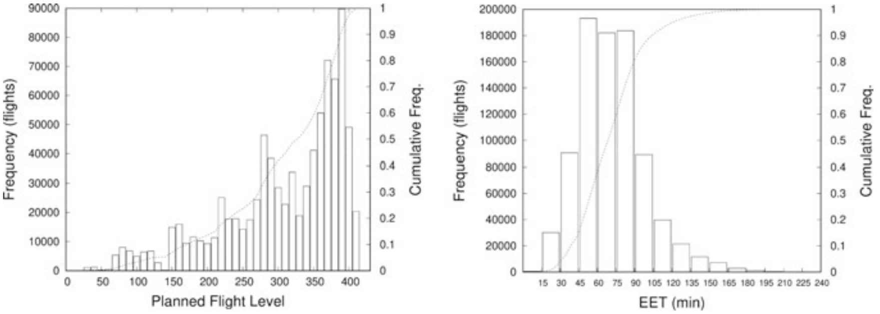

Fig. 1 Histogram and cumulative frequency of (left) planned level and (right) EET of RJJJ domestic flights in 2019

Table 1 Japanese domestic city pairs with highest service frequencies in 2019

Rank	City pair	Distance (NM)	Flights	Roundtrip/day	Note
1	RJCC/RJTT	442	39,611	54	
2	RJFF/RJTT	477	39,368	54	
3	RJTT/ROAH	839	22,937	31	
4	RJOO/RJTT	219	21,731	30	Only 8 flights above FL335
5	RJFK/RJTT	506	16,681	23	
6	RJFF/ROAH	466	14,462	20	
7	RJCC/RJGG	527	13,068	18	
8	RJFT/RJTT	473	13,053	18	
9	RJFM/RJTT	471	12,989	18	
10	RJOA/RJTT	345	12,950	18	

year divided by (365 × 2) and rounded to give an indication of the daily service frequency. The distance is the direct distance between the aerodrome reference points in nautical miles (NM). The top 10 city pair traffic accounted for just under 25% of the total domestic traffic. Note that because the distance of the fourth ranked city pair, RJOO/RJTT, is only 219 NM, nearly all of the flights of that city pair were below FL335.

Since the city pairs in Table 1 (except RJOO/RJTT) account for almost 25% of all domestic traffic (and consequently approximately 50% of domestic traffic operating above FL335), they should be prioritised for direct route and FRA implementation. Longer distances give greater possibilities for fuel/time benefit from wind-optimal routes, so should be further prioritised.

For preliminary design to implement Direct Routes/FRA between a domestic city pair, we applied the following procedure:

1. Identify the most commonly filed flight plan route(s) as a baseline for analysis. (The most commonly filed routes can vary according to traffic level (typically time-of-day related). Variations from these routes are typically for day-to-day operational reasons such as weather avoidance, and are not considered.)
2. Identify the en-route segment endpoints, i.e. the last point of the Standard Instrument Departure (SID) and first point of the Standard Terminal Arrival (STAR).
3. Determine corresponding FRA vertical entry and exit points using radar tracks to judge the altitude at which flights ascend/descend above/below the FRA floor.
4. Establish FRA intermediate points as necessary to avoid restricted airspaces with a suitable buffer.

Instrument arrival and departure procedures are published for the TMA of major airports, and the en-route flight plan is typically between the last waypoint of the SID to the first waypoint of the STAR. The upper airspace/FRA floor (FL335) is above the TMA ceiling, so these points cannot be used as endpoints for the free route segment of a flight plan. EUROCONTROL's airspace design guidance [5] describes the designation of FRA Departure Connecting Points (D) and FRA Arrival Connecting Points (A) as FRA entry and exit points around TMAs, and arrival and departure connecting routes that join these points to the SID and STAR respectively. (FRA significant point types are listed in Table 2). The locations of these points

Table 2 FRA significant point types and indicators

Type	Indicator letter
FRA Horizontal Entry Point	(E)
FRA Horizontal Exit Point	(X)
FRA Intermediate Point	(I)
FRA Arrival Connecting Point	(A)
FRA Departure Connecting Point	(D)

depend on the climb/descent gradient of aircraft from the SID/STAR en-route interface points. Design for each TMA would require careful analysis of all inbound and outbound traffic flows, considerations to separate arrival and departure traffic flows etc. In this paper, we make a more rough analysis to show the principle.

For the city pairs in Table 1 (except RJOO/RJTT), we extracted the expanded flight plan routes for flights during the period 1 January–1 June 2019 (i.e. before major airspace changes in July 2019 and to avoid other minor AIP changes in June 2019) and radar tracks for 20–26 May 2019. We then plotted the most common filed routes between each city pair and radar tracks above and below FL335. Some sample plots are shown below, where the dotted black line is the most common flight plan route from the traffic sample, grey lines show radar tracks below FL335 and red lines show radar tracks above FL335. Red polygons show restricted airspaces above FL335 and green polygons show training areas above FL335 and areas below FL335 that affect arrivals/departures. In this study, we made an approximate determination of candidate FRA(D) and FRA(A) points from this limited sample of radar tracks,[3] but aircraft performance guidelines associated with procedure design should also be applied. Some findings and results are discussed below.

ATC Intervention Tendencies

Radar tracks show a tendency for Air Traffic Control (ATC) intervention to reduce flight distance by "short cuts" over doglegs or minor inflections in the flight plan route. Such discrepancies between the planned and flown trajectory reduce predictability, and an aim of trajectory-based operations is to increase predicability by reducing the discrepancy. We assume that radar tracks reflect what is possible in actual operations, and propose that Direct Routes and free routeing introduced to reflect that actuality and increase flight planning flexibility (Fig. 2). On the other hand, short cuts and route leg extension are also used by ATC for separation purposes as shown in Fig. 3. Free route and trajectory-based operations might remove some of this flexibility, requiring alternative ways to manage separation.

Radar vectoring to separate and sequence arrival traffic at TMAs when demand is high is also observed, e.g. in Figs. 3 and 4. It could be argued that radar vectoring of arrivals by lower sectors rather than in FRA, which is intended for en-route traffic, would given a better separation of responsibilities. Arrival radar vectoring areas in the FRA also makes placement of the FRA(D) points more complex, since they can prevent aircraft departing on the SID flying direct once they enter FRA. Compulsory FRA connecting departure routes could be established to avoid arrival traffic. Studies are required, however, to understand the affect on overall fuel burn of tradeoffs between arrivals and departures.

TMA/Free Route Airspace/Direct Route Interface

Some routes (e.g. between RJCC and RJGG) are very close to great circle segments and are well-aligned with the TMA entry and exit points and in such cases, appropriate

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[3] Climb performance depends on factors including aerodrome elevation (hardly a factor in Japan or Korea), aircraft type, weight and temperature, so a spread of radar data over a longer span of time than the sample presented here is required.

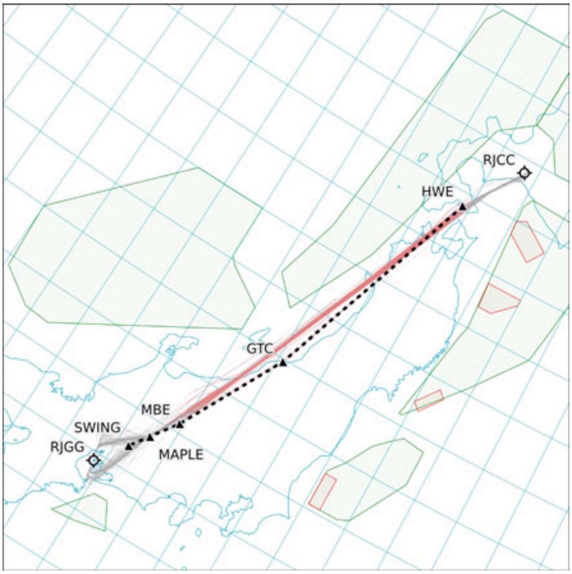


Fig. 2 RJCC (New Chitose) to RJGG (Chubu). The most common flight planned route has an inflection at GTC but radar tracks show that almost all traffic is cleared direct from HWE to MBE or MAPLE. This suggests a Direct Route could be published between HWE and MAPLE for this traffic. Points near to HWE and MBE could be used as FRA(D) and FRA(A) points respectively

FRA(D) and FRA(A) points can be fairly clear (see Fig. 2). When the SID final point or STAR initial point are *not* so-well aligned, discrepancies between flight plan route and flown tracks are greater; radar tracks show ATC “cleared direct to” instructions are often issued to a waypoint further along the route during the climb phase, e.g. in the cases of departures from ROAH to RJTT (Fig. 6) and particularly RJFF (Fig. 5). ROAH is a case where the SID final point (AMAMI) is sufficiently far from the aerodrome that traffic is above the FRA floor when it reaches that point. Where there are frequently large discrepancies between the SID and actual operations, it might be worthwhile considering revising the SID; in the case of FRA implementation, for example, by adding transitions that connect to FRA entry points that more closely align with operational practice.

Routing Around Restricted Use Airspaces

Airspaces that are nominally restricted use (reserved for training or military purposes) can sometimes be crossed by civil traffic when they are “cold”. Depending on their status, FRA intermediate points (FRA(I)) could be established to allow flight plan routes to avoid such airspaces with a minimum “buffer” distance (e.g. 10 or 5 NM depending on navigation performance) when they are “hot”, otherwise to route directly over when they are “cold”, for example as shown in Figs. 5 and 6.

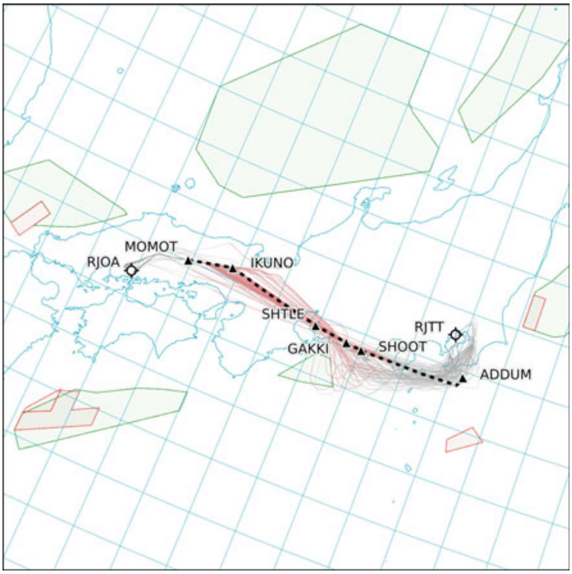


Fig. 3 RJOA (Hiroshima) to RJTT (Tokyo International). From radar tracks above FL335, a published Direct Route from MOMOT to SHOOT or GAKKI may reduce flight distance. However, both short cuts and route leg extension occur before and after IKUNO, which it is assumed are used by ATC to separate this eastbound traffic from a crossing an NE-SW flow. FRA may reduce this flexibility. Note also vectoring of traffic inbound to RJTT from the west and southwest beginning at around 137°E (near SHTLE), 150 NM from the aerodrome and while traffic is still above FL335. RJTT arrivals could therefore be descended below FRA at peak times; e.g. set an FRA(A) between SHTLE and SHOOT

4 Fukuoka FIR Overflight Traffic Between Korea and North America

We now consider airspace design to facilitate free and more direct routeing for overflight traffic through the northern part of Fukuoka FIR radar-controlled airspace, shown in Fig. 7, specifically traffic that crosses the RJJJ/RKRR boundary via points between RUGMA and ANDOL and the east side of RJJJ radar controlled airspace north of approximately 32°N. This traffic is mostly between airports in RKRR and northeast China to the west and North America and Hawai'i to the east. The work here extends our previous analysis [3] which only considered traffic to/from RKSI, and examines flight plan routes over a longer time period (one year 2019 instead of May 2019). For reasons of space, we discuss here FRA design for only one traffic flow in detail.

Tables 3 and 4 show the breakdowns of origin and destination of all RJJJ overflight traffic that crossed the RKRR/RJJJ boundary between RUGMA and ANDOL eastbound and westbound, respectively, during 1 January–31 December 2019. This

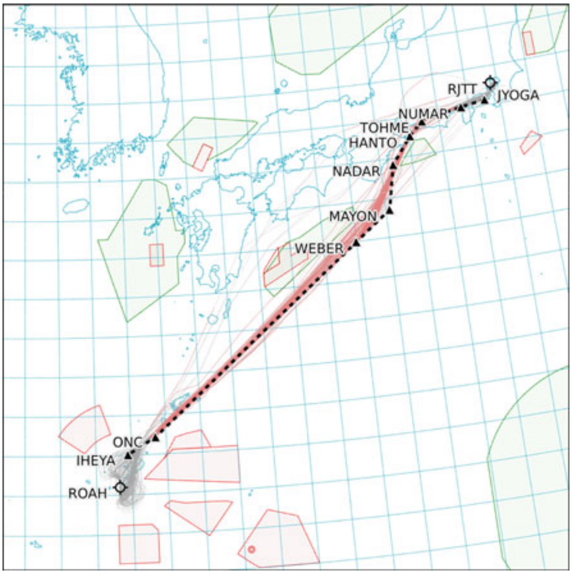


Fig. 4 RJTT to ROAH. Vectoring of RJTT arrivals in upper airspace between SOPHY and CHALK might prevent departure traffic from RJTT to the southwest taking a more direct route after climbing above FL335 between NUMAR and TOHME. An FRA(D) point at NUMAR and a compulsory departure connecting route NUMAR DCT TOHME DCT HANTO DCT NADAR could be set to avoid this area and a training area (when hot) to allow free routing from NADAR. Establishing an FRA(A) point at SOPHY to vector arrivals below FL335 could allow such departures a more direct route, as well as giving a better separation of responsibilities between upper airspace (FRA) and lower sectors

traffic contains two components: (a) traffic to and from Korea, and (b) RKRR overflight traffic, which is mostly to/from northern China and crosses between RKRR and Shanghai FIR (ZSHA) at the AGAVO point. (Traffic between Japan and Korea and Japan and China are omitted from this analysis.) In the tables, each row shows traffic between origins and destinations on either side of the RKRR/RJJJ boundary, and percentages in each row except the Total column indicate fractions of the traffic in that row. Percentages in the Total column indicate proportions of each row's traffic flow to the entire eastbound or westbound traffic flow (omitting traffic to/from Japan). The tables show that 80% of the RJJJ overflight traffic through the part of the RKRR/RJJJ boundary under consideration is to/from RKSI and less than 20% of traffic is to/from other aerodromes in RKRR. Traffic to/from North America and Hawai'i account for 41% of eastbound traffic but only 25% of westbound traffic. This is because of the westerly Polar Jet Stream; eastbound flights tend to fly through RJJJ oceanic airspace to take advantage of the tailwind even though the route may be south of the great circle between RKSI and North America aerodromes. Westbound flights tend to fly north of the jet stream core to avoid strong headwinds and so some traffic from North America to RKSI flies via Russian Federation and China airspace instead of over the Pacific. Since the average latitude of the jet stream core and its strength

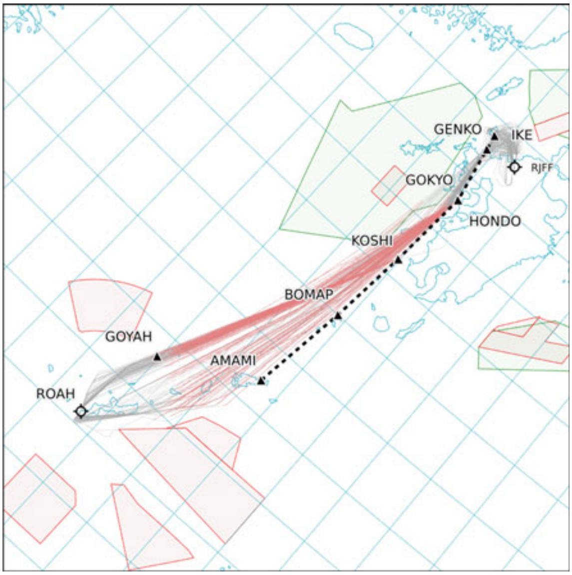


Fig. 5 ROAH (Naha) to RJFF (Fukuoka). The SID final point (AMAMI) is sufficiently far from the aerodrome that traffic is above the FRA floor when it reaches that point. Traffic taking off from ROAH to the south for RJTT or to the north for RJFF in particular actually bypass this point. Where there are large discrepancies between the SID and actual operations, it might be worthwhile revising the SID. For takeoffs to the north from ROAH, an FRA(D) point approximately 110 NM northeast of ROAH near the great circle between GOYAH and HONDO could be established. Traffic routing from this point direct to HONDO (which appears a reasonable FRA(A) for RJFF) would cross training airspace Area P (the green area to the west of Kyushu), so FRA intermediate points could be added abeam KOSHI (which is 20 NM from Area P) to allow it to be avoided by e.g. 10 NM and 5 NM when it is "hot", depending on navigation performance

vary during the year, the most favourable flight plan routes also vary with season. Other traffic/from to other origins/destinations on the east side of the RKRR/RJJJ boundary (Philippines, Guam, SE Asia, Australasia/Oceania) enter/leave Fukuoka FIR to/from the southeast and south and are not greatly affected by the Polar jet stream.

Regarding North America/Hawai'i traffic, we further broke this down into four flows F1–F4 shown in Table 5. Details of the criteria of FIR boundary points and origin and destination aerodromes that defined the flows are shown in Table 6. (The FIR entry and exit points to which the criteria were applied were determined from the SDB fields of the Dayplan records, which give times and altitudes abeam waypoints that are generated based on the actual flown track. This was necessary because sometimes flight plans contain DCT segments between two points on either side of the FIR boundary and so an FIR boundary point does not always appear in the expanded flight plan.) For each flow, we calculated the extension between the flight plan route across RJJJ radar-controlled airspace and the direct route (ellipsoidal distance) across the airspace as follows (see Fig. 8):

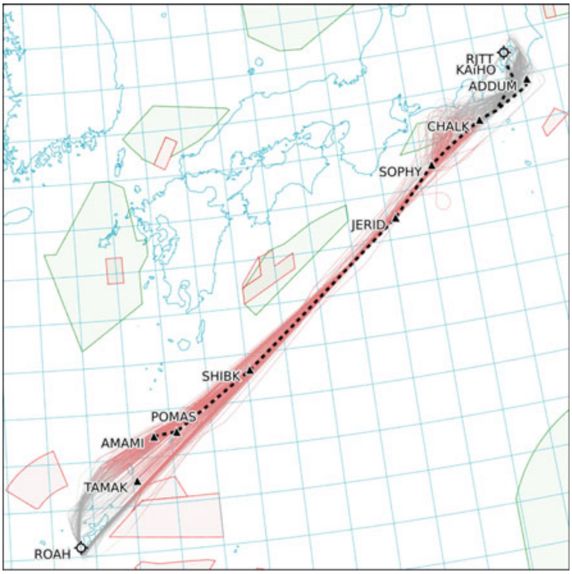


Fig. 6 ROAH (Naha) to RJTT (Tokyo International). Restricted airspace areas (W-173A and W-173) to the northeast of ROAH are sometimes crossed by radar tracks. It might be beneficial to establish FRA entry points around 130 NM northeast of ROAH that allow flight across the restricted area when it is “cold” and to avoid W-173A by a suitable buffer (e.g. 10 NM, at a point slightly northeast of TAMAK)

5. Select flight plan routes from the Dayplan data according to the criteria in Tables 4 and 5.
6. Perform flight plan route expansion using a database of ATS routes within RJJJ and a limited database of ATS routes, navaids and significant points outside RJJJ to give planned flight trajectories as linestring geometries (that is, two-dimensional geometries consisting of multiple straight line segments between waypoints) between the destination and origin aerodromes.
7. Trim the linestrings derived from step (2) to a polygon which is the union of the radar controlled airspace sector boundaries. This gives the clipped flight plan route in Fig. 4.
8. Calculate the distance along the trimmed linestring and the *route extension*, i.e. the difference between the difference along the linestring and the ellipsoid distance between the linestring endpoints (i.e. the distance along the Direct path in Fig. 4). Route extension and proportional route extension are defined as:

$$\text{route extension} = \text{flight plan route distance} - \text{direct distance} \quad (1)$$

$$\text{proportional route extension} = \text{route extension/direct distance} * 100 \quad (2)$$

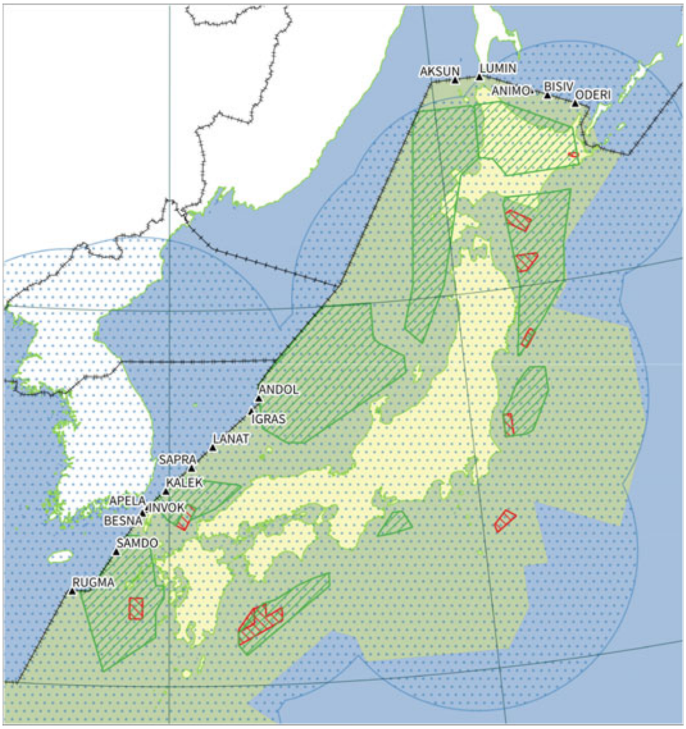


Fig. 7 Fukuoka FIR radar controlled airspace (yellow). FIR boundaries are shown as black lines. Approximate radar coverage limits of upper air space are shown as the blue dotted area. Green hatched areas indicate training areas above FL335, and red areas indicate restricted airspaces above FL335. Boundary significant points used for traffic selection are labelled

Table 3 Origins and destinations of eastbound overflight traffic

Origin				Total (%)	Destination
RKSI (%)	RKRR other (%)	China (%)	Other (%)		
14,590 (94)	153 (1)	715 (5)	6 (0)	15,459 (41)	North America and Hawai'i
8,182 (80)	2,012 (20)	5 (0)	0 (0)	10,199 (27)	Philippines (RP)
4,444 (74)	1,396 (23)	156 (3)	0 (0)	5,996 (16)	Guam (PG)
2,183 (77)	641 (23)	0 (0)	0 (0)	2,824 (8)	SE Asia (V, W)
1,661 (66)	6 (0)	843 (34)	0 (0)	2,510 (7)	Australasia/Oceania (Y, N, PT)
154 (23)	527 (77)	1 (0)	0 (0)	682 (2)	Khabarovsk FIR (UH)
				161 (0)	Other
31,313 (83%)	4,790 (13)	1,720 (5)	8 (0)	37,831	All

Table 4 Origins and destinations of westbound overflight traffic

Origin	Total (%)	Destination			
		RKSI (%)	RKRR other (%)	China (%)	Other (%)
North America and Hawai'i	8,951 (25)	8,736 (98)	102 (1)	109 (1)	2 (0)
Philippines (RP)	10,227 (29)	7,656 (75)	2,568 (25)	3 (0)	0 (0)
Guam (PG)	6,038 (17)	4,445 (74)	1,435 (24)	158 (3)	0 (0)
SE Asia (V, W)	6,768 (19)	5,263 (78)	1,505 (22)	0 (0)	0 (0)
Australasia/Oceania (Y, N, PT)	1,843 (5)	1,820 (99)	3 (0)	20 (1)	0 (0)
Khabarovsk FIR (UH)	1,222 (3)	690 (56)	529 (47)	3 (0)	0 (0)
Other	111 (0)				
All	35,160	28,664 (81)	6,198 (18)	293 (1)	5 (0)

Table 5 Traffic flows and flow criteria

Flow	Description	Eastbound traffic criteria	Westbound traffic criteria
F1	Traffic via RKRR to North America via UHHH	Destination: North America FIR entry: RKRR boundary (north) FIR exit: UHHH boundary	Origin: North America FIR entry: UHHH boundary FIR exit: RKRR boundary (north)
F2	Traffic via RKRR to North America via NOPAC	Destination: North America FIR entry: RKRR boundary (north) FIR exit: NOPAC routes	Origin: North America FIR entry: NOPAC routes FIR exit: RKRR boundary (north)
F3	Traffic via RKRR to North America via Central Pacific flex track area	Destination: North America FIR entry: RKRR boundary (north) FIR exit: NOT (UHHH boundary or NOPAC routes)	Origin: North America FIR entry: NOT (UHHH boundary or NOPAC routes) FIR exit: RKRR boundary (north)
F4	Traffic via RKRR to Hawai'i	Destination: Hawai'i FIR entry: RKRR boundary (north)	Origin: Hawai'i FIR exit: RKRR boundary (north)

Table 6 Details of flow criteria

Criterion	Details
North America	ICAO aerodrome code prefixes: M, T, CY, PA, K
Hawai'i	ICAO aerodrome code prefix: PH
RKRR boundary (north)	Via boundary waypoints: ANDOL, LANAT, SAPRA, KALEK, INVOK, APELA, BESNA, SAMDO, RUGMA
UHHH boundary	Via boundary waypoints: LUMIN, BISIV, ODERI, ANIMO, AKSUN
NOPAC routes	Via boundary waypoints: NIPPI, OMOTO, PASRO, AKISU, CUTEE

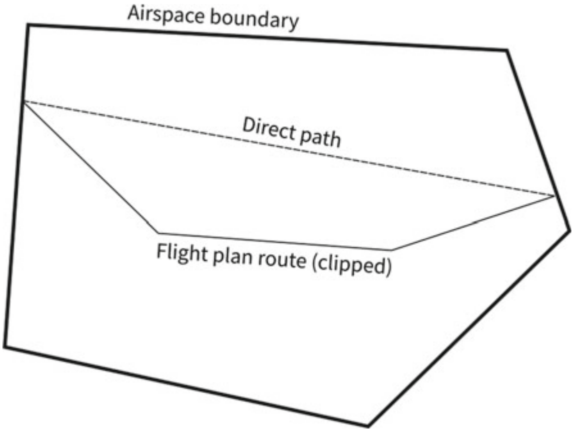


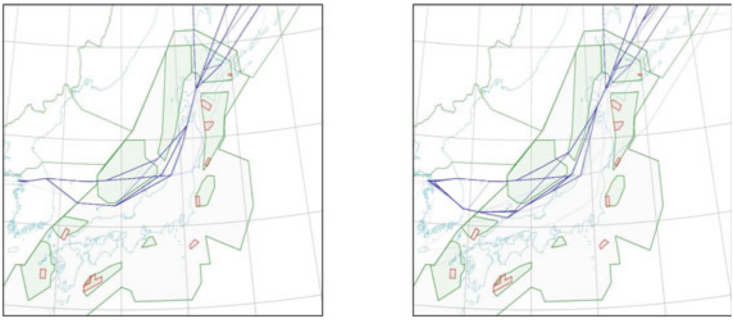
Fig. 8 Calculation of route extension. The flight plan route is clipped to the RJJJ radar-controlled airspace boundary and the distance along the clipped route is compared to the distance of the direct path between its endpoints

Extracted flight plan routes for flows F1—F3 are shown in Fig. 9 and descriptive statistics are presented in Table 7. (The F4 routes across RJJJ radar-controlled airspace are similar to F3 and are omitted to save space.) In Table 6, the *n* column is the sample size (number of flights), and mean values, 25th percentile, median and 75th percentile distances are rounded to the nearest nautical mile. Proportional route extensions (percentage) statistics are computed from each individual route rather than from the flight route distance and route extension statistics values.

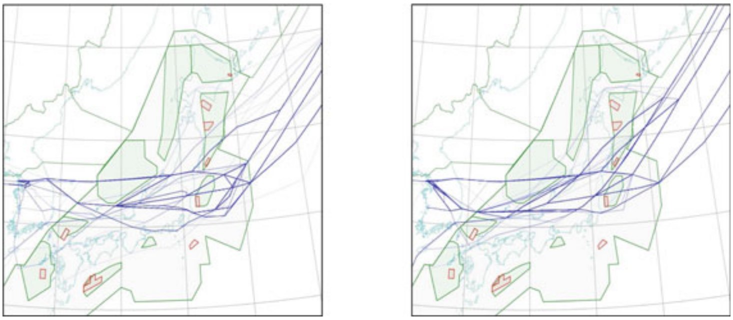
Note that in Fig. 9 there are routes that do not apparently conform to the selection criteria. This is because the route selection was applied to the actual FIR boundary fix which the flight passed rather than the flight plan filed fix. Such outlier cases are few, and the closeness of the median and mean values of route extension in Table 6 indicate that their effect on our results is negligible.

Table 7 shows the greatest route extensions occur for flow F1, between the RKRR/RJJJ boundary and the UHHH boundary, which suggests that this should be a priority for direct route/FRA implementation (although the traffic volume is comparatively low). Figure 10 shows histograms of RJJJ entry times for eastbound (left) and westbound (right) flights of this traffic flow for one year of traffic. Eastbound flights show peaks of traffic in the morning (between 10:00–13:00), in the evening (19:00–21:00) and a peak of Anchorage (PANC) flights at night (22:00–01:00), which are assumed to be cargo flights. There is almost no traffic between 01:00–10:00. Westbound traffic shows peaks around 00:00–03:00 and around 12:00–16:00, with a small peak of flights from PANC between 08:00–10:00.

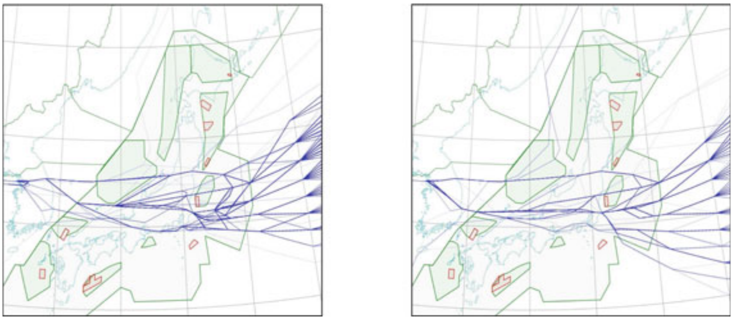
We now elaborate our previous preliminary FRA concept [4]. Our initial concept set the FRA floor at FL310. This was to accommodate particularly cargo flights departing RKSI for PANC, which are the dominant night traffic from Korea to North America, a significant proportion of which were found to have an initial cruise altitude



(a) F1 (via Khabarovsk FIR) eastbound (b) F1 (via Khabarovsk FIR) westbound



(c) F2 (via NOPAC) eastbound (d) F2 (via NOPAC) westbound



(e) F3 (via CENPAC) eastbound (f) F3 (via CENPAC) westbound

Fig. 9 Flight plan routes of RJJJ overflights in 2019. Green polygons show training areas above FL335 and red polygons show restricted (military) areas above FL335. Routes are plotted with transparency so strength of line segments indicates frequency

of FL310 and above prior to the Fukuoka FIR boundary [3]. However, since Japan has set its upper airspace floor at FL335, it is desirable that this would be the FRA floor in RJJJ radar-controlled airspace. An analysis of step climbs in a one-day traffic sample by Harutaka Suizu of Tokyo Metropolitan University found that for traffic entering RJJJ at LANAT, there was a concentration of step climbs within 100 NM after crossing the boundary, within the Kinki West sector. Following that, there were

Table 7 Statistics of flight plan route distance and route extension across Fukuoka FIR radar-controlled airspace, 2019 traffic sample

Flow	n	Flight plan route distance (NM)				Route extension (NM (%))			
		μ, σ	25th pc	Median	75th pc	μ, σ (%)	25th pc	Median (%)	75th pc
F1 east	494	843, 55.6	778	868	880	104 (14), 25.8	85	107 (14)	135
F1 west	735	861, 78.3	749	898	904	79 (10), 20.1	24	81 (10)	82
F2 east	6718	673, 53.6	612	709	715	19 (3), 13.4	11	17 (3)	23
F2 west	6008	650, 72.3	547	691	696	29 (5), 9.3	24	24 (5)	31
F3 east	7080	684, 33.7	691	692	699	13 (2), 10.9	4	8 (1)	20
F3 west	1020	717, 51.2	727	732	735	12 (2), 11.1	5	8 (1)	14
F4 east	1178	691, 27.9	692	692	696	16 (2), 11.3	9	10 (1)	19
F4 west	1185	697, 62.7	724	727	730	23 (4), 16.2	8	26 (4)	31

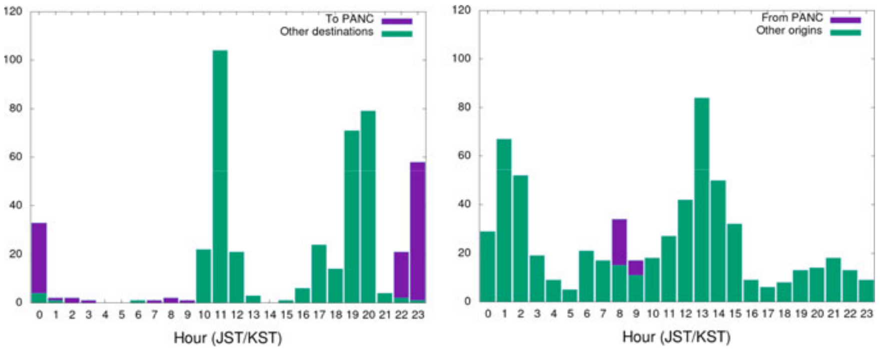


Fig. 10 Histogram of Fukuoka FIR entry times of flow F1 (left) westbound and (right) eastbound, 1 Jan 2019–31 Dec 2019. Magenta bars show flights to/from PANC, which are assumed to be cargo flights. Green bars show flights to/from other aerodromes

relatively few step climbs until within the Kanto East sector just prior to oceanic airspace entry. Further work is necessary to confirm that these step climbs were to altitudes above FL335, but it suggests a possibility of a lower FRA altitude floor of FL310 from the RKRR boundary north of LANAT extending to approximately 100 NM east of the boundary.

Figures 9(a) and (b) show the planned flight routes of the F1 flow over one year (2019). There appear to be two main constraints preventing direct routes between FIR entry and exit:

1. the FIR boundary geometries mean that direct paths between the RKRR boundary and UHHH boundary run parallel and very close to the FIR boundary line and in some cases cut across Pyongyang FIR (ZKKP), and
2. a number of training areas exist which are sometimes unavailable to civil air traffic. These training areas are typically "cold" at night, so there are conditional routes (CDR) allowing traffic to cross Area G to/from ANDOL.

A proposal to address these issues is shown in Fig. 11. For better clarity, the left figure shows FIR boundaries (grey line), the Fukuoka FIR radar area (heavy black line, which overlaps the RKRR/RJJJ boundary), training airspaces (green hatched) and restricted airspaces (red hatched), existing named points and navigation aids (black triangles) and new proposed named points (green triangles). Figure 11 (right) shows the same figure with radar tracks from 20–26 May 2019 superimposed. We propose three new points to allow traffic to fly almost parallel to the FIR boundary with adequate separation from the boundary: HIROK (20 NM east of LANAT), SUIZU (20 NM east of the FIR boundary) and MARKY (30 NM from junction between ZKKP, RJJJ and UHHH boundaries), with a flight plannable route between KAMSA and MARKY for flights between ANDOL and LUMIN. We also establish points NAVVI, TORAT and AKINO which along with existing points SAMON, TATAM and MKE allow flights to avoid Area G, Area C and Area B with an approximately 10 NM buffer. Although it should be possible to fly west of Area C when it is cold, there were no tracks in this area. (There are north–south ATS routes in this area but no northeast/southwest routes.) The reason for this is unknown and

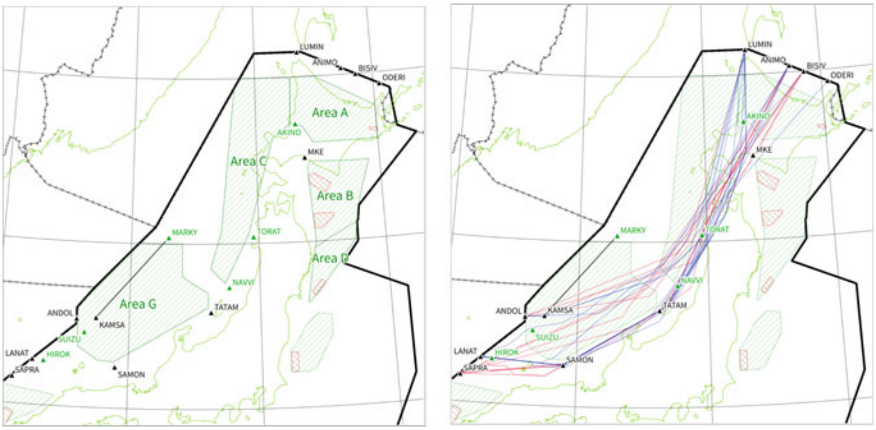


Fig. 11 Free Route Airspace proposal for routes between Incheon FIR and Khabarovsk FIR. The figure on the right shows radar tracks for the period 20–26 May 2019 superimposed. Blue tracks are eastbound and red tracks are westbound

should be investigated if there are any operational or ATC constraints (poor VHF communication performance is suspected).

5 Concluding Remarks

In this paper, we started to elaborate our initial FRA proposal by looking at transitions between TMA and FRA to allow direct routeing and free routing between high demand domestic city pairs and free routing across the RJJJ radar-controlled airspace using analyses of existing flight plan routes and radar tracks. For detailed design, a knowledge of actual operational factors is required that may not be apparent from flight plan and radar data. Airspace design for each aerodrome considered would have require a much more detailed analysis and considerations of local operational factors such as other traffic flows, terrain and noise impact.

The design of airspace, airways and ATC/ATM operations are continually being revised, and the RJJJ airspace has seen major restructuring to accommodate Point Merge arrivals in the Tokyo TMA and introduce high altitude airspace. Further FRA design work should be based on up-to-date AIP, flight plan and radar track data. However, the principles we have discussed in this paper remain valid.

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