Extracting Radar Vectoring Instructions Using Recorded ADS-B Trajectories

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Although air traffic volume around the world has been stagnant due to the COVID-19 pandemic, it is expected to increase steadily in the future as the number of aircraft operations increases and next-generation air transportation such as drones and Urban Air Mobility are commercialized. Therefore, air traffic congestion problem is expected to become more complicated. Accordingly, research on efficient and systematic future air traffic management concepts are being actively conducted. This paper attempts to automatically extract the air traffic controller's radar vectoring instruction using only the trajectory data obtained from the Automatic Dependent Surveillance-Broadcast (ADS-B) receivers. The proposed methodology was applied to the trajectory data of 2019 inside the National Airspace of the Republic of Korea. Analysis of the four major airports show in average around one heading or altitude change instructions. For most commonly used departure and arrival procedure at the Incheon International Airport, about five instructions per flight was identified. The proposed methodology enables a large scale statistical analysis of the status of radar vectoring and the controller workload at a busy terminal airspace using the historic trajectory data that is relatively easy to obtain. It is expected to be used for research related to enhancing safety and efficiency of the terminal area operation under continuously increasing traffic volume.

Key Words: Automatic Dependent Surveillance-Broadcast (ADS-B), Radar Vectoring, Air Traffic Management (ATM)

Nomenclature

V	:	Velocity
h	:	Altitude
T	:	Time
C	:	Coordinate
GSD	:	Ground Speed
VRT	:	Vertical Rate
CRS	:	Course Angle
Bdry	:	Boundary
V_n	:	The number of vectoring instructions
U_n	:	Number of route used
Bdh	:	Buffer altitude difference

1. Introduction

Traffic congestion is expected to worsen due to the continuous increase in air traffic volume. To maintain safe and efficient operation, in addition to numerous next generation air traffic management concepts, it is important to assess the complexity of the airspace and the controller workload, which are the two important factors that determines the capacity of the airspace.

Number of controller instruction that is studied in this paper is a metric that affects the airspace complexity and controller workload. There has been numerous studies[1–3)] that attempted to characterize the airspace complexity. Direct measurement of controller workload is mostly performed during Human-in-The-Loop (HiTL) simulations.[4)]

Data driven approach to estimate controller workload has been undergoing. Chatterji and Sridhar[5)] used neural network and real traffic data to estimate controller workload.

This study, and extension of the previous study,[8)] extracts the feature points from a historic trajectory, and then compare those points against the estimated flight plan of the flight to determine whether the flight is following the flight procedures or maneuvered according to the controller instructions. The methodology is applied to the entire traffic inside the Incheon Flight Information Region (FIR) in 2019. Number of heading change and altitude change instructions are counted for each flight and the results are analyzed for all the IFR departure, arrival, and approach procedures at the four major airports. In average around one heading or altitude change instructions per flight was given. For most commonly used departure and arrival procedure at the Incheon International Airport (RKSI), about five instructions per flight were given.

The proposed methodology enables a large scale statistical analysis of the status of radar vectoring and, consequently, airspace complexity and controller workload at a busy terminal airspace. Even though it may not be as accurate as a method that uses full flight plan and voice communication data, the current study provides insight using only the historic trajectory data that is relatively easy to obtain.

Following this introduction, Section **2.** describes the characteristics of the ADS-B data used in this paper, as well as how the flight plans are estimated. Section **3.** describes the methodology to find vectoring instructions based on the trajectory data and the estimated flight plans. In Section **4.**, the analysis results of number of radar vectoring instructions is presented. Finally, Section **5.** concludes this paper.

2. Estimation of Flight Plan Using ADS-B Trajectories

2.1. ADS-B Data

The trajectory data used in this paper is 2019 ADS-B data purchased from FlightAware. This data consists of almost one million flights that contain at least one track point within the Incheon FIR. Table 1 shows an example of ADS-B data for a single aircraft. The data include flight data and flight information from the departure airport to the arrival airport of a flight.

2.2. Flight Plan Estimation Algorithm

One of the key ideas of this work is comparing the flown trajectory with its flight plan to identify whether any changes in

Table 1. ADS-B Trajectory data format

Callsign	AAR108					
Type	A321					
Origin	RKSI					
Destionation	RJAA					
Time	Lat (deg)	Lon (deg)	Alt (ft)	GSD (knot)	VRT (fpm)	CRS (deg)
2019-06-02 7:03:22 PM	37.49192	126.42738	1500	177		327
2019-06-02 7:03:39 PM	37.50448	126.41735	2250	179	2338	328
2019-06-02 7:03:56 PM	37.51598	126.40833	2825	182	2091	328

heading or altitude are results of following the flight plan or not. Consequently, it is necessary to identify the flight plan in detail that includes Standard Instrument Departure (SID) procedure, serious of routes (en-route), Standard Terminal Arrival Route (STAR), and Instrument Landing System (ILS) approach procedure.

In general, flight plan information in this level of detail is not available to public partly because some of the components are modified during the flight. For the current study, data driven flight plan estimation algorithm that finds the closest matching set of SID, routes, STAR, and ILS approach procedures from the Aeronautical Information Publication (AIP) to a flown track is used.[6] As the majority of civi operation within Incheon FIR use one of the four major airports, Incheon International Airport (RKSI), Gimpo International Airport (RKSS), Jeju International Airport (RKPC), and Gimhae International Airport (RKPK), flight plans are estimated for all flights that departed or arrived at any of the four airports during 2019. Figure 1 shows and example of the estimated flight plan of a flight that flew from RKPK to RKPC. Black circles denotes the flown trajectory while the colored lines show each estimated procedures or routes. Table 2 lists the names of the SID, en-route, STAR, and ILS.

Table 2. Example of flight plan estimation result

Callsign	KAL1007-1546493700-schedule-0000-0
SID	Departure Route - RWY 36L to TOPAX
EN-route	A586/Y579
STAR	RNAV MAKET 2P
ILS	ILS/LOC Approach to RWY07 from YUMIN

3. Finding Vectoring Instructions

3.1. Estimation of Feature Coordinates

Feature coordinates were extracted from the ADS-B trajectory data to find candidate points for the controller's radar vectoring instructions. For the current study, heading and altitude maneuver instructions are estimated. Speed instructions are omitted because the speed data was noisy and did not have enough resolution. To find the coordinates where the heading change occurred, Ramer-Douglas-Peucker (RDP) algorithm was applied to the two-dimensional aircraft trajectory.[7,8]

When using the RDP, the choice of tolerance value, ϵ, can change the outcome. As can be seen in Fig. 2, number of feature points decreases as ϵ becomes smaller. In this paper, ϵ values from 10 ft to 6,000 ft are tested. Optimal ϵ for each trajectory is selected at a point the rate of decrease in the number of feature points starts to slow as shown in Fig. 2.[8]

For altitude instruction, a rule based decision tree is used. Unlike heading instructions, aircraft level out once they reach the commanded altitude. Consequently, a pattern of climb to level or descend to level consists of one altitude instruction.

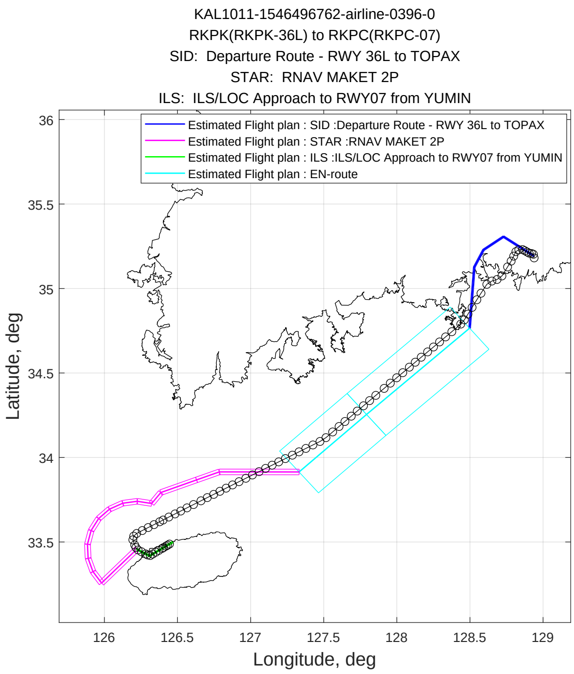

Fig. 1. Example of flight plan estimation algorithm result

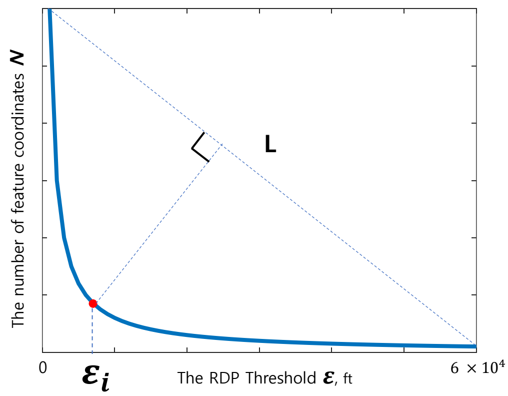

Fig. 2. ϵ - N graph

Assuming that the altitude change instruction would occur when the aircraft is cruising, whether the aircraft is in a cruising state was first determined. If the altitude of the next point is within 25 ft of the previous point this point is recorded as curising. If the altitude difference exceeds 25 ft, then the average vertical speed, v_{hi}, shown in Eq. (1) is checked. If $|v_{hi}|$ exceeds 50 fpm, this point is recorded as the feature point where the aircraft starts to climb or descend. The process is summarized in Fig. 3.

$$v_{hi} = \frac{h_i - h_{i-1}}{t_i - t_{i-1}} \tag{1}$$

3.2. Estimation of radar vectoring coordinates

Based on the result of extracting the feature coordinates, whether the coordinates include the radar vectoring instruction is determined by comparing the flight's flight plan and feature coordinates.

If a feature point is inside the horizontal boundary of the estimated flight plan and also within the altitude boundary, the

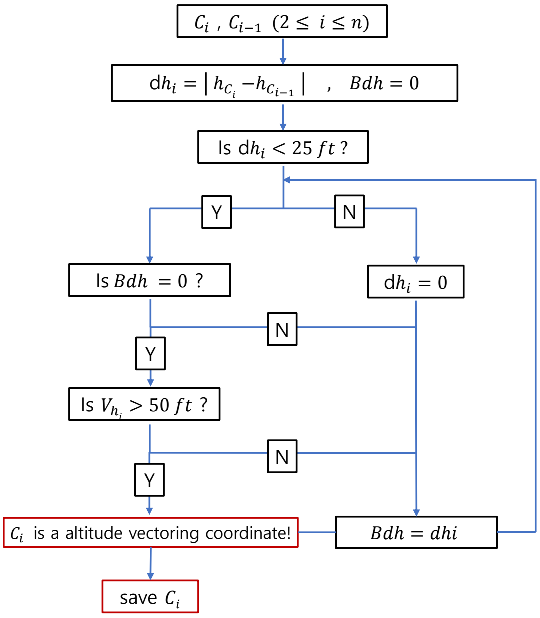

Fig. 3. Estimation methodology of altitude coordinates

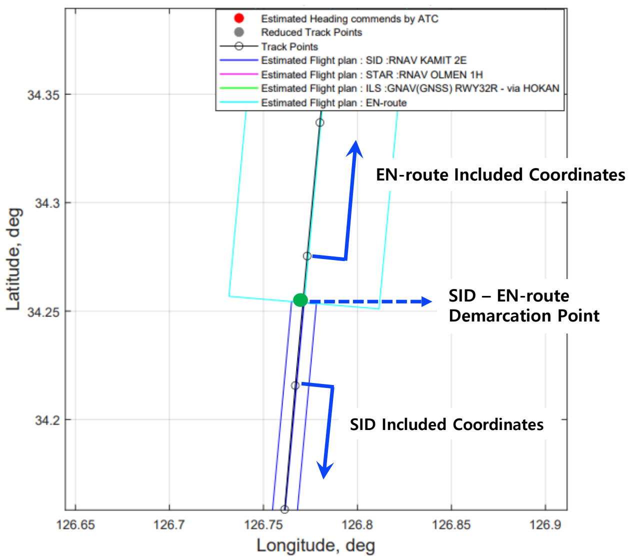

Fig. 4. Different horizontal boundaries

point is not considered a vectoring instruction. If a feature point is outside the horizontal boundary, the point is counted as a heading instruction. In this case, if the point is a feature point in terms of altitude instruction, it is also counted as an altitude instruction. Horizontal boundaries are specified in the AIP and can be different from one segment to another segment as shown in Fig. 4. If the feature point is within the horizontal boundary, the next feature point is checked. If the next feature point is less than two minutes from the current point and at the same time inside the horizontal boundary, it is not considered as a heading instruction. If this next point within two minutes is outside the horizontal boundary, it is counted as a heading instruction. For both the cases, the feature point is counted as altitude instruction only when the next point is outside the altitude boundary. The decision tree is summarized in Fig. 5.

An example of the estimation of radar vectoring is shown in Figs. 6 and 7 for a flight from RKPC to RKSS.

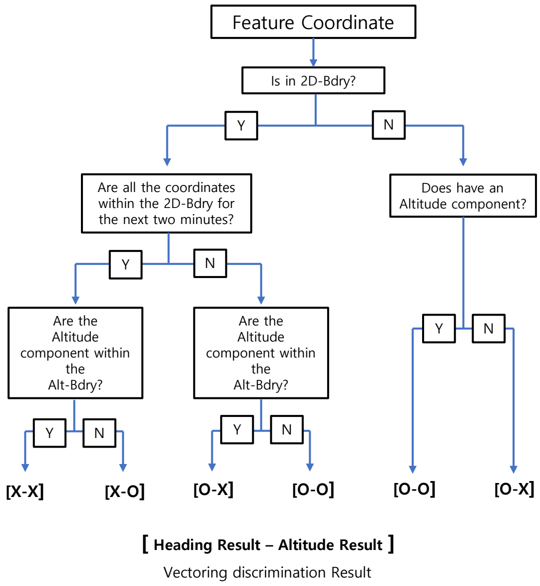

Fig. 5. Decision tree of algorithm

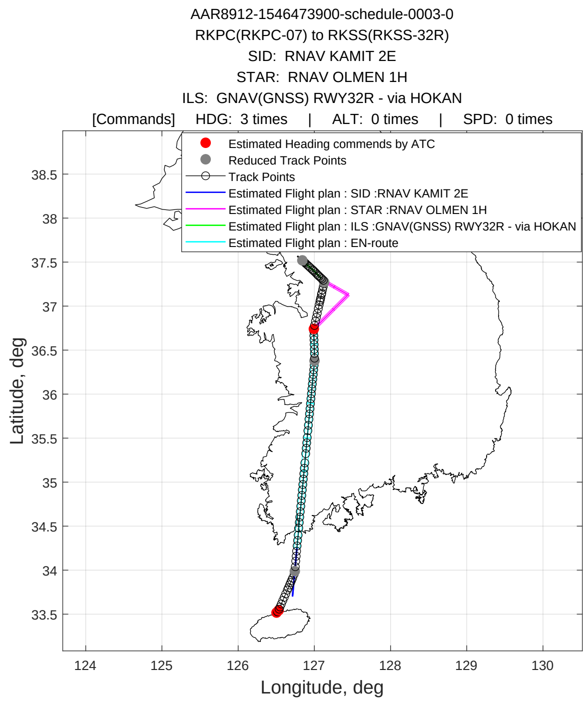

Fig. 6. The estimation result of coordinates including heading radar vectoring

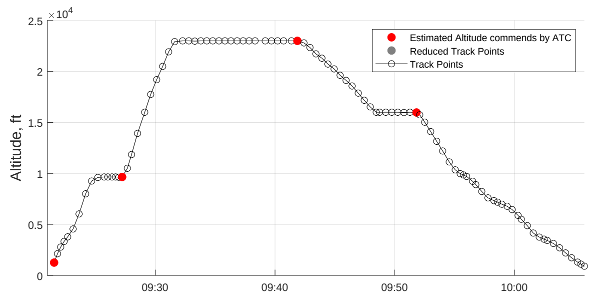

Fig. 7. The estimation result of coordinates including altitude radar vectoring

4. Analysis of Number of Radar Vectoring Instructions

Using the methodology described in the previous section, the number of controller's vectoring instructions, that is the number of heading change and altitude change instructions are calculated for all flights that depart or arrive at one of the four major airports in the data set. After obtaining the instruction counts of each flight, the counts are added for each IFR departure, arrival, and approach procedures. Figure 8 shows the total number of radar vectoring instructions for the flights that are supposed to using one of the STARs of RKSI, "RNAV CUN 1M".

Based on the analysis results, this paper calculated the average per flight instruction count, *R*, for each SID, STAR, and ILS for the four airports. Tables 3 to 6 show the most commonly used SID, STAR, and ILS of the four airports and corresponding instruction counts for those procedures. In general, there were more heading instructions than altitude instructions. As can be expected, vectoring instructions during ILS approach were rare. However, the "RNAV(GNSS) - B to RWY 18L" procedure of RKPK had relatively larger number of vectoring count.

Table 3. Result of the number of radar vectoring instruction by RKSI

RKSI					
Type		Route Name	V_n	U_n	R
SID	Heading	RNAV BOPTA 1L	97571	23435	4
	Altitude		24756		1
STAR	Heading	RNAV GONAV 2M	117712	34639	3.4
	Altitude		59162		1.7
ILS	Heading	RNAV(GNSS) RWY33R - via PULUN	882	31508	0.03
	Altitude		387		0.01

Table 4. Result of the number of radar vectoring instruction by RKSS

RKSS					
Type		Route Name	V_n	U_n	R
SID	Heading	RNAV BULTI 1J	51281	29868	1.7
	Altitude		44092		1.5
STAR	Heading	RNAV OLMEN 1H	26961	20463	1.3
	Altitude		18267		1
ILS	Heading	GNAV(GNSS) RWY32R - via HOKAN	410	12569	0.03
	Altitude		26		0.002

Table 5. Result of the number of radar vectoring instruction by RKPC

RKPC					
Type		Route Name	V_n	U_n	R
SID	Heading	RNAV KAMIT 2E	45151	31651	1.4
	Altitude		40996		1.3
STAR	Heading	RNAV DOTOL 2P	81553	35841	2.3
	Altitude		47305		1.3
ILS	Heading	RNAV(GNSS) RWY 25	563	17082	0.03
	Altitude		84		0.005

Table 6. Result of the number of radar vectoring instruction by RKPK

RKPK					
Type		Route Name	V_n	U_n	R
SID	Heading	Departure Route - RWY 36L to TOPAX	32096	10107	3
	Altitude		11471		1
STAR	Heading	RNAV DIMON 1 - PSN Transition	1579	9891	0.2
	Altitude		896		0.1
ILS	Heading	RNAV(GNSS) - B to RWY 18L	1266	2344	0.5
	Altitude		873		0.4

5. Conclusions

In this paper, a methodology of estimating the number of radar vectoring instructions using only the historic trajectory data is proposed, and the results of analyzing the traffic within the Incheon FIR for radar vectoring instructions are presented.

Among the heading and altitude change instructions that were analyzed in this paper, it was discovered that the heading change instructions occurred more frequently.

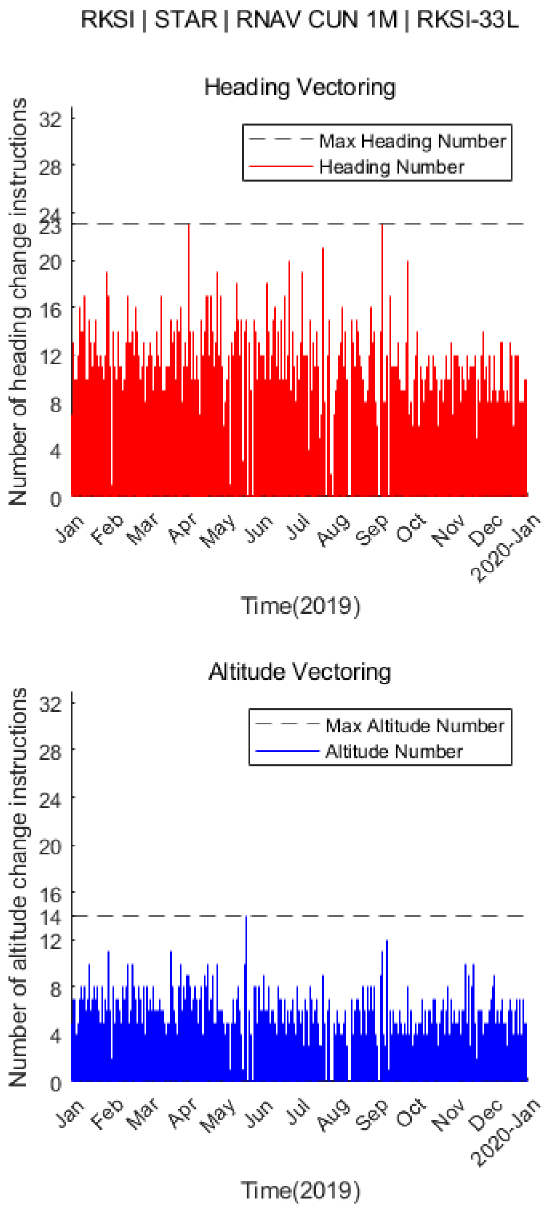

Fig. 8. Result of the number of radar vectoring instructions

In the future, the with higher quality data, speed change instructions will also be analyzed. With the capability to count most of the vectoring instructions, the correlation between instruction counts and other metrics such as controller workload, severe weather events, or any other unusual traffic events such as Notice to Airmen will be studied.

Acknowledgments

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