AVIA

Original Article

Required Navigation Performance (RNP) Analysis for ADS-B Data of Makassar-Jakarta Flight using Dot Product Method

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Required Navigation Performance (RNP) is known as a performance parameter for a navigation system, where its function is to keep an aircraft within a certain radius of containment. During the flight, an aircraft transmits its real-time location based on Global Navigation Satellite Systems (GNSS) technology via Automatic Dependence Surveillance-Broadcast (ADS-B) protocol. However, there are questions about the flight position accuracy. This research aims to analyze the accuracy of ADS-B flight data about RNP requirements. The flight data used is gathered from the FlightRadar24 website and filtered for each flight phase. The selected route used is Makassar (UPG) – Jakarta (CGK) because the route has the highest number of flights per week. The Dot Product method is proposed to calculate the distance between the flight trajectory to the line of flight procedure towards the destination airport. The analysis is conducted based on the compliance of the flight data to the RNP threshold. It is concluded that the majority of evaluated flights in the selected route fly within the RNP boundary. However, some non-complying flights become within the RNP boundary when they are evaluated with other possible published procedures.

Keywords: ADS-B; dot product; point to line distance; RNP; trajectory analysis

1. Introduction

Transportation has an important role in our society. As the population increases, the number of commuters will increase. On the contrary, the space available for transportation decreases along with the increasing number of transportations. This applies to any form of transportation, notably air transportation. Although COVID-19 slows aircraft productions and limits airlines flights, the number of commercial aircraft is predicted to double the number for the next 20 years [1].

Most modern commercial aircraft are equipped with high-tech radar and positioning systems to maintain a high level of safety. Engineers are still enhancing the current system and developing better ones to crank up the safety level as well as the efficiency level. The surging numbers of aircraft will gradually affect the traffic in airspace; therefore, navigation systems are required to be very accurate and reliable during flight.   Multiple platforms support navigation and communication using flight instruments. ATC (Air Traffic Controller), Navaids such as VOR (VHF Omnidirectional Frequency Range), and ground stations, all together provide bridges to communicate with aircraft, while transmitting and receiving data at the same time.

Navigation systems play a crucial part in keeping the flight safe and sound, such as PBN (Performance Based Navigation), RNAV (Area Navigation System), or Required Navigation Performance (RNP). They are responsible to provide spacing between aircraft and defining optimized

flight routes or trajectory. The main advantages of the systems are the optimized use of flight trajectory and use of airspace, which lead to cost efficiency and optimal flight time. Like any GNSS (Global Navigation Satellite System), there is a certain degree of deviation that might occur in the process. Although the systems were found to be accurate and reliable, this paper will provide calculation of errors or deviations, as it is needed to prove the accuracy of the flight data; followed by visualization of the flight trajectory of multiple aircraft.

The purpose of the research is to find out how precise and accurate the flights are in Indonesia. And the result will be shown in graphs illustrating the deviation that occurred in the gathered flight data also the flight trajectory of each flight.

This report will start with materials and methods in Section 2. Then the result and discussion are in Section 3. In the end, the conclusion and recommendation are given in Section 4.

2. Materials and Methods

This section consists of a literature review, background theory, and the research methods.

2.1. Literature Review

Based on the literature found related to RNP flight analysis, there are 2 categories of the methods used. The first one is position domain analysis which includes numerical calculation and the second one is non-position domain analysis which is based on the data of characteristics received from the aircraft.

There are three reviewed papers discussing position domain analysis. The first paper published work containing **a** table of the elements of SBAS OT&E (Operational Test and Evaluation) and OM (Offline Monitoring). One of the elements is Position Domain Analysis which consists of accuracy, integrity, continuity, and availability analysis [2].

The second and third papers used a similar method by analyzing RNP items and visualizing them. The similarity between the papers lay in the technique, calculating the protection level and position error (both HPE and VPE), and then plotting the statistical deviation from the data [3,4].

Contrary to position domain analysis, non-position domain analysis does not include complex numerical calculation, rather an analysis based on data that will retrieve the behavior of the aircraft, potentially exposing further the advantages of RNP. Two publications are using a similar approach and method called "Geometric and Intent Conformance". The result from both papers involves the Integrity of ADS-B Data and the noise-related issue [5,6].

Another publication from MIT was showing the implementation of the RNP Approach (AR) Procedure, by comparing the differences between RNP-AR and other approaches such as ILS and RNAV, on multiple runways of four selected Airports [7].

2.2. Background Theory

This section defines the research background concept regarding RNP analysis. The chapter will be broken down into several background theories– How GPS (Global Navigation System) as most of the popular GNSS and ADS-B (Automatic Dependent Surveillance-Broadcast) work, and the RNP concept.

2.2.1. How GPS works

GPS consists of 3 main objects; satellites, ground stations, and receivers. Although GPS requires at least 4 satellites to track your location, more satellites will provide higher reliability and accuracy. There are 24 GPS Constellation Satellites orbiting around the six earth-centered orbital planes. In general, 4 satellites are needed to determine your location accurately while 1 of the 4 satellites will determine the time errors.
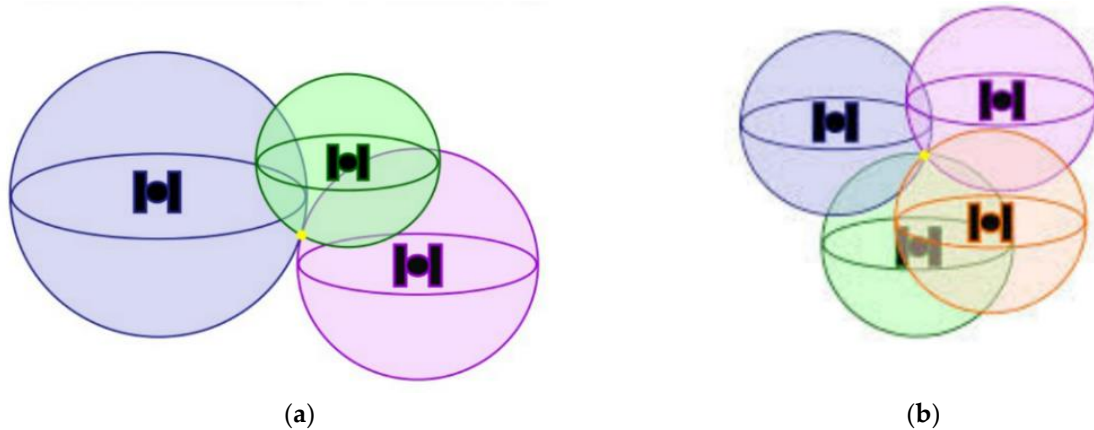

(a)   (b)

Figure 1. Trilateration mechanism of GPS: (a) 2D position; (b) 3D position [3]

GPS uses Trilateration mechanism, 2 Dimensions (2D) and 3 Dimensions (3D) as shown in Figure 1. The 2D requires at least 2 satellites and tracks the u ins by longitude and latitude coordinate, while 3D requires at least 3 satellites and tracks the user with longitude, latitude, and altitude, resulting a spherical-like possibilities. Most receivers have built-in GPS module, but do not have the atomic lock in its module, the 4th satellite would come in handy to calculate the time offset(Δt_{offset}) through the atomic clock. As seen in the figure, the yellow dot is the final user position with 15-20 m accuracies for Consumer-Grade GPS [8].

GPS satellites are driven by an atomic clock, where 10.23 MHz is the fundamental clock frequency. Each satellite has three types of L-band signals and two carrier signals could be described as sine waves and created by multiplying the carrier signals the fundamental clock frequency.

2.2.2. How ADS-B works

Since ADS-B relies on GPS and other navigation instruments to receive and distribute the information, errors are inevitable despite its magnitude. By using User Differential Range Error (UDRE) and Grid Ionospheric Vertical Error (GIVE) to determine a position error (PE) and a protection level (PL) [5]. The pseudo-range error varieties could be expressed in the following equation.

$$P = \rho + d_\rho + Cpseudo - range + d_{trop} + \varepsilon_{mp} + \varepsilon_p \qquad (1)$$

Where: P =the pseudo range measurement

ρ = the true range

d_ρ = satellite orbital errors

C = the speed of light

dt = satellite clock offset from GPS time (s)

dT = receiver clock offset from GPS time (s)

d_{ion} = ionospheric delay (s)

d_{trop} = tropospheric delay (s)

ε_{mp} = multipath
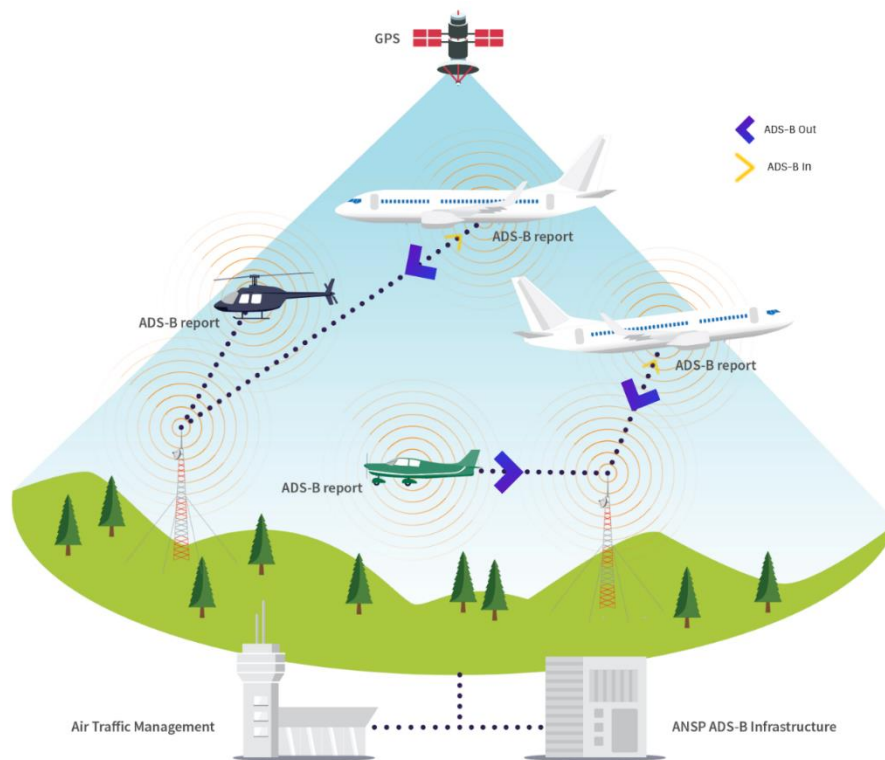
ε_p = receiver noise

Figure 2. Principle of ADS-B [5]

ADS-B has similar sections as GPS such as satellites, receivers, and ground stations, with more receivers and transmitters as shown in Figure 2. The main difference is that an aircraft with ADS-B would have the ability to self-broadcast independently [5]. Starting from 1st January 2020, FAA's Final Rule dictates that any operating aircraft in the airspace is required to have ADS-B as defined in 14 CFR 91.225 within the performance requirements as written in 91.227. ADS-B perform two types of broadcasting:

- ADS-B "Out": the ability of an aircraft to transmit information to the ground stations and other aircrafts with ADS-B.
- ADS-B "In": The ability of an aircraft to receive information from other aircraft and ground stations.

ADS-B operates mostly in 1090 MHz for both ADS-B "Out" and "In", however 978 MHz or UAT becomes widely used as it is believed to be cheaper and helped to decrease the frequency congestion on 1090 MHz [9]. The 978 MHz users do not receive direct information from 1090MHz, rather relying on the ADS-R (Automatic Dependent Surveillance-Rebroadcast) indirectly that it rebroadcasts the cross-band traffic towards 978 MHz. Ground radars responsible for transmitting TIS-B (Traffic Information Service-Broadcast) and FIS-B (Flight Information Service-Broadcast) signal through 1030 MHz and receiving a signal through 1090 MHz.

ADS-B has a message structure that will be encoded. The message is 112 bits long with 5 parts, starting with the Downlink Format 17 (DF-17) or 18 (DF-18) for TIS-B. The first 5 bits correspond to 10001 or 10010 I binary while bits 6-8 are used as an identifier that has different meanings within each ADS-B message such as shown in Table 1.

Table 1. ADS-B Data Structure [10]

nBits	Bits	Abbr.	Name
5	1 - 5	DF	Downlink Format
3	6 - 8	CA	Capability (additional identifier)
24	9 - 32	ICAO	ICAO aircraft address
56	33 - 88	DATA	Data
	[33 - 37]	[TC]	Type code
24	89 - 112	PI	Parity/Interrogator ID

2.2.3. RNP concept.

RNP has a similar analogy to a highway, but with stricter regulations and inviolable procedures, unless an emergency occurred. RNP has a similar concept as "*The Tunnel Concept*" as shown in Figure 3, in which the tunnel sub-parts depict the separation between terrain,   other aircraft around the vicinity, or ground obstacles [4]. It is adapted and developed the concept according to Appendix A for the ICAO definition of RNP. Since the paper was published earlier in the 1990s, it mainly derives the detailed base knowledge regarding RNP, such as how effective the RNP is, definition of RNP and its elements, and deriving how the system and concept are applicable for CAT I, II, and III (stages of aircraft before touchdown) operations.
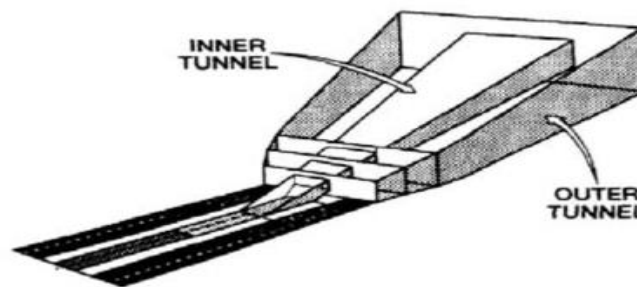

Figure 3. RNP Concept [4]

Figure 4 represents the analogy of Total System Error (TSE), the deviation of an aircraft's true position with the desired path, which involves path definition error (PDE),   flight technical error (FTE), and navigation system error (NSE) [3].
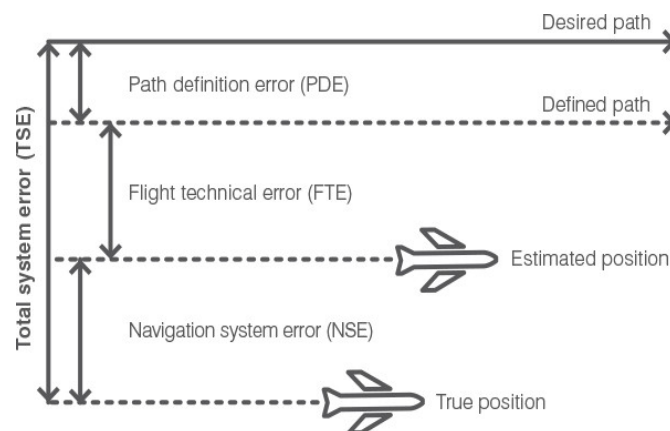

Figure 4. Total System Error visualization [3]

In RNP the navigation requirements as depicted in Figure TSE are:

- Accuracy: Where TSE is equal to or less than xRNP (x is a unit in NM) 95% of the flight time
- Integrity: Probability of true TSE of the aircraft exceeding the 2 times of xRNP

2.3. Research Methods

This section will break down the processes used in this research, from pre-processing data, explanation of Dot Product method, and the algorithm implementation in python programming language.

2.3.1. Pre-Processing Data

Initially, data will be obtained from the FlightRadar24 website, where various types of flights, airports, airlines, and routes could be chosen to fit the requirements of the research. The airport of interest will be Soekarno-Hatta International Airport (CGK/WIII) with flights from Makassar (UPG) - Jakarta (CGK). Because the number of flights per week is high reaching at least 300 flights.

There are diverse options for the airlines, but the number of flights with status 'canceled' and 'unknown' in Lion Air, Sriwijaya, and Batik Air is also high. Therefore, Garuda Indonesia is chosen to be analyzed. Most of the flights will land in Runway 25L and sometimes Runway 25R of Soekarno-Hatta, therefore, the data for STAR (Standard Arrival Chart - Instrument) and waypoints will be obtained from AIM – Ministry of Transportation website [8].

After the data is obtained, sorting will be necessary to elevate the data's neatness, leading to effective data processing. Then, create data frames from each flight and choose only the Latitude and Longitude. In case the data is not in the right form or separated by a comma, slice the data column using python programming.

2.3.2. Dot Product Method

The dot product method is used to perform distance calculation between line and a point. Its principle is shown in Figure 5 [11].
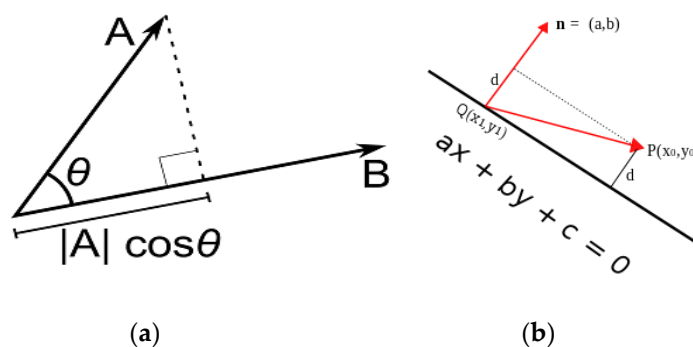

(a)   (b)

Figure 5. Dot Product method: (a) Projection of vector; (b) Geometry Proof.

The projection of vector A times B would be:

$$a \cdot b = (\|a\|)(\|b\| \cos \theta) \qquad (2)$$

From the geometry proof, d is an orthogonal projection of vector $\overrightarrow{(QP)}$

$$d = \|QP\| . \cos \theta \qquad (3)$$

Multiplying both numerator and denominator with normal vector $\vec{n}$, we get

$$d = \frac{\|QP\| \cdot \|n\| \cos\theta}{\|n\|} \tag{4}$$

We know that $\|QP\|$ .is equal with dot product of $\overrightarrow{QP} \cdot \vec{n}$

$$d = \frac{\overrightarrow{QP} \cdot \vec{n}}{\|n\|} \tag{5}$$

where: $\overrightarrow{QP} = x_0 - x_1, y_0 - y_1$
   $\vec{n} = (a, b)$

The distance is calculated by:

$$d = \frac{|ax_0 - ax_1 + by_0 - by_1|}{\sqrt{a^2 + b^2}} \tag{6}$$

Derived from the distance formula above, the distance from an aircraft's position to a line from two waypoints is the shortest distance forming perpendicular segment, within a condition of the line must not be vertical or horizontal. The figure below illustrates a line passing through two waypoints (A & B), anusing aircraft coordinate (C).
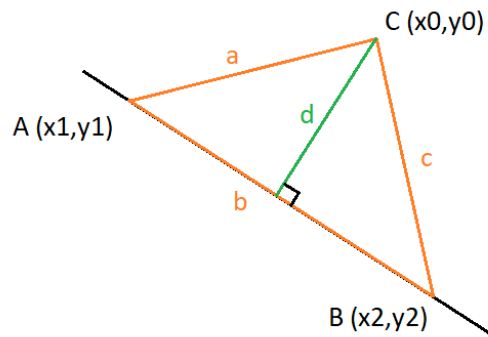

Figure 6. Point to Line Distance

Both waypoints and aircraft coordinate are using Latitude (ϕ)and Longitude (λ). The shortest distance (d)

$$d(A, B, (x_0, y_0)) = \frac{|(x_2 - x_1)(y_1 - y_0) - (x_1 - x_0)(y_2 - y_1)|}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}} \tag{7}$$

And since coordinate consist of upper and lower boundary in latitude, the absolute is removed, then equation (7) will be:

$$d(A, B, (x_0, y_0)) = \frac{(x_2 - x_1)(y_1 - y_0) - (x_1 - x_0)(y_2 - y_1)}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}} \tag{8}$$

2.3.3. Algorithm Implementation

By using the computer programming, data processing will be more efficient, as it contains multiple libraries of tools for processing multiple types of data. In this case, processing the flight data in form of .CSV. The language for the algorithm in this research is the Python programing language. The pseudo-code of the data processing and Dot Product method is shown in Figure 7.

```
1.   //CREATE DataFrame
2.   //df.Aircraft and df.Waypoint
3.   //IF df.Aircraft and df.Waypoints ≠ [lat, lon]
4.          SLICE into [lat,lon]
5.          STORE []
```

```
6.
7.   //SCATTER [wptlat, wptlon]
8.   //PLOT (aclat,aclon)
9.    //SAVEFIG .PNG


1.   //From df.Aircraft & df.Waypoints
2.   //IF (aclat, aclon) < (wptlat1, wptlon1, wptlat2, wptlon2)
3.   //      CALCULATE distPointLine ((aclat,aclon),(wptlat1,
             wptlon1, wptlat2, wptlon2))
4.          Else
5.          CALCULATE distPointLine ((aclat,aclon),(wptlat1,
             wptlon1, wptlat2, wptlon2))
6.          STORE []
7.   //CALCULATE avg_distPointLine, std_distPointLine
8.   //PLOT distPointLine, avg_distPointLine & std_distPointLine
9.   //SAVEFIG .PNG
```

Figure 7. Pseudo-code of data processing and Dot Product method

3. Results and Discussions

Overall, the gathered data is about a month, starting from November 1st to December 25th, 2020, the main constraint is the FlightRadar24 website's regulation to limit subscribed user membership up to 10 data per day and reset every day UTC time. The main parameter that will be analyzed is accuracy and integrity. Since the calculation requires only the latitude and longitude data of each aircraft, aircraft type, altitude, and speed will be neglected in the calculation. The plotting of data is shown in Figure 8.
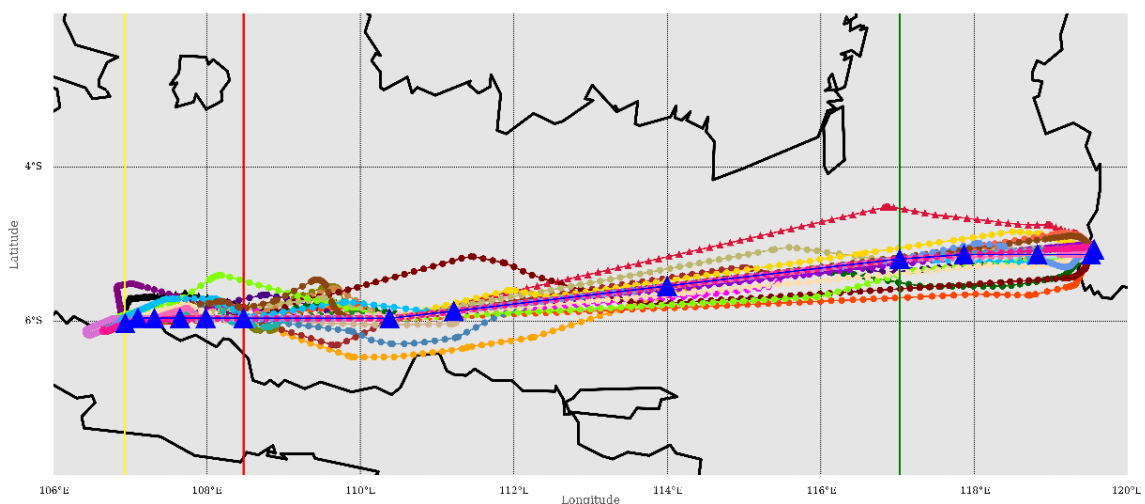

Figure 8. Flight Data plots of UPG-CGK route

The data consists of 37 flights and will be divided into three phases, Departure, Enroute, and Arrival. The published procedure of Departure at Makassar airport and Arrival at Jakarta airport is shown in Figure 9. Due to the lack of waypoints data limitation, the flight plotting in enroute is narrowed into the main waypoints only. For reference, RNP departure has 1.0 NM containment, enroute has 2.0 NM containment, and RNP Arrival has 0.3 NM containment [12].
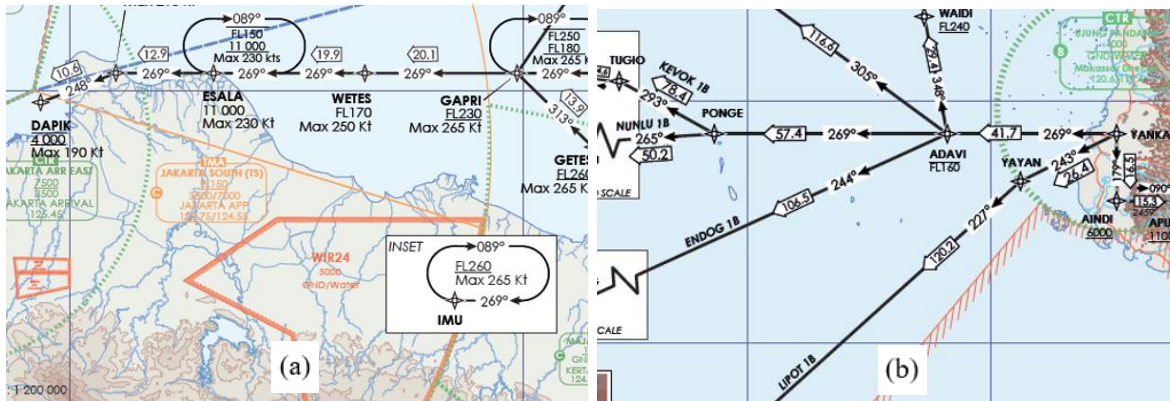

Figure 9. Published Flight Procedure for: (a) Arrival at Jakarta airport (CGK); (b) Departure at Makassar Airport (UPG)

3.1. Departure Flight Data

The departure starts after the aircraft take-off from Makassar (UPG) airport via waypoint YANKA or AULIA until waypoint NUNLU. There are multiple waypoints available for each aircraft depending on which runway they take off from. The calculated deviation distance between flight trajectory and departure procedure is shown in Figure 10 (a). The shades represent the RNP containment limit. The accuracy is the dark shade, RNP 1.0 NM and the lighter shade is aircraft integrity 2xRNP. It shows that most of the flights are inside the RNP 1.0, 5 flights within 2xRNP and only 4 are outside the 2xRNP.

The result of point to line distance in the form of a boxplot graph is shown in Figure 10 (b). The boxplot presents the statistical characteristics of each aircraft trajectory: minimum, 1st quartile, median, 3rd quartile, maximum, and the outliers. It shows that 99% of data is within the minimum and maximum values. According to the boxplot, there are 28 flights within RNP 1.0. The 9 flights (F14, F19, F31-F37) outside the RNP 1.0 could be due to traffic and take-off runway selection. Those flights will be analyzed further as the special case.

For the special cases, we look deep on the 2 of the flights (F33 and F37) as shown in Figure 11. When we consider other published departure route as shown in Figure 11(a) with blue color and compare it with the 2 flight trajectories in green and magenta, the distance differences are within RNP 1.0 as shown in Figure 11(b) and (c). From our finding, the 9 flights which are outside RNP 1.0 as mentioned in the previous paragraph, are following other published departure procedures.
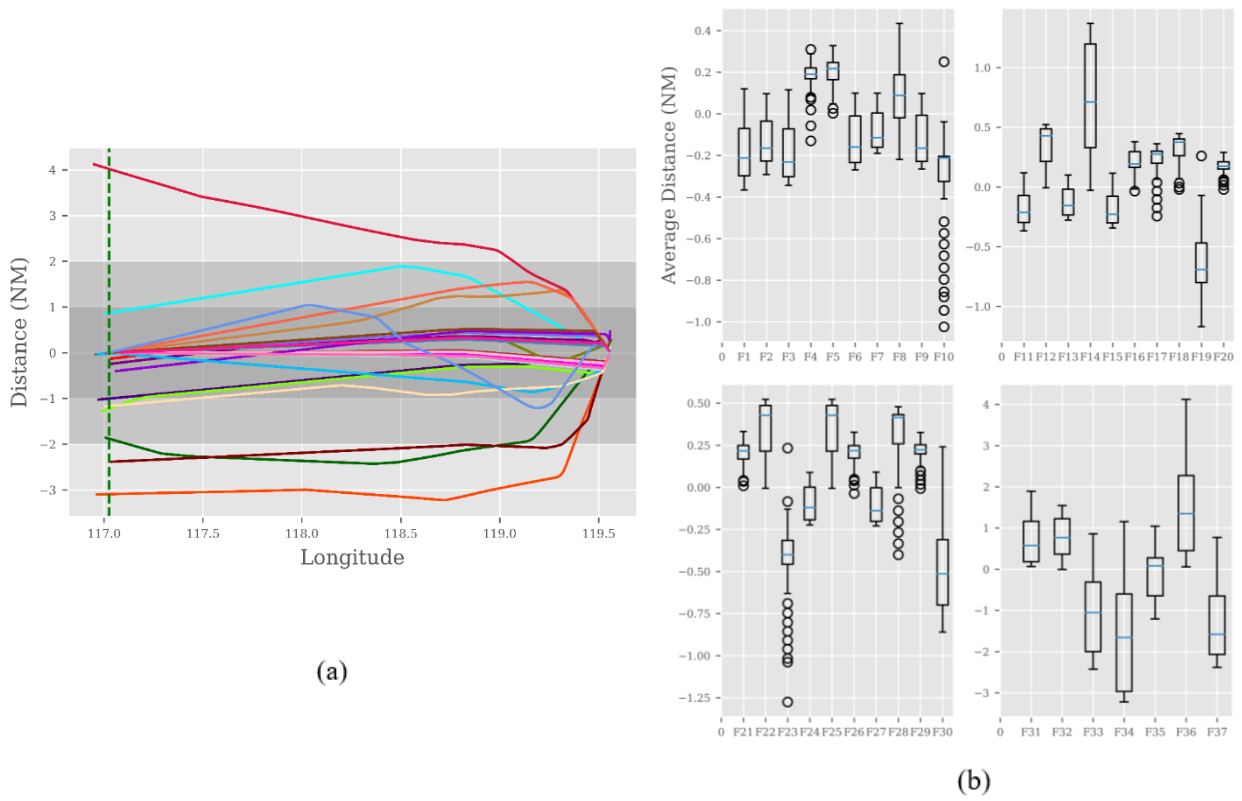
Figure 10. Deviation distance of Departure segment: (a) Distance to Longitude; (b) Box plot of deviation distance of each flight data
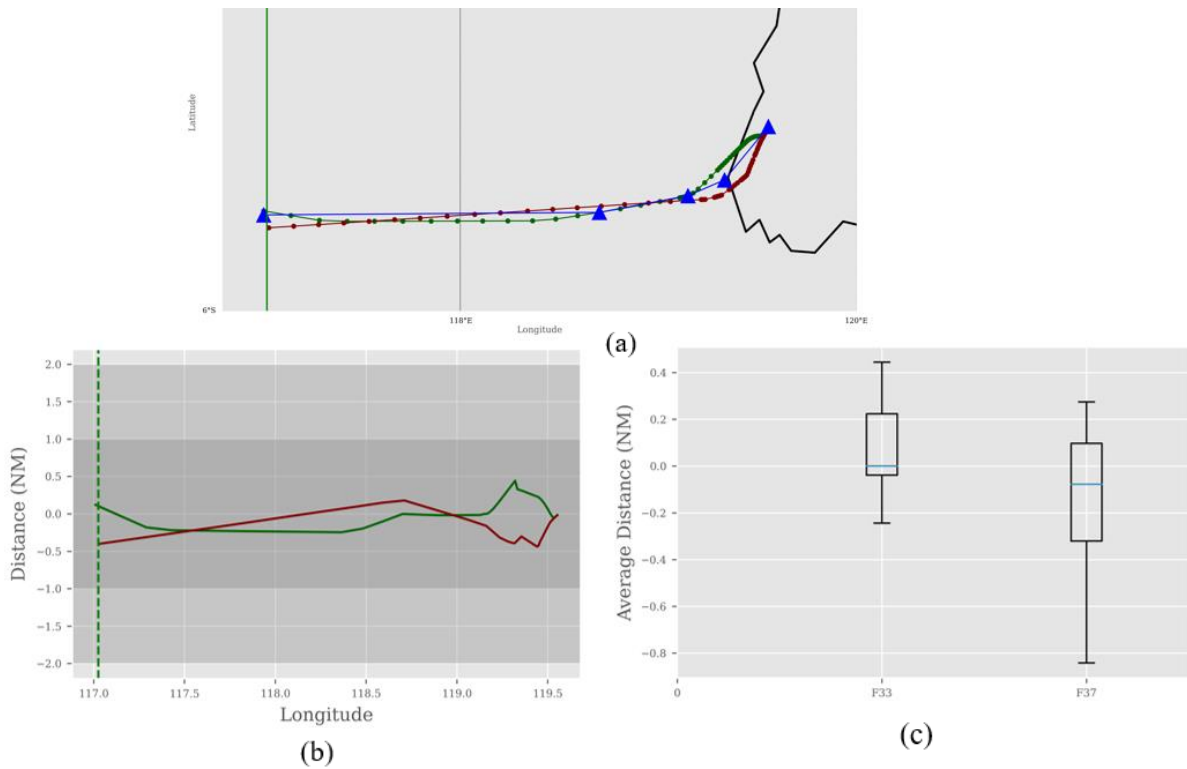

Figure 11. A special case of Departure segment: (a) plotting departure procedure and flight trajectory; (b) Deviation distance to Longitude plot; (c) Box plot of deviation distance.

3.2. Enroute Flight Data

Continuing from departure segment, flight procedure from waypoint NUNLU to KURUS showcasing the flights in enroute phase. There are some flights with big alteration, that could be due to avoiding weather along the route and shortcuts to the fastest route (in marron, gold, steel blue colors) as shown in Figure 12 (a). The boxplot shows that only 6 flights (F15, F20, F31, F32, F35, F37) are outside RNP 2.0.

For the special cases, we look deep on the flight F31 as shown in Figure 13. When we consider other published enroute routes as shown in Figure 13(a) with blue color and compare it with the flight trajectory in magenta, the distance differences are within RNP 1.0 as shown in Figure 13(b) and (c). From our finding, the 6 flights which are outside RNP 2.0 as mentioned in the previous paragraph, are following other published enroute procedures. However, we did not have further information about the reason for choosing those routes.
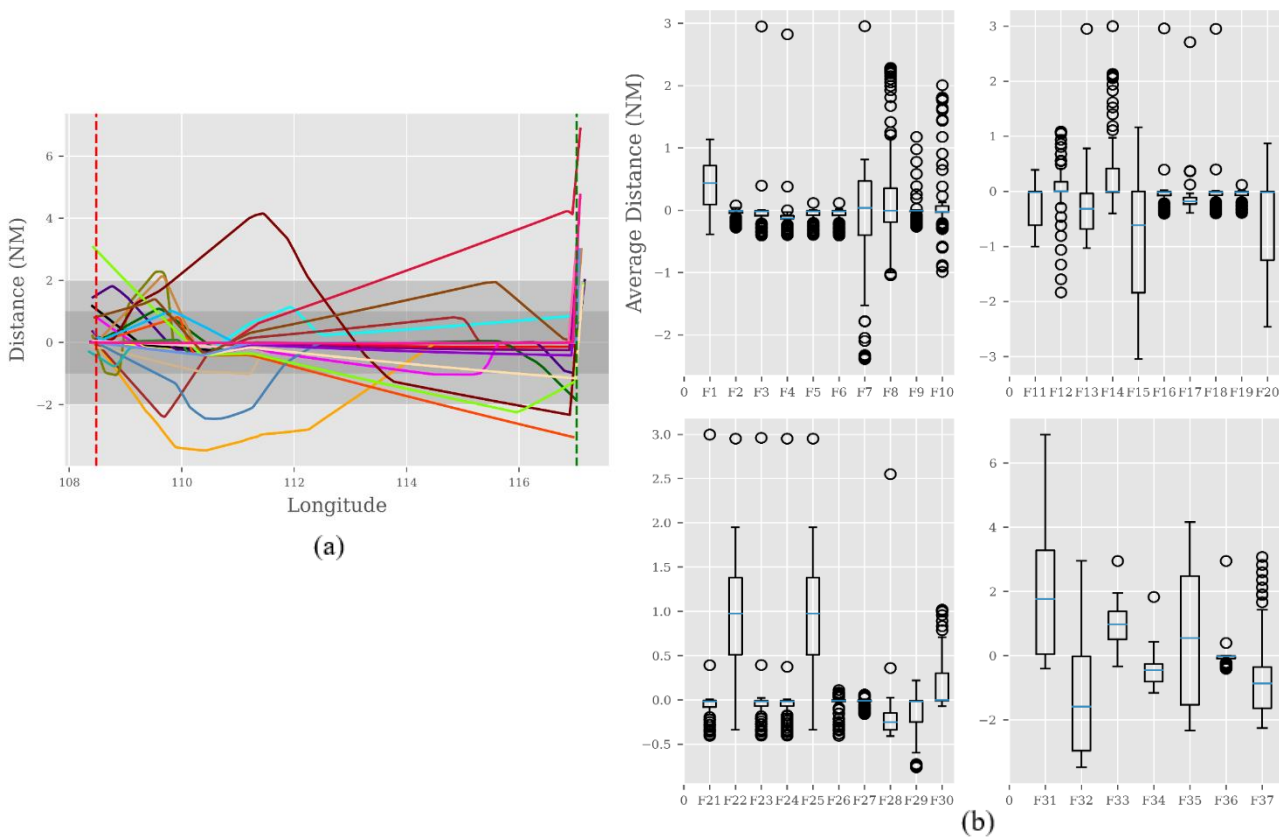

Figure 12. Deviation distance of Enroute segment: (a) Distance to Longitude; (b) Box plot of deviation distance of each flight data
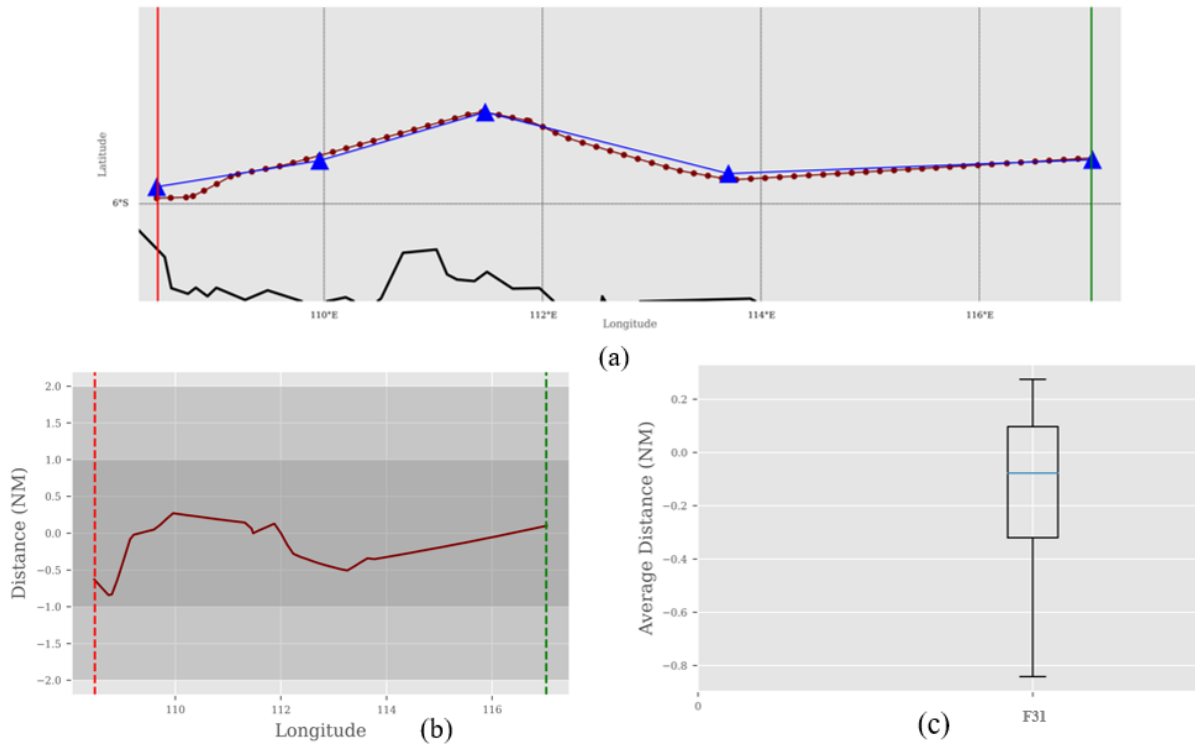
Figure 13. A special case of Enroute segment: (a) Plotting enroute procedure and flight trajectory; (b) Deviation distance to Longitude plot; (c) Box plot of deviation distance.

3.3. Arrival Flight Data

The arrival segment starts from waypoint KURUS until the runway of Soekarno-Hatta airport. The deviation distance between the arrival procedure and the flight trajectory is shown in Figure 14(a). It shows that most of the flights are within RNP 1.0 containment. From the boxplot in Figure 14(b), it shows clearly only 4 flights (F31, F33, F35 and F37) are outside RNP 1.0.

For the special cases, we look deep on the flight F37 as shown in Figure 15. When we consider other published arrival routes as shown in Figure 15(a) with blue color and compare it with the flight trajectory in black, the distance differences are within RNP 0.3 as shown in Figure 15(b) and (c). From our finding, the 4 flights which are outside RNP 1.0 as mentioned in the previous paragraph, are following other published arrival procedures. This selection of flight procedures is mentioned in the flight plan but is subject to ATC approval during flight.
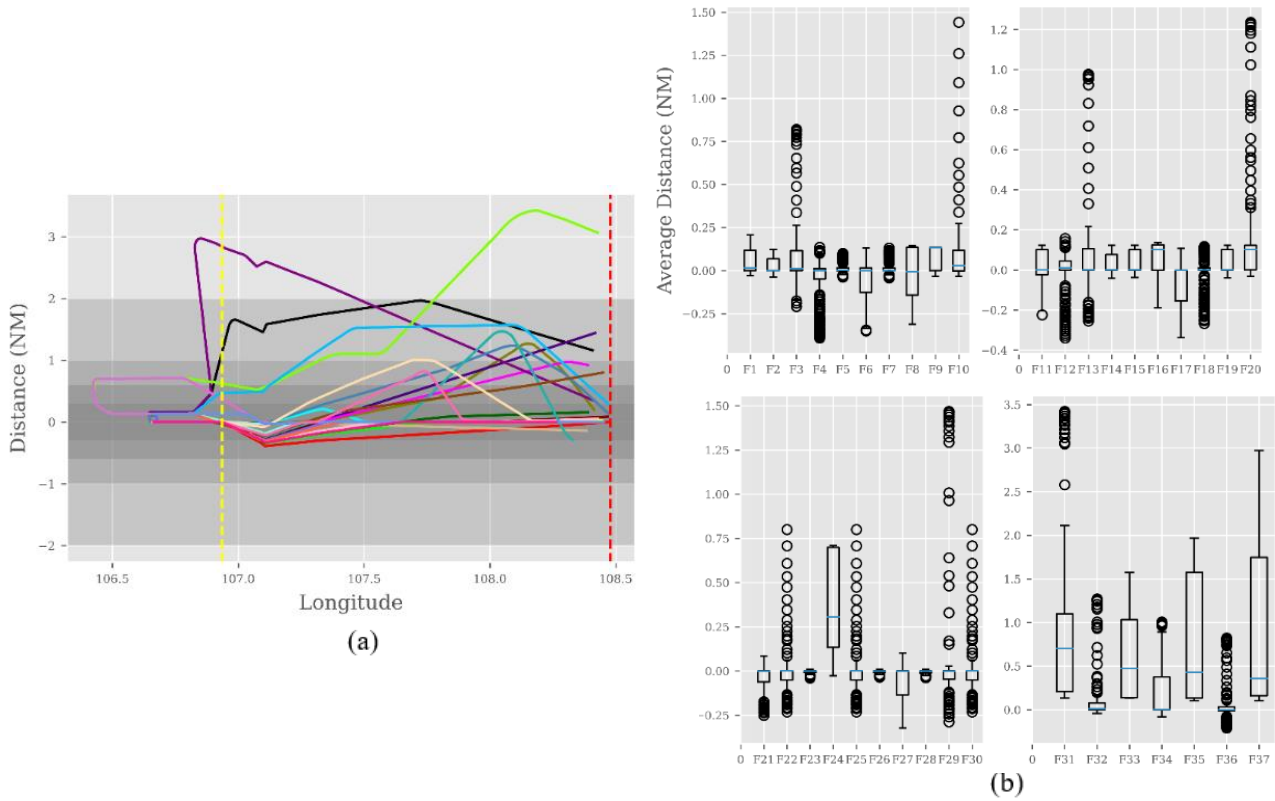
Figure 14. Deviation distance of Arrival segment: (a) Distance to Longitude; (b) Box plot of deviation distance of each flight data.
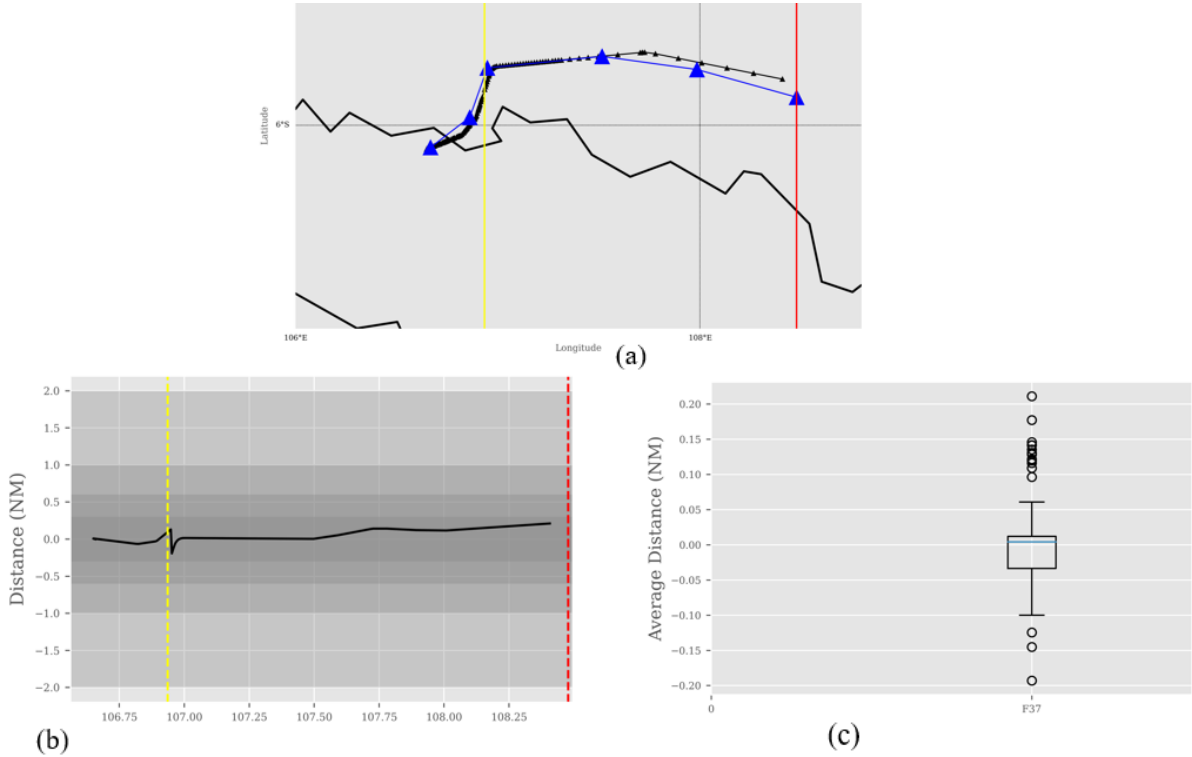

Figure 15. Special case of Arrival segment: (a) plotting arrival procedure and flight trajectory; (b) Deviation distance to Longitude plot; (c) Box plot of deviation distance of flight data.

4. Conclusions

Most of the flights from Makassar (UPG) – Jakarta (CGK) is following RNP requirements. The deviation of the aircrafts position is still within the containment of RNP. However, many non-complying RNP flights are become within RNP containment when they are evaluated with other possible published procedure. Thus, the dot product method could be used as the tool to calculate the deviation of flight trajectories regarding the RNP requirements. It is recommended that the flight trajectory data is supported by flight planning data where we could know the flight procedures planned to be used. Thus, the result will be more specific to that flight and its planning route.

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