Calculation of Turn Radius and Bank Angle at Different Altitudes Based on RNP AR

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Abstract—In this study, different kinds of turns based RNP AR procedures such as flyby and RF will be introduced. For fly by turn radius at different altitudes will be calculated. Moreover, the relation between bank angle (α) and altitude (h) will be investigated and assessed for RF turns. At the end of the study, it is noted that for fly by turns at standard α (18°), the turn radius increases in higher altitudes. However, for RF turns, turn radius is considered constant as 7 nms and it is observed that α alters proportional with h. It is concluded that in order to keep same turn radius (7nms) at higher levels, aircraft needs to increase α. The results showed that α alters between 6° < α < 18° at 1,000<h<19,000 ft.

Index Terms—performance based navigation, required navigation performance authorization required, radius turn, bank angle

1. INTRODUCTION

Air traffic demand is increasing every year, which indicates the need of development air traffic management. Therefore, increasing capacity and flight efficiency with regards to safety and environment is a significant goal. In order to achieve this goal, designing optimum and efficient flight routes can be one of the solutions.

Performance based Navigation (PBN) is a concept used en route for reducing separation minima between aircraft and in terminal control area for optimizing the arrival and departure procedures. PBN could be defined as a navigation method which is based on aircraft performance and onboard equipment. PBN trusts area navigation systems which include satellite signals with advanced cockpit technology and allows aircraft to fly without depending on ground based navigational aids. PBN has several benefits which are summarized below.

PBN:
- Allows continuous descent profiles (CDA),
- Reduces track miles and so provides fuel savings,
- Reduces environmental impacts such as noise and emissions,
- Provides more efficient use of airspace.

Navigation specifications explain the area navigation performance requirements such as accuracy, integrity, availability and continuity. Also, navigation specification identifies Area Navigation (RNAV) specification and Required Navigation Performance specification (RNP). RNAV and RNP specifications are similar but, the only difference, RNP includes the performance monitoring and alerting system on board for the aircrew (Fig. 2).

Finally, it could be noted that PBN consists of Area Navigation (RNAV) and Required Navigation
Performance (RNP). PBN aims to enhance the flight operations providing high level of safety and efficiency.

RNAV is a point to point navigation which reduces the need of ground based navigation aids and allows aircraft to implement operations with modern avionics. So RNAV procedures allow more direct routes (Fig. 3).

Besides, another PBN procedure is RNP which is defined as a navigation performance accuracy (RNP type) to be required within a defined airspace [1]. In the other ICAO document called Report of the Special Communications/Operations Divisional Meeting-9650, RNP is defined as required navigation performance accuracy, integrity, availability and continuity within a defined area in the 95 percent of total time for flight duration [2].

In PBN, approach phases are categorized as RNP approach and Required Navigation Performance Authorization Required (RNP AR) approach. RNP AR procedures achieve higher performance accuracy level by providing extra accuracy and integrity. RNP AR improves the access the airports surrounded by higher mountainous terrain and affected by bad weather and allows safer and efficient flight operations [3], [4]. RNP AR allows more repeatable and predictable routes so that obstacle assessment areas of RNP AR procedures are smaller than RNP APCH procedures (Fig. 4).

II. RNP AR APCH PROCEDURES

Required Navigation Performance Authorization Required procedures are referred as RNP AR APCH by ICAO; however, FAA is used a term as Special Aircraft and Aircrew Authorization Required (SAARAR) instead of RNP AR [1], [5]. The title of published approach procedure chart is defined as RNAV (RNP) and the minima values are presented as RNP x [6]. Currently, majority of airports which apply to RNP AR procedures are in the USA.

RNP AR APCH, designed with straight and/or fixed radius segments, supports RNAV operations with final approach segment of RNP 0.3 or lower [7]. RNP AR procedures provide extra navigation accuracy, integrity, and allow higher level of navigation performance. These procedures enables curved routes, referred to as radius to fix (RF), in any segment of flight operations including final and missed approach. Thus, flight operations could be implemented in safe, even at airports located in high mountainous terrain [3]. The target level of safety (TLS) for RNP AR operations, is a probability of risk collision of less than 10⁻⁷ per flight. Advantages of RNP AR procedures could be summarized below. RNP AR procedures:

- Provide additional accuracy, integrity,
- Enable optimum flight paths,
- Improve more reliable, repeatable flight routes,
- Improve safety level of operations,
- Allow aircraft to fly on terrain challenged airports,
- Enable to fly in bad weather conditions,
- Reduce the environmental impacts (noise, emissions etc.) [8].

A. Path Terminator and Transitions

Path terminators could be defined as a set of two alphabetic characters. The first introduces the flight path type and the second one presents how the route leg terminates. For instance, Track to a Fix (TF) refers a route from one waypoint to another waypoint and Radius to a fix (RF) refers a constant radius turn between waypoints.

For Precision RNAV (P-RNAV) operations aircraft will be capable of flying initial fix (IF) track to a fix (TF), from a fix to an altitude (FA), course to a fix (CF) and direct to a fix (DF). However, for RNP-RNAV operations, aircraft will be capable of flying RF legs besides others.

In case of track angle change of 5 degrees or more, transitions could be made in four ways such as fly by transitions, fly over transitions, constant radius arc to fix and conditional transitions [9].

While designing RNP segments the appropriate types of legs called Track to Fix (TF) or Radius to turn fix (RF) are used. TF legs are standard normal legs for RNP AR and first considered. TF legs are normally connected by fly by waypoints. Maximum turn angle is 70 degrees at above FL190 and 90 degrees at and below FL190 [10].

RF legs could be used where obstacles prevent to apply fly-by turns. RF legs allow aircraft to turn with fixed-radius track. In case of preventing straight in approach due to obstacles or operational requirements in the final segment, RF turn could be designed. Fly by turns are not allowed. RF legs enables curved approaches in order to facilitate the challenging operations in mountainous terrain. Recent years, in Europe, RNP AR is preferred also due to noise reduction [3], [4], [10].

B. RNP AR Instrument Procedure Design

RNP AR procedure requires a lateral TSE as low as ±0.1nm. The protection area of the flight path has a semi diameter of 2*RNP. For RNP AR procedures, there are no secondary areas or buffer areas. Final approach segment (FAS) lateral guidance is based on RNP. Vertical guidance is based on Baro-VNAV avionics.

Figure 3. RNAV procedure design [1]

Figure 4. Examples of RNP APCH (left) and RNP AR APCH (right) procedure design [1]
In the FAS, maximum lateral accuracy, optimum and minimum accuracy values are 0.5nm, 0.3nm and 0.1nm, respectively. RNP values are shown in Table I.

<table>
<thead>
<tr>
<th>Segment</th>
<th>RNP AR Maximum</th>
<th>RNP AR Standard</th>
<th>RNP AR Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrival</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Initial</td>
<td>1</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Intermediate</td>
<td>1</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Final</td>
<td>0.5</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Missed approach</td>
<td>1.0</td>
<td>1.0</td>
<td>0.1*</td>
</tr>
</tbody>
</table>

The sequence of TF-RF legs or RF-RF legs are used for constructing the flight path (Fig. 5) [11].

In case of preventing straight-in approach due to obstacles or operational requirements, RF legs are used for designing the final approach phase. Fly by turns are not authorized [10].

C. Calculating Turn Radius for Fly by Turns

Speed is an important factor for aircraft performance. At RNP AR procedures, Eq. (1) is used for calculating turn radius for fly by and RF turns. Tailwind component is chosen from the Table II. At fly by fixes, turn radius (r) is calculated based on a standard bank angle (α) 18°. Eq. (2) is used for converting Indicated Air Speed (IAS) to True Airspeed (TAS).

\[
V = TAS + \text{an assumed tailwind} \quad (1)
\]

\[
TAS = IAS \times 171233 \left\{ \frac{0.00198 \times H}{(288-0.00198 \times H)^{0.5}} \right\}^{2.628} \quad (2)
\]

where IAS = indicated airspeed (kt or km/h, as appropriate); TAS = true airspeed (kt or km/h, as appropriate); VAR = variation from international standard atmosphere (ISA) (standard value +15) or local data for 95 per cent high temperature, if available H = altitude (ft or m, as appropriate).

While determining the radius of turn (r) Eq. (3) is used, but, first, rate of turn (R) could be calculated using by Eq. 4.

\[
r = \frac{V}{20 \times \pi \times R} \quad (3)
\]

\[
R = \frac{3431 \tan \alpha}{\pi \times (TAS + W)} \geq \frac{3}{3^\circ/\text{sec}} \quad (4)
\]

where V = (TAS + wind speed); R = Rate of turn in degrees/seconds; \(\alpha\) = bank angle; up to a maximum value of three degrees/second.

D. Calculating Bank Angle RF Turns

If RF turns are applied, for a given TAS, the \(\alpha\) is calculated by using Eq. (5) below.

\[
\alpha = \arctan \left( \frac{(TAS + W)^2}{68625 \times r} \right) \text{ given } R \leq \frac{3431 \times \tan \alpha}{\pi \times (TAS + W)} \leq 3^\circ/\text{sec} \quad (5)
\]

where W = tailwind speed; r = turn radius

As it is mentioned before, 18° is the standard \(\alpha\) value. However, for smooth transitions, lower or higher values could be used. Nonstandard \(\alpha\), for at or below FL190, are shown in Table III. For turns above FL 190, 5° bank angle could be used [10].

TABLE II. TWc AND ALTITUDE [10]

<table>
<thead>
<tr>
<th>TWC (kt) for turn calculations</th>
<th>Turn height above aerodrome (ft)</th>
<th>Standard tailwind component (kt)</th>
<th>tailwind component (kt)</th>
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<tr>
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</table>

III. RESULTS AND DISCUSSION

For this study, while determining turn radius for fly by turns, and the bank angle for RF turns the limitations below are considered. These are: Categori D aircraft, final segment (IAS=185kts); standard \(\alpha\), 18°; for RF turns, constant turn radius is assumed as 7 nms.

For fly by turns, r is calculated by using Eq. (3), (4), and it is found that the r at standard (18°) increases with the higher flight levels. The results showed that r alters between 2nm – 7 nm until FL 190 (Fig. 6).
IV. CONCLUSIONS

In this study, fly by turns and RF turns for RNP AR procedures are examined. For fly by turns, turn radius is analyzed for category D aircraft on final segment, at standard $\alpha = 18^\circ$, and at different altitudes. Aircraft speed is faster at higher levels, and as it is known, speed is a significant parameter for turn radius. Under the defined limitations, it is appeared that turn radius changes between 2 nm and 7 nm, and turn radius increases at higher altitudes. For RF turns, aircraft keeps a constant turn radius as considered 7 nm in this study, it is found that bank angle increases with higher altitudes. The results show that bank angle alters between $6^\circ$-$18^\circ$ at 1000ft and 19000ft. It is noted that aircraft needs higher bank angle in order to keep constant turn radius.

REFERENCES


Ozlem Sahin Meric was born in Eskisehir, Turkey in 1980. She received her B.S. degree in The School of Civil Aviation, Department of Air Traffic Control from Anadolu University in 2003. She began as a research assistant at The School of Civil Aviation, Anadolu University in 2003. She received her M.S. degree and Ph.D. degree from Graduate School of Science at Anadolu University in 2006 and 2011, respectively. She has been working at Anadolu University, Faculty of Aeronautics and Astronautics, Department of Air Traffic Control as an Assistant Prof. Dr. Her research interest includes flight procedures, navigation and aircraft operations.