Actual Navigation Performance of Helicopters in the Final Approach Phase of RNAV (GPS) Approaches

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This paper presents a method to determine ANP of helicopters during the final approach phase of a RNAV (GPS stand-alone) approach procedure. In the context of a data sampling campaign at a Eurocopter's helicopter airport at Donauwörth,Germany, we analyzed flight tracks recorded during RNAV approaches. For this data sampling campaign a BO 105 was equipped with an independent high precision differential GPS (DGPS) recording each flight track in terms of latitude, longitude and altitude in a frequency of 10 Hz. Altogether more than 100 approaches were performed during the data sampling campaign, also taken different weather conditions as well as different times of the day (night approaches) into consideration. Based on these data deviations from the intended flight path in vertical and lateral direction were determined in discrete steps (cross sections) from the FATO (Final Approach and Takeoff Area). This finally shows the evolution of ANP along the flight path and as a result revealing much higher approach precision as required, even comparable with the ANP of ILS approaches. Furthermore, using statistical methods, probability density functions (PDF) for each cross section were derived, which allows to calculate collision probabilities with ground based obstacles based on specific ANP for this procedure similar to ICAOs Collision Risk Model (CRM) for ILS approaches.

Keywords: Safety Assessment; Actual navigation performance (ANP); helicopter operations; RNP-RNAV procedures; statistical data analysis

I. Introduction

The final approach phase during an instrument approach is one of the most critical flight phases [2] during aircraft and helicopter operations, due to ground proximity in a potentially obstacle rich environment. So the flight phase landing is a preferred field to improve safety in the European air traffic system [1]. Improvements may be reached by introducing new approach procedures such as RNP/RNAV approaches, requiring a navigational accuracy during final approach (non-precision) of at least 0.3 NM in 95% of the flight time [3], [6].

But the advantages of RNP/RNAV approaches are not fully reflected in less stringent obstacle limitation surfaces compared to conventional non-precision approaches (NPA) yet. Consequently, the obstacle limitation surfaces of RNAV non precision approaches are comparable in size to conventional NPA approach surfaces (e.g. VOR-DME), leading to comparable OCA/H values (of course both depending on the obstacle situation).

Although RNAV approaches are nowadays implemented at numerous airports and very frequently used, the actual navigational performance (ANP) compared to the requirements (RNP 0.3) of these procedures are not very well researched yet, especially for helicopters.

Furthermore RNAV approaches allow more flexible definition of the approach path compared to conventional approaches, due to independency from ground based navigation facilities. This flexibility allows very specific route design, even in the intermediate approach phase, to avoid noise sensitive areas around airports. As an example, at Frankfurt/Main Airport a so called segmented RNAV approach was implemented in February 2011. This basically means that the initial approach segment is divided into short lags with many heading changes and designed in a way to avoid noise sensitive areas below the extended centerline. But finally, this is resulting in a very short final approach segment of only 5 NM, which is the shortest possible length of final approach segment for such a procedure according to ICAO Annex 14 [8] and ICAO Doc. 8168 PANS OPS [3].

In [5] we could show that the Actual Navigation Performance of aircrafts flying this specific procedure is way higher than Required Navigation Performance. In detail, during the entire approach ANP values of 0.12 NM were never exceeded, even for the initial approach phase with RNP 1.0 NM.

The method of calculating ANP as shown in [5] is based on statistical evaluation of approach path deviations using empirical flight track data (radar data). This method now shall be applied for another RNAV procedure, implemented at Eurocopter's helicopter airport Donauwörth, Germany, taking helicopter operations into consideration.

II. Navigational errors

The following section will state a systematic overview of navigational errors during RNP- RNAV procedures.

A. *Navigational error of RNP-RNAV procedures*

The inability to achieve the required navigation performance during RNAV procedures may be due to navigation errors related to aircraft tracking and positioning in the context of on-board performance monitoring and alerting as it is mandatory for RNAV procedures. According to ICAO Manual on Performance Based Navigation (PBN) [6] the navigational errors for RNAV contain the following three main error categories:

- Path definition error (PDE)
- Flight technical error (FTE) and
- Navigation system error (NSE)

The PDE occurs when the path defined in the RNAV system database does not correspond with the desired path. Flight Technical Errors are errors induced by the pilot/autopilot including display errors. The NSE refers to the difference between the aircraft's estimated position and actual position. So this is the error of the multi-sensor navigation system, as e.g. the error of the GPS. The TSE is the root sum square of these three error categories, here PDE, FTE and NSE.

Due to the nature and characteristics of the ANP analysis applied here, by using radar data only, the TSE is the only one that can be measured and stands as a result of all three error categories.

B. *Accuracy requirements for RNAV approach procedures*

The ICAO PBN Manual [6] defines two types of RNAV approach procedures which are applicable to the final approach segment. First, the "non precision alike" RNP APCH which is defined as a RNP approach procedure that requires a lateral TSE (Along Track and Cross Track) of ±1 NM in the initial, intermediate and missed approach segments and a lateral TSE of ±0.3 NM in the final approach segment. Second, the RNP AR APCH (authorization required), which is defined as RNP approach procedure requiring a lateral TSE of at least ±0.3 NM and down to ±0.1 NM for all approach segments.

As the researched RNAV (GPS) approach belongs to the first category - the RNP values are 0.3 NM during final approach and 1.0 NM during initial and intermediate approach. Furthermore the procedure is designed as a non precision approach meaning, there is no vertical guidance during the final approach phase.

C. *Errors of independent DGPS system*

Before applying the method to analyse the helicopter's ANP one more additional error needs to be considered.

Although the TSE of the researched procedure (regardless of which) can be measured with the here applied data analysis of independent DGPS position estimations, it should be noticed, that this measurement may be non-precise due to the erroneous DGPS system data itself.

The DGPS system is independent from the on-board FMS and is using augmented GPS Data. The augmentation is achieved by a ground reference station installed at Donauwörth helicopter airport. According to the manufacturer of the DGPS system the accuracy is extremely high, within an error range less than +/- 1 m for both lateral and vertical direction.

III. DATA SOURCE

A. *Description of the approach procedure*

The analysed DGPS data are covering final approaches during RNAV (GPS) approaches at Eurocopter's helicopter airport at Donauwörth, Germany. The implemented RNAV procedure is according to ICAO PANS OPS [3] designed as a non precision approach with only lateral guidance (LNAV), which means there is no vertical guidance (VNAV) given, like for APV BARO or APV I/II procedures.

As described above, two types of RNP values are defined for the RNAV NPA. At the initial and intermediate segment the navigational accuracy must be at least of +/- 1 NM (RNP 1) for 95% of the flight time. At the final approach segment, which is 3.3 NM (appr. 6,100 m) long, the navigational performance must be at least +/- 0.3 nm (RNP 0.3). Furthermore the obstacle clearance altitude/height (OCA/H) is set due to obstacle situation at 1860 ft /540 ft (GND).

The following figure shows the lateral flight path of the RNAV (GPS) procedure as an extract according to the relevant AIP of Donauwörth Helicopter airport:

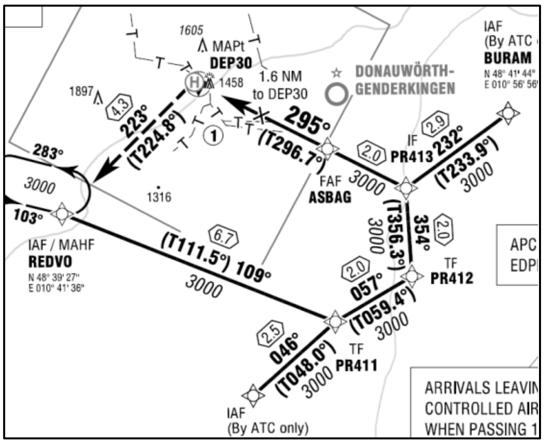

Figure 1. Horizontal definition of the RNAV (GPS) procedure at Donauwörth as of AIP

In the vertical plane a steep descent profile with a decent angle of 4.58° (8%), as typical for helicopter operations and in line with the requirements of ICAO Annex 14 Vol. 2 [9], beginning at the FAF is defined. Following the nominal descent path, the OCA/H will be reached at an FATO (Final Approach and Take off Area) distance of 1936 m, from where a horizontal segment will be flown until PAPI interception (1555 m FATO distance), with an descent angle of 6° (10.51%) during this visual segment of the approach. Following Figure shows the vertical descent profile as an abstract of the AIP approach chart for this procedure:

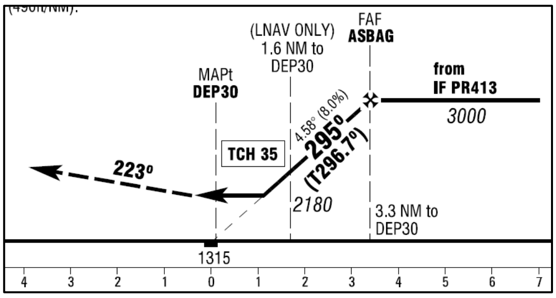

Figure 2. Vertical definition of the RNAV (GPS) procedure at Donauwörth as of AIP

All following analysis will only focus on the final approach segment from FAF ASBAG to DEP30.

B. DGPS data

For data acquisition a BO 105 helicopter a typical operating model at Donauwörth was chosen. The helicopter was equipped with a high-precision DGPS. With the DGPS receiver it is possible to track the flights with high accuracy. The DGPS records a large number of parameters at a rate of 10 Hz. The following parameters are relevant for the analysis:

- Time stamp
- Lateral WGS 84 coordinates (Lat/Long)
- Vertical coordinate (m ASL)
- Standard deviation (vertical/horizontal)
- Dilution of precision

By means of standard deviation and dilution of precision it is possible to make a statement about the current DGPS accuracy.

C. Description of the data sampling campaign

The data sampling campaign was performed at four different days with the DGPS equipped BO 105, as seen in the following figure:

Figure 3. BO 105 with equipped independend D-GPS antenna

To avoid effects such as a learning curve, the following conditions were applied to the test flights:

- The flights performed by different crews, under different conditions (wind, precipitation, etc.) by night and day.
- Under the same conditions one crew flew about 20 consecutive approaches.

To reduce the required time, the following simplifications are allowed:

- There is no touchdown on the FATO required - a go-around can be initiated shortly before touchdown.
- After the departure/ go-around it is not necessary to fly the entire approach via the IAF - a direct to the FAF is permitted.

Furthermore, protocols were prepared by the flight crew for each flight. In this protocols flight abnormalities are registered, e.g. evasion manoeuvres due to other traffic. Altogether 124 approaches were performed, due to DGPS inaccuracy and unscheduled approaches 99 flights were used for the following analysis.

IV. Methodologic Overview

In order to quantify the Actual Navigation Performance of helicopters flying the RNAV (GPS) approach, various steps using standardized statistical techniques needs to be performed.

Following major steps during the statistical analysis of flight track deviations were performed (a more detailed description of these steps can be found in [4] and [5]):

1. Define cross section windows in discrete steps along the final approach path,
2. Determine each helicopter position relative to its nominal flight path at each cross section window (so to speak the navigational error in lateral and vertical direction),
3. Calculate statistical distribution parameters (e.g. mean value and standard deviation) at each cross section window for the vertical and lateral direction,
4. Analysis of generalized distribution patterns for the cross section window, in order to define a describing distribution function (e.g. Gaussian distribution function),
5. Statistical test for the fitting of the distribution function (e.g. Chi-Square Test) for each cross section window,
6. Analysis of the parameter evolution along the final approach path.

The statistical test used here in step 5, is the well-known Chi-Squared Test (also Pearson's chi-squared test or χ^2 Test), which allows to quantify the fitting of a modeled PDF. The Chi-Squared test calculates a so called *test-statistic* which describes the differences between the observed frequencies based on real data and the expected frequency based on a modeled PDF. The *test-statistic* is calculated as follows:

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{(O_i - E_i)^2}{E_i} \right) \tag{1}$$

Where:

χ^2 = Chi Square test-statistic

n = the number of classes (specific data range)

O_i = observed frequency in class i

E_i = expected frequency in class i

After determination of *the test-statistic*, the critical value of the chi-squared distribution with d degrees of freedom needs to be determined and compared to test-statistic. The number of degrees of freedom is calculated as follows:

$$d = n - p - 1 \tag{2}$$

Where:

d = degrees of freedom

n = number of cells

p = number of estimated parameters (e.g. 2 for a normal distribution)

If the critical value of the chi-squared distribution is smaller than the test-statistic the hypotheses cannot be rejected, which basically means that the modeled PDF is valid.

V. STATISTICAL ANALYSIS OF APPROACH PATH DEVIATIONS DURING RNAV APPROACH

A. Overview of sampled data tracks

As mentioned before the flight tests were made sequentially on four different days. In the following figure 4, the 99 recorded flights are shown as an overlay to the AIP in the lateral plane.

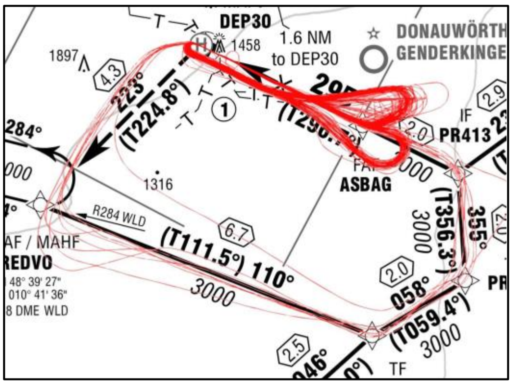

Figure 4. Lateral Flight Tracks of the flight tests as an overlay of the AIP

As seen in figure 4, most of the flights, were flown as go-arounds to minimize the flight time for the data sampling campaign, as only the visual segment of the final approach was focussed during the data campaign. Due to the shortened approaches there are a few late intercepts at the FAF. So the relevant section of the final approach, where all flights are established on the final approach path, is 4,500 m before the threshold. Therefore all following analysis will focus on an area between the touchdown on the FATO and a maximum distance of 4500 m before the FATO. For this section the vertical plane is shown in the following figure 5:

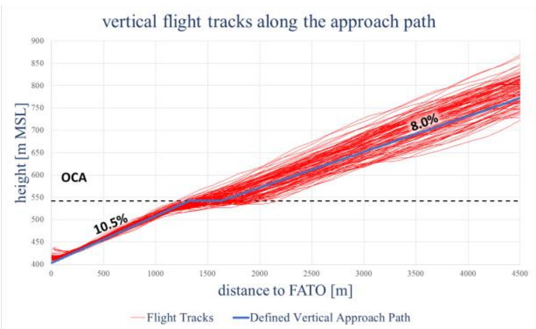

Figure 5. Vertical Flight Tracks along the designated approach path

According to the presented method of ANP determination in Chapter IV, first of all the cross section windows perpendicular to the flight path in steps of 100 m were defined and deviations from the nominal flight path for each approach and each cross section window were determined.

The following figure 6 exemplarily represents the flight intersection points for 3,000 m cross section window:

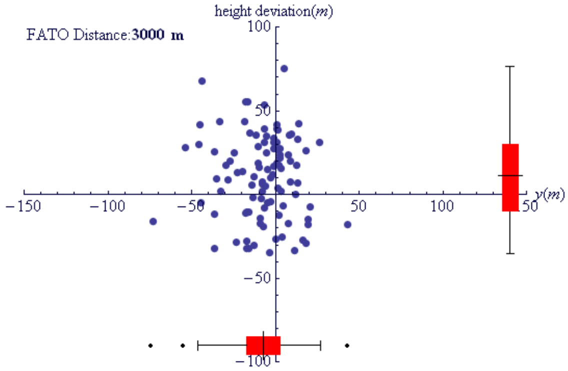

Figure 6. Measured deviations from the nominal approach pathat 3,000 m FATO distance

As seen in figure 3 most flight tracks are within a 50 m by 50 m square around the nominal flight path, showing a very low distribution in both lateral and vertical direction. In detail, looking at the Box-Whisker-Plots, the 50%-quantile (red box) is around 10 m for the lateral direction and around 30 m for the vertical direction.

The statistical analysis of approach path deviations during the final approach phase was performed for the lateral and vertical direction independently. The next section presents the results of the statistical analysis for the lateral direction.

B. Lateral deviation analysis

1) Test for distribution

First of all we analysed the distribution characteristics for each cross section window along the approach path, as described in Chapter IV. As mentioned there, now for each of the cross section windows the lateral and vertical distributions needs to be analyzed in order to determine the underlying distribution characteristics. Therefore the measured lateral and vertical distribution at each cross section window needs to be described by a probability density function (PDF). From experience (see also [4] and [5]) the Normal or Gaussian distribution function is the most suitable one. It is characterized by the mean (μ) value and the standard deviation (σ) value of the underlying distribution and is defined as follows:

$$p(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \tag{3}$$

So for each cross section window the parameters μ and σ of the normal distribution function were calculated based on the data and the statistical test was executed. Following Figure 7 shows the results of the Chi-squared test for each of the 45 cross section windows. The blue bars indicates the test-statistic for each cross section window calculated based on formula (1) and the horizontal red line indicates the critical value of the chi-squared distribution.

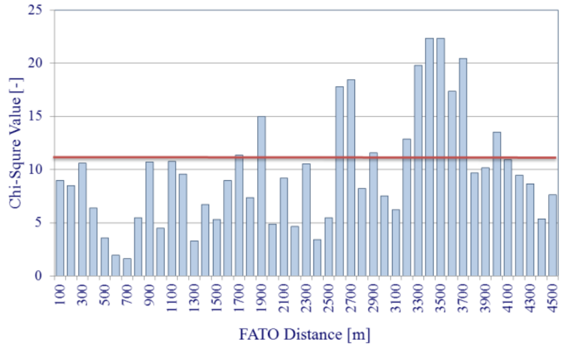

Figure 7. Results of the chi-squared tests for the normal distribution

As seen in figure 7 for most of the cross section windows the chi-squared test is passed positively (test-statistic < critical value). All together for only 12 out of 45 cross section windows the chi-squared test didn't pass. As a result it can be assumed, that the navigational accuracy of helicopters (in the lateral direction) is normal distributed.

Consequently, following figure 8 shows the actual distribution (blue bars) and the modelled PDF (red line) exemplarily for the 1000 m, 2000 m, 3000 m and 4000 m cross section window:

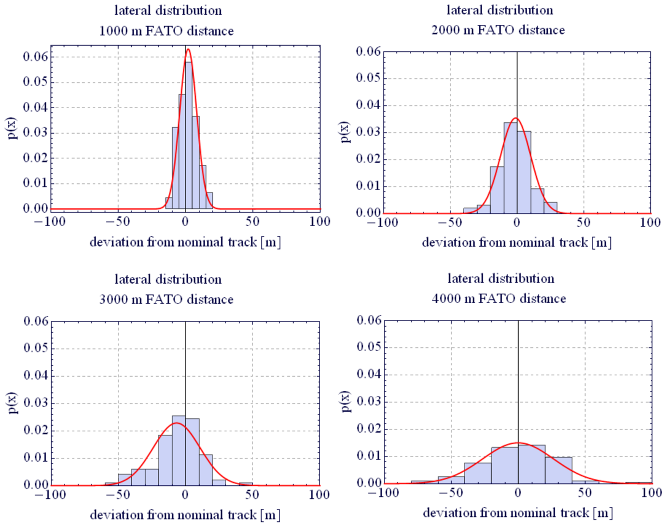

Figure 8. Exemplary lateral distributions in discrete steps along the approach path for 1000 m, 2000 m, 3000 m and 4000 m FATO distance

As seen and proven by the chi-squared test the actual distribution follows a normal distribution very well. But what is also seen very clearly – the standard deviation decreases with decreasing FATO distance. Therefore the following section will take a closer look into the evolution of the distribution along the approach path.

2) Evolution of distribution characteristics along the approach path

Following figure shows the measured standard deviation for each cross section window for the lateral direction:

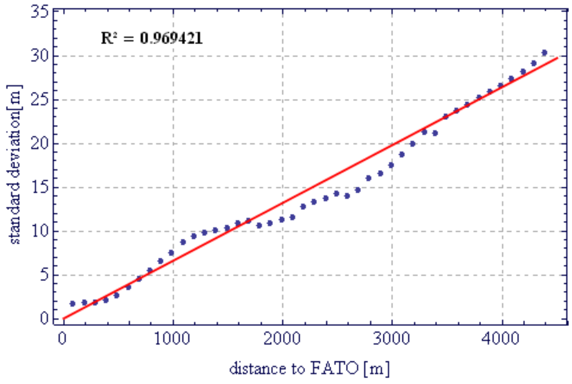

Figure 9. Evolution of standard deviation along the approch path for the lateral direction

First of all figure 9 shows the very high lateral navigation performance (low sigma values) for the entire approach path, leading to a maximum standard deviation of less than 32 m for 4500 m FATO distance. Converted to ANP values (95% or two sigma interval) this is less than 0.05 NM for this GPS-approach, which has a RNP of 0.3 NM.

Hence this very high lateral navigation accuracy may be enhanced by the metrological conditions, as during most of the flights good weather conditions in terms of visibility were present. Therefore flight crews may be used the visual reference to improve the quality of their approaches. As mentioned before, surprisingly we also see a clear distance dependency of the lateral distribution, although the flown approaches are GPS-only approaches, which should not show such behaviour.

For a modelled distribution ANP we decided to adopt these function, by adding 2 m to each measured standard deviation. This way all measured ANP values are below this modelled linear function, leading to a conservative assumption of lateral distribution.

According to this, for lateral deviation applies the following distance dependency for the standard deviation linear fitted:

$$\sigma_{lat}(x) = 0.0066x + 2.02 \qquad (2)$$

with x = FATO distance in [m] and $\sigma_{lat}(x)$ = lateral standard deviation in [m]. Thus the standard deviation amounts to 2 m on FATO and is increasing about 6.6 m per each 1000 m distance to the FATO. Consequently, the following table shows exemplary values for the approach path deviation in the lateral direction, for both the standard deviation in meter, as well as the corresponding ANP values according to RNAV convention (95% or two sigma containment in NM):

FATO distance [m]	Standard deviation [m]	XTT [NM]
0	2.02	0.002
500	5.32	0.006
1000	8.62	0.009
1500	11.92	0.013
2000	15.22	0.016
2500	18.52	0.02
3000	21.82	0.024
3500	25.12	0.027

FATO distance [m]	Standard deviation [m]	XTT [NM]
4000	28.42	0.031
4500	31.73	0.034

Table 1: Exemplary standard deviation and ANP values for the lateral direction

Finally, the probability of deviations outside the 95% containment area (0.3 NM) based on these ANP values can be calculated, showing a probability of less than $1*10^{-18}$ even for the farthest FATO distance analysed here (4.500 m).

3) Vertical deviation analysis

For the vertical direction the same methodology applies. First of all the underlying distribution was analysed, assuming a normal distribution. Again mean value and standard deviation for each of the 45 cross section windows were calculated and a corresponding normal distribution was tested using the chi-squared test. The chi-squared test again shows a very good fit for the normal distribution, where for only 14 out of 45 cross section windows the chi-squared test didn't pass.

Following figure shows again the measured standard deviation for each cross section window, now for the vertical direction:

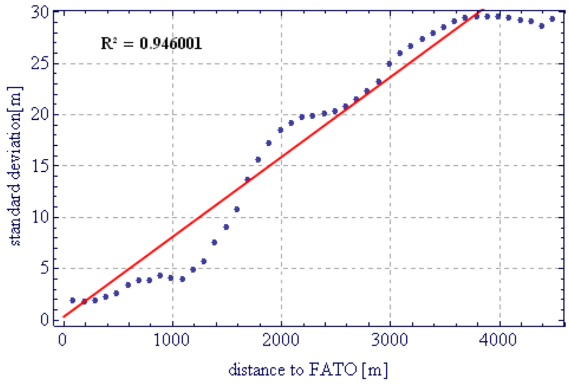

Figure 10. Evolution of standard deviation along the approch path for the vertical direction

Again, a very high navigational accuracy, as well as a clear distance dependency can be seen, with standard deviations below 30 m or ANP less than 0.04 NM for the entire approach. Also a significant drop of vertical distribution during the horizontal segment of the approach (roundabout 1.700 to 1.200 m FATO distance) is noticeable, leading to even lower values during the visual segment of the approach.

Consequently, it can be concluded that the PAPI is a huge advantage for navigation during the visual segment improving the navigational accuracy and leading to deviations from the approach path to less than 5 m at the beginning of the visual segment and around 2 m at the very end.

Again, presuming a conservative assumption, by adding 4.5 m to the measured standard deviation, leading to the following linear function describing the sigma values of a normal distribution in dependency of the FATO distance:

$$\sigma_{vert}(x) = 0.0078x + 3.91$$

Thus the standard deviation amounts to 4 m on FATO and is increasing about 7.8 m per each 1000 m distance to the FATO, as exemplary shown in the following table:

FATO distance [m]	standard deviation [m]	VTT [NM]
0	3.91	0.004
500	7.8	0.008
1000	11.7	0.013
1500	15.6	0.017
2000	19.49	0.021
2500	23.39	0.025
3000	27.29	0.029
3500	31.18	0.034
4000	35.08	0.038
4500	38.97	0.042

Table 2: Exemplary standard deviation and ANP values for the vertical direction

VI. Comparison to Navigational Accuracy of Fixed-Wing Aircrafts

Concluding it was shown, that the lateral and vertical deviation decrease with smaller distances to the FATO. It also could be shown, that the lateral ANP is less than the vertical ANP and that in all cases ANP is much higher than RNP. The following figure 11 shows the comparison to former analysis of ILS [4] and segmented RNAV approaches [5] for the lateral plane.

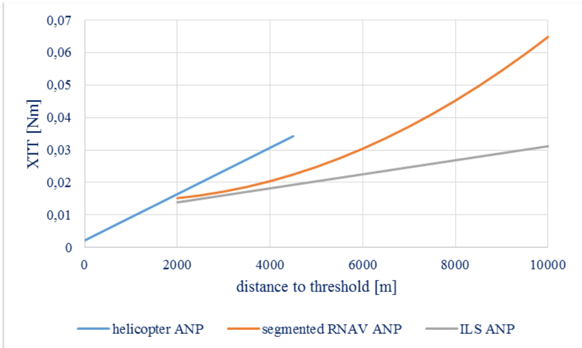

Figure 11. Comparison of lateral helicopter ANP along the approach path to the ANP ILS [4] and segmented RNAV [5] approaches

All three procedures have a lateral guidance, but only the ILS approach is a precision approach. However the non-precision approaches are slightly less accurate, but significantly within the limits of the RNP 0.3 of the ICAO PBN concept.

For the vertical plane the comparison of the three procedures is shown in the following figure 12.

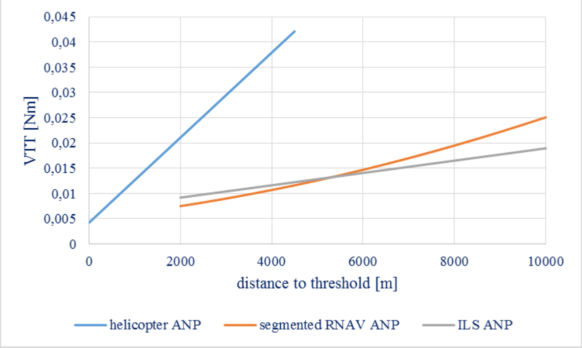

Figure 12. Comparison of vertical helicopter ANP along the approach path to the ANP of ILS [4] and segmented RNAV [5] approaches

As seen the determined ANP for helicopter operations is in comparison to ILS and segmented RNAV approaches imprecisely. Mentioned that there is no vertical guidance for helicopters at Donauwörth and only for about the last 1300 m the guidance through PAPI is usable. On the other hand is the in [4] analyzed ILS approach a precision approach with vertical guidance. And for the analyzed segmented RNAV approaches in [5] the ILS signal was possibly usable on the final approach segment. Compared to that, the non-precision approaches were still performed with high accuracy in Donauwörth.

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