Concept for Evaluation of the RNAV 5-Capability of Terrestrial Navigation Aids in Germany

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ABSTRACT

The following paper presents a new method for acquiring and evaluating data in the context of Performance Based Navigation (PBN). It describes the creation of a route network over Germany using the EUROCONTROL tool DEMETER, the operational measurements of these routes as a replacement for ferry flights, and the evaluation of the data obtained from the terrestrial navigation systems VHF Omnidirectional Range (VOR) and Distance Measuring Equipment (DME).

The evaluation is based on the sliding window technique and the position error, calculated from the received VOR and DME signals, and shows that RNAV 5-capability is largely available across Germany through VOR/DME navigation, while a few areas of Germany have repeatedly little to no coverage. The data is based on measurements of the route network over a period of two years. A detailed evaluation shows that the greatest influence on RNAV 5-capability is the power density of the VOR, while the influence of the power density of the DME and the position error, calculated from the VOR and DME signals, is low. Furthermore, the extent to which the measurements of the route network can be used as a substitute for VOR orbit flights is investigated.

INTRODUCTION

The increased occurrence of GPS jamming and spoofing is a well-known phenomenon and has been observed regularly, with a growing impact on the Federal Republic of Germany. This has led to the general intention to establish robust backup systems. Owing to the high number of VORDME navaids already in place in Germany, their utilisation within the context of Performance Based Navigation (PBN) and RNAV 5 presents itself as a viable option. According to the PBN Manual ICAO Doc 9613 [1], VORDMEs constitute a suitable navigation solution for area navigation under RNAV 5, and the required levels of accuracy should generally be achievable.

The internal concept referred to as Performance Based Operation (PBO) emerged from the desire to represent this RNAV-capability within Germany. In addition to internal digitalisation projects, it encompasses in particular the PBO Enroute project, which aims to enable the classification of RNAV 5-capability. As a replacement for unused ferry flights, so-called PBO routes are introduced, defined between two RNAV waypoints and forming an overall route network across Germany. In doing so, these ferry flights are repurposed into productive calibration missions. Beyond determining the RNAV 5-capability, these PBO routes also provide the opportunity to establish the actual coverage ranges of the navaids and to determine their full azimuthal characteristics. As a result, additional orbit measurements, which are required annually in Germany, could potentially be reduced.

This paper presents the full scope of the PBO Enroute concept: from the pre-planning of the routes and therefore the network setup, to their operational implementation, and the evaluation of the measurements. The evaluation concept is comprised of several steps, ranging from the assessment of the individual components of the navaids to their combined performance and the resulting RNAV 5-capability. This evaluation is then demonstrated using a sample route. Thereafter, selected results for Germany are presented alongside further detailed assessments. Finally, the orbit-like inspection is introduced.

OPERATIONAL CONCEPT

The definition of the PBO routes and the overall route network is outlined first, followed by a description of the actual operational measurement procedures and day-to-day usage of the route network.

Network Planning and Setup

The planning of the PBO routes, which are intended to form a consistent route network, is based on two RNAV waypoints and a constant flight altitude. Furthermore, the terrestrial navigation facilities to be inspected are specified for each PBO route. In order to ensure operability under Instrument Flight Rules (IFR), the routes are defined above the Minimum Vectoring Altitude (MVA), which in Germany defines the minimum level for IFR flights. The selection of a constant altitude facilitates consistent execution and the utilisation of a uniform dataset in the subsequent simulation of the navaid coverage. For Germany, a suitable altitude of 7000ft Above Mean Sea Level (AMSL) is derived, which lies above the MVA in almost all regions and thus also above the major controlled airspace of the large commercial airports.

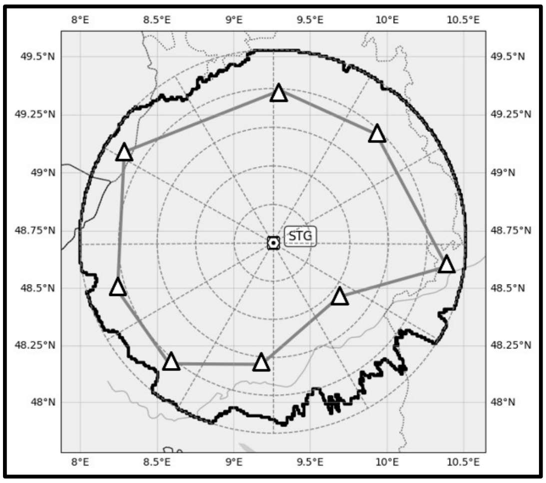


Figure 1. Definition of the PBO Routes for the full azimuthal Characteristics of DVORDME STG (Stuttgart). Concentrical circles are 10NM apart.

Using the EUROCONTROL DEMETER tool, the theoretical coverage area of all relevant en-route and terminal navigation facilities within the responsibility of the Air Navigation Services Provider was subsequently simulated for 7000ft AMSL, shown in Figure 1 in black. The PBO routes, shown in grey in Figure 1, are than defined as close as possible to the boundary of this coverage area while simultaneously covering every azimuth angle of the respective navaid. This ensures that the measurement results provide a realistic and robust assessment of the performance of the navaid.

Figure 2 illustrates the planned route network for the 2023 measurement cycle. Routes shown in black are available for measurement, while those shown in grey are currently excluded for operational reasons but may be reactivated at a later stage.

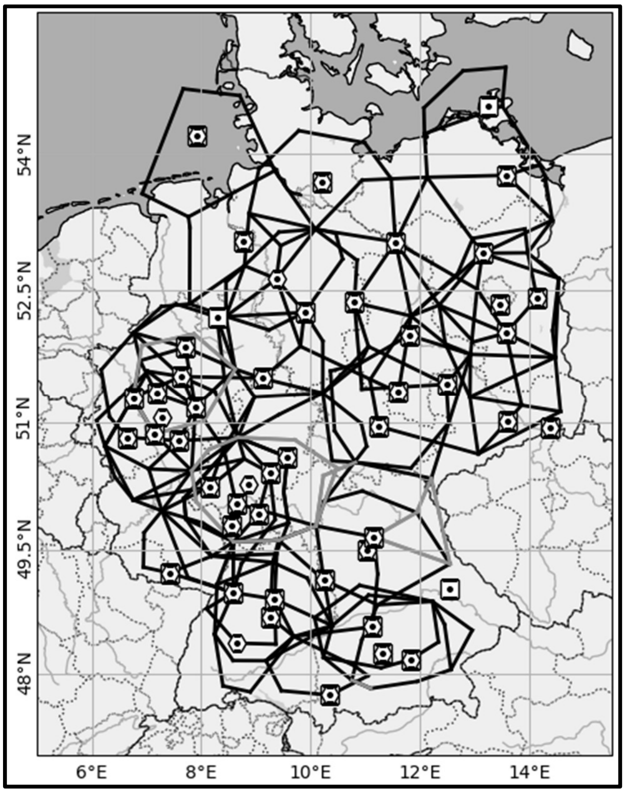


Figure 2. PBO Route Network in Germany for Evaluation of RNAV Capability. Also shows the relevant terrestrial Navaids at the time.

Flight Inspection

The calibration aircraft crew conducts the PBO route measurements according to daily operational planning. Instead of performing a ferry flight, a flight path consisting of several consecutive PBO routes is selected. Air traffic controllers receive the corresponding flight plan containing the public RNAV waypoints. The flight inspection engineer ensures that the navaid to be measured are operational and transmitting on the required transmitter. The composed PBO routes do not necessarily follow the shortest flight track to the desired destination.

The inspection flights are carried out at a constant groundspeed of 180 kts, with waypoint transitions depending on the interior angle between two consecutive PBO routes. If this angle is less than 90 degrees, the waypoint is flown as a fly-over, and the new segment is initiated via a procedure turn. For larger interior angles, the speed is reduced where possible to allow a fly-by transition. The raw data collected in flight are subsequently exported and serve as the basis for further calculations in the later evaluation phase of the measurement.

EVALUATION CONCEPT

It must first be determined which evaluation criteria, parameters, and tolerances should be used to assess the RNAV 5-capability. The fundamental reference for this is the PBN Manual ICAO Doc 9613 [1]. This document demonstrates that both the performance of the individual components of the terrestrial navaid and their combined performance is of importance. Ultimately, these two characteristics are consolidated into a so-called ErrorCode, which is subsequently assessed using the sliding window technique.

Performance of the Individual Components

For the individual components of the navigation facilities, the standard and well-established tolerances for VOR and DME, according to ICAO Annex 10 [2] and Doc 8071 [3], apply. In the case of the VOR, the following parameters must be evaluated: signal structure, modulation, and field strength. Modulation should be considered only as a secondary parameter, as the large distances and relatively low flight altitude result in a small elevation angle, making the modulation highly susceptible to environmental influences. The VOR signal structure is divided into a low-frequency and a high-frequency component, also known as Path Following Error (PFE) and Control Motion Noise (CMN). The corner frequency is determined in accordance with ICAO specifications in ICAO Doc 8071 [3], depending on flight speed. For the DME component, the distance error and field strength must be evaluated, also no unlocks should occur.

Combined Performance of VOR/DME Navigation

As specified in the PBN Manual ICAO Doc 9613 [1], the combined accuracy performance of VOR/DME navigation is to be assessed in accordance with the Total System Error (TSE), which is composed of the Flight Technical Error (FTE) and the Navigation System Error (NSE). Depending on the source (see for example [1] and [4]), the Display Error (DE) and the Path Definition Error (PDE) are either already taken into account here, or together with the Position Estimation Error (PEE), form the NSE. For this assessment, the PDE and DE may be regarded as negligible, such that PEE = NSE. In the following sections, therefore, only the PEE is considered.

Since the distributions of the PEE and FTE is assumed to be independent, zero-mean and Gaussian, the TSE derives from the root sum square of their standard deviations [1]:

$$\mathrm{TSE} = \sqrt{\mathrm{FTE}^2 + \mathrm{PEE}_{\mathrm{max}}{}^2}$$

The FTE, representing the deviation of the pilot or autopilot from the actual flight track, is defined as half of the required navigation accuracy. For area navigation under navigation specification RNAV 5, this accuracy is specified as 5 NM, resulting in the standard deviation for the FTE of 2.5 NM. Using the equation above, the standard deviation of the PEE can be calculated to:

$$\mathrm{PEE}_{\mathrm{max}} = \sqrt{\mathrm{TSE}^2 - \mathrm{FTE}^2} = 4{,}33\mathrm{NM}$$

This value is therefore also regarded as the maximum PEE in 95% of the time [4]. Furthermore, it consists of the contributions from both the airborne receiver and the received Signal-in-Space (SiS). Since only the SiS can be directly measured, corresponding limits must also be applied to the receiver contribution. Therefore:

$$\mathrm{PEE}_{\mathrm{SiS}} \leq \sqrt{\mathrm{PEE}_{\mathrm{max}}^2 - \mathrm{PEE}_{\mathrm{air}}^2}$$

Finally, it is necessary to determine how the PEE of VOR/DME navigation is composed from the individual error components of VOR and DME. According to [5], the position calculation for rho-theta navigation is used. After simplification and linearisation, the PEE is calculated as:

$$\mathrm{PEE} = \sqrt{\delta_{\mathrm{DME}}^2 + (R\alpha_{\mathrm{VOR}})^2}$$

With the DME distance error δ_{DME} in nautical miles, the VOR azimuth error α_{VOR} in degrees, and the distance to the navaid R in nautical miles. For the airborne receiver contribution to the PEE ($\mathrm{PEE}_{\mathrm{air}}$), the corresponding standard deviations from the receiver specifications may be applied. According to [1] and [2] these are $\sigma_{\mathrm{VOR,\,air}} = 1.5°$ and $\sigma_{\mathrm{DME,\,air}} = 0.085\mathrm{NM}$ or 0.125% of the distance to navaid, whichever is greater. This results in a distance-dependent tolerance for the PEE, which decreases with increasing distance from the navaid.

Finally, the influence of filtering on the VOR signal, or more specifically on the VOR azimuth error, must be considered: for the calculation of $\mathrm{PEE}_{\mathrm{SiS}}$, the low-frequency azimuth error, also known as PFE, of the VOR is used. This error is obtained by low-pass filtering of the VOR azimuth error at the speed-dependent corner frequency according to ICAO Doc 8071 [3].

ErrorCount and Sliding Window

Based on the parameters already described, a so-called ErrorCode is created, see Table 1, which has the following characteristics: the code consists of eight bits, each representing a specific state of the RNAV 5-capability at the corresponding measurement point. Bits 1–3 represent the VOR parameters: signal structure, modulation, and field strength. Bits 4–6 indicate the DME parameters:

distance error, unlocks, and field strength. Bit number 7 reflects the combined performance of the individual components of the navaid, i.e., the calculated PEE compared with the distance-dependent tolerance. Finally, bit 0 provides information about the general state of the measurement point and is referred to as the status bit.

Table 1. Definition of ErrorCode.

Bit	Name	Remarks
0	Status Bit	
1	VOR Signal Structure	PFE, CMN
2	VOR Modulation	30Hz-, 9960Hz-AM
3	VOR Field Strength	AGC corrected
4	DME Range Error	
5	DME Status	Unlocks
6	DME Field Strength	AGC corrected
7	RNAV PEE	Calculated PEE

The assessment of RNAV 5-capability is then carried out using the created ErrorCode and the sliding window technique. A sliding window of 40 seconds is applied to the sequence of ErrorCodes, and the evaluation is based on the 95% criterion as set out in the PBN Manual [1]. If more than 5% of the ErrorCodes within the 40-second sliding window have a status bit of zero, RNAV 5-capability is not met at that measurement point. The sliding window is applied retrospectively so that the previous 40 seconds are continuously evaluated.

EVALUATION OF RNAV 5-CAPABILITY IN GERMANY

To demonstrate the evaluation of RNAV 5-capability, the individual analytical steps are presented in sequence. First, the assessment of a single route is illustrated using an example. This is followed by an explanation of how the result of one route can be expanded to an area. Finally, all measured routes are combined to obtain a complete overview for Germany, accompanied by additional analysis of the measurement data.

RNAV 5-Capability of a single Route

In Figure 3 a PBO route located along the Baltic Sea coast, designated as Route 150, is displayed. The numbering of the PBO Routes is largely arbitrary. Along this route, the DVORDME FLD (Friedland) is inspected, see Figure 4.

Figure 4a presents the key VOR quantities: it is evident that the field strength initially lies below the conventional tolerance of $-107\,\frac{\mathrm{dBW}}{\mathrm{m}^2}$, while the modulation and structure remain largely within tolerance. A noticeable effect is the relatively constant deviation of the mean azimuth error by more than one degree. However, prior to a realignment of the navaid, it is essential that all routes are completed, given that this route represents only a segment of the navaid. In addition, ErrorCode bits 1–3 are shown. The data reveal that whenever the field strength approaches its tolerance limit, bit 3 frequently alternates between zero and one.

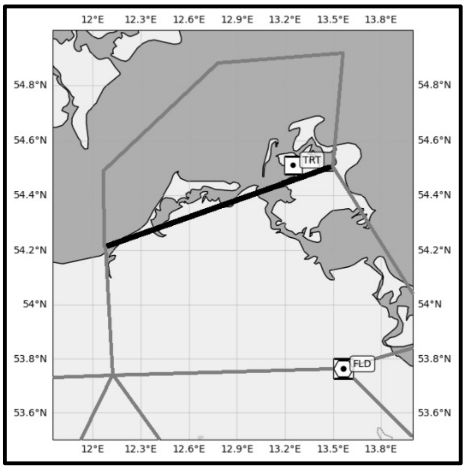
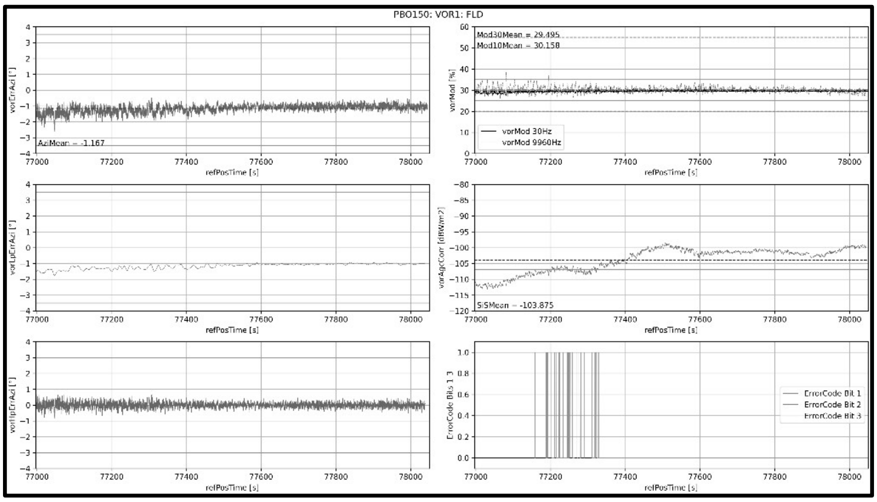


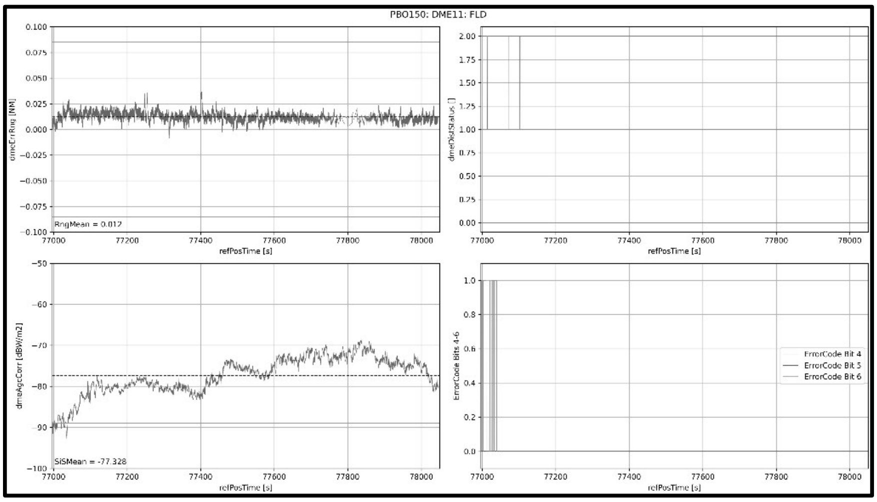
Figure 3. PBO route 150 above the Baltic Sea coastline in black. In grey other PBO routes. DME TRT and DVORDME FLD are also shown.

Figure 4b presents the parameters for the associated DME. Again, it is visible that the field strength at the beginning lies below the conventional tolerance threshold. The distance error remains entirely within tolerance, and no unlocks occur. As with the VOR, the relevant ErrorCode bits are shown, here bits 4–6, which correspond to the DME. A frequent alternation of one of the bits is also observable. Bit 6, representing the DME field strength, alternating repeatedly between zero and one in the initial part of the route.

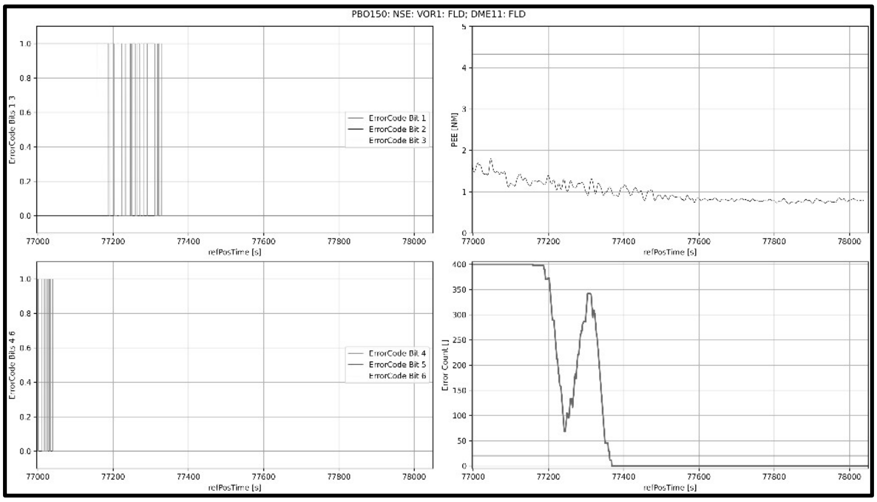
The final figure of this sequence, Figure 4c, illustrates the combined evaluation of both types of terrestrial navaids. For this purpose, the ErrorCode bits are presented once more, grouped according to navaid component. In addition, the final remaining parameter, the calculated PEE, is shown. Together, these elements form the ErrorCount, defined as the number of ErrorCodes with tolerance exceedances summed within each sliding window. At the beginning of the sequence, this counter is observed at a value of 400, indicating that every measurement point within the 40-second window exhibits at least one tolerance violation. The maximum value of 400 results from the 10 Hz recording frequency and the 40-second sliding window length. The tolerance limit of 20 corresponds to 5% of the 400 measurement points. Once the ErrorCount drops and remains below this limit, RNAV 5-capability is considered to be met.



a. VOR Component of DVORDME FLD.



b. DME Component of DVORDME FLD



c. Combined Performance of the DVORDME FLD

Figure 4. Evaluation of the Performance of the DVORDME FLD (Friedland) on the PBO Route 150. The Figure is split into three Subfigures a. VOR Component, b. DME Component and c. combined Performance for Evaluation of the RNAV 5-capability

RNAV 5 Extension to an Area

Based on the evaluation described above, a statement regarding RNAV 5-capability can only be made precisely at the measured position. This assessment is now extended to an area.

A positive statement regarding RNAV 5-capability may be propagated from the measured point towards the navaid at the same altitude. This is supported by the fact that, with increasing elevation angle, the environmental influence on the SiS decreases; moreover, the signal reception improves as the distance to the navaid decreases, resulting in a stronger field strength. In addition, as derived from the earlier equations, the calculated PEE decreases with decreasing distance to the navaid, while the corresponding tolerance increases. Consequently, no tolerance exceedance is expected within this region.

A negative conclusion regarding RNAV 5-capability cannot be drawn for the same reasons: in cases of a negative evaluation at the inspected position, individual parameters improve as the distance to the navaid decreases; however, this improvement cannot be inferred from the measured data.

Similarly, no positive or negative conclusion regarding the RNAV 5-capability can be made for distances beyond the measured PBO route. Since the assessment is valid only for a specific flight level, no conclusions can be drawn for other altitudes or elevation angles of the signal.

Germany-wide Overview

The Figure 5 presents the results for RNAV 5-Capability based on VOR/DME navigation within Germany. As described in the previous chapter, the shaded areas indicate regions where RNAV 5-capability has been assessed positively. In addition, several regions can be identified in which coverage appears to be insufficient. These areas are located primarily in the northern part of Germany, along the national borders with neighbouring European states, and within Germany in the Thuringia-Franconia region. Apart from these exceptions, coverage is largely ensured and, for the most part, redundant. As previously mentioned, no negative assessment can be made regarding RNAV 5-Capability; therefore, the areas in question must be examined more closely to determine the actual reason for the lack of a positive assessment.

Especially at the borders with neighbouring countries, RNAV 5-capability is underestimated for two reasons: firstly, flight routes are defined only within German airspace and do not always run directly along the border. As the evaluation can only be carried out up to the PBO route itself, an unassessed area remains beyond that point up to the border. Secondly, for the most past, only German navaids have been inspected, thereby overlooking the large number of foreign navaids which are also expected to contribute to RNAV 5-Capability in Germany.

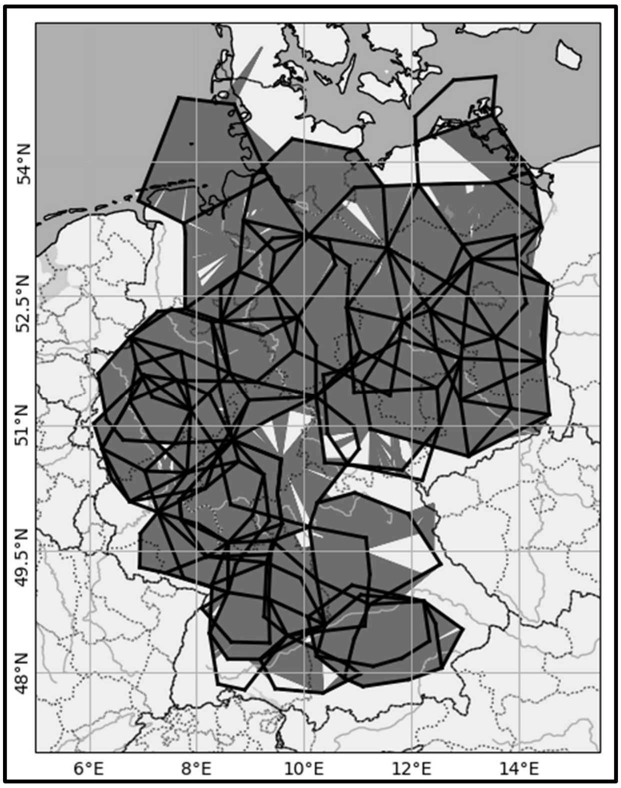
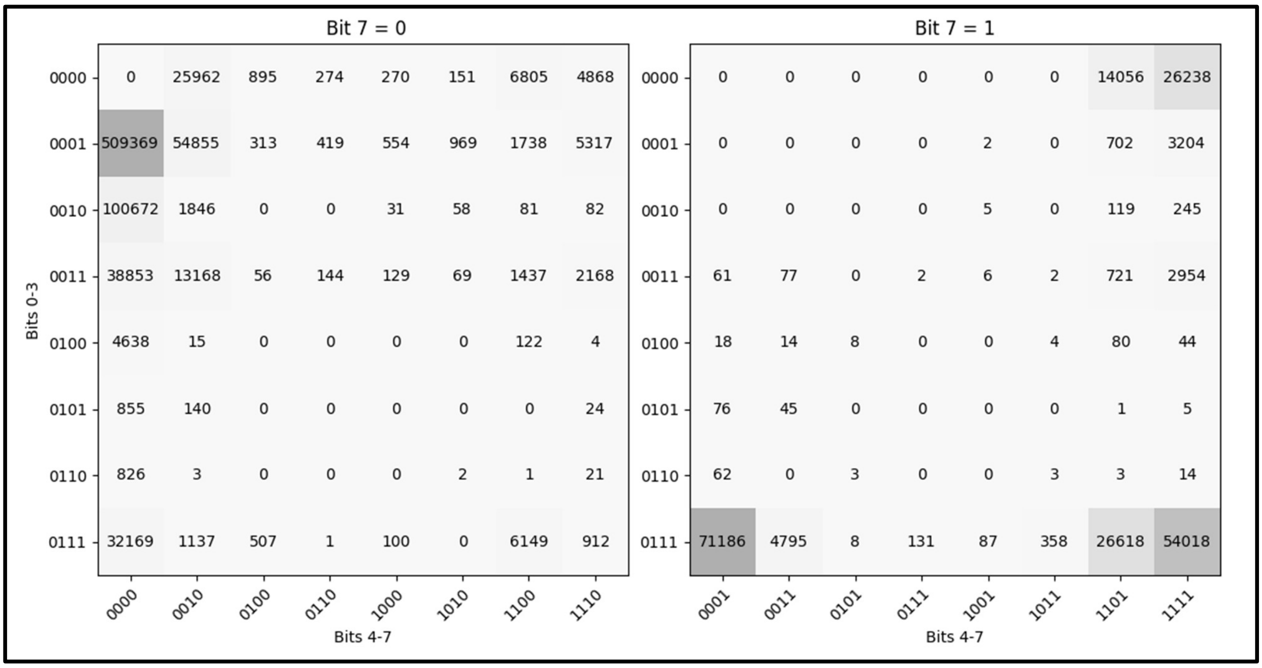


Figure 5. Results of the Evaluation of the RNAV 5-Capability of the Terrestrial Navaids in Germany. The Lines represent the prior defined PBO Routes, while the shaded areas represent positive Evaluation of the RNAV 5-Capability.

One area of interest is northern Germany along the Baltic Sea coast. Due to the decommissioning of the VORDME TRT (Trent), see Figure 3, RNAV 5-Capability here is only available via navaids located far inland. The coverage of these navaids is already realistically achieved, as evidenced by the measured field strength of the VOR components of the navaids.

In addition, the Thuringia-Franconia region in central Germany is also of interest. It is located approximately between 50° and 51° north and 10° and 12° east. Due to the terrain, the navaids in the north are unable to provide RNAV 5-capability in this area. With the removal of a further navaid in the south, there remains an area in Germany which cannot provide RNAV 5-Capability at the examined flight altitude of 7000ft AMSL.



	0000	0010	0100	0110	1000	1010	1100	1110
0000	0	25962	895	274	270	151	6805	4868
0001	509369	54855	313	419	554	969	1738	5317
0010	100672	1846	0	0	31	58	81	82
0011	38853	13168	56	144	129	69	1437	2168
0100	4638	15	0	0	0	0	122	4
0101	855	140	0	0	0	0	0	24
0110	826	3	0	0	0	2	1	21
0111	32169	1137	507	1	100	0	6149	912

	0001	0011	0101	0111	1001	1011	1101	1111
0000	0	0	0	0	0	0	14056	26238
0001	0	0	0	0	2	0	702	3204
0010	0	0	0	0	5	0	119	245
0011	61	77	0	2	6	2	721	2954
0100	18	14	8	0	0	4	80	44
0101	76	45	0	0	0	0	1	5
0110	62	0	3	0	0	3	3	14
0111	71186	4795	8	131	87	358	26618	54018

Figure 6. Heat-Map for the ErrorCode Analysis. On the Left are the ErrorCodes for the 7th Bit being Zero. On the Right are the ErrorCodes for the 7th Bit being One.

Analysis of the ErrorCodes

To conclude the presentation of the results, an analysis of the PBO routes measured during the 2023 inspection cycle is provided. The simple encoding and storage of measurement data using the ErrorCode now allow the creation of a heat map across all measurement points. The total number of measurement points recorded during the 2023 inspection cycle is 4.137.266. Of these, approximately 24.8% exhibit a status bit of zero, meaning that at least one parameter exceeds its respective tolerance.

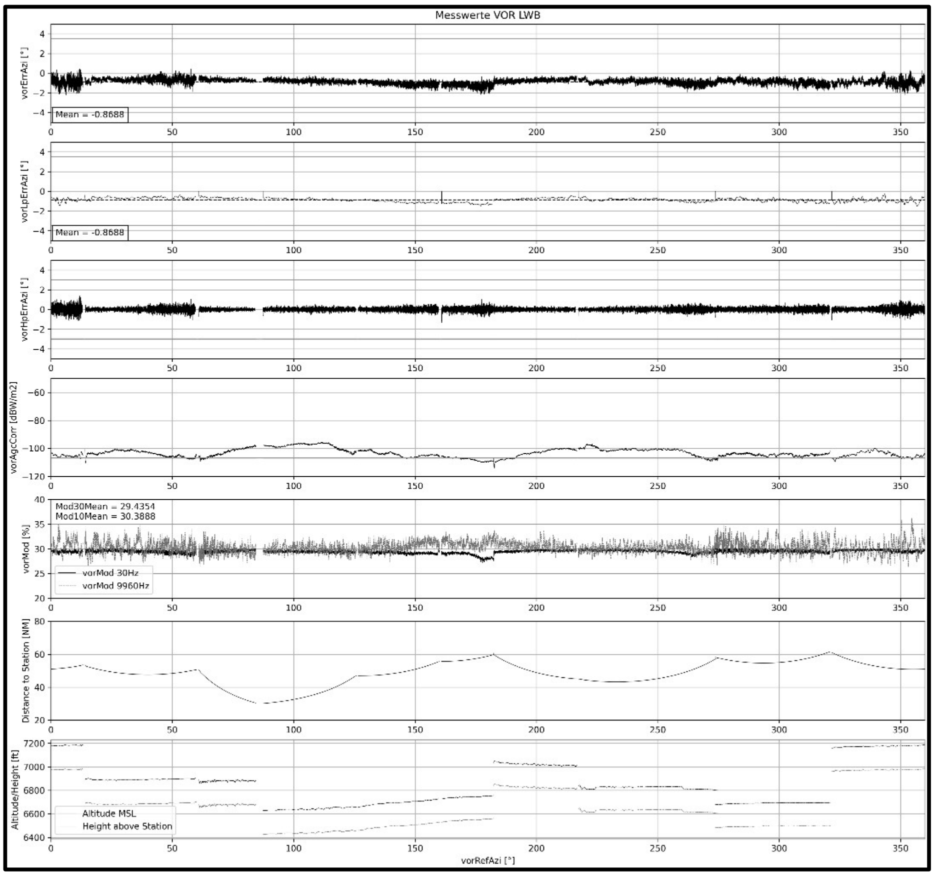
For improved clarity, the heat map in Figure 6 is divided into two grids. The first displays all ErrorCodes for which the RNAV PEE does not exceed the tolerance, i.e. where bit 7, see Table 1, is zero. The second grid displays all ErrorCodes in which the RNAV PEE does exceed the tolerance. The figure reveals that a small number of ErrorCodes occur frequently, whereas many ErrorCodes appear only rarely.

The largest cluster of ErrorCodes is associated with bit 4, which corresponds to the VOR field strength, see Table 1. The *0001 0000* combination is observed most frequently overall with approximately 49,7% of the ErrorCodes with a status bit of zero, suggesting that in many cases the VOR's range is significantly shorter than that of the corresponding DME. Concurrently, the ErrorCode does not indicate any tolerance violations in the VOR structure or VOR modulation. This suggests that the VORDME would still be usable for RNAV 5 despite falling below the conventional field strength tolerance.

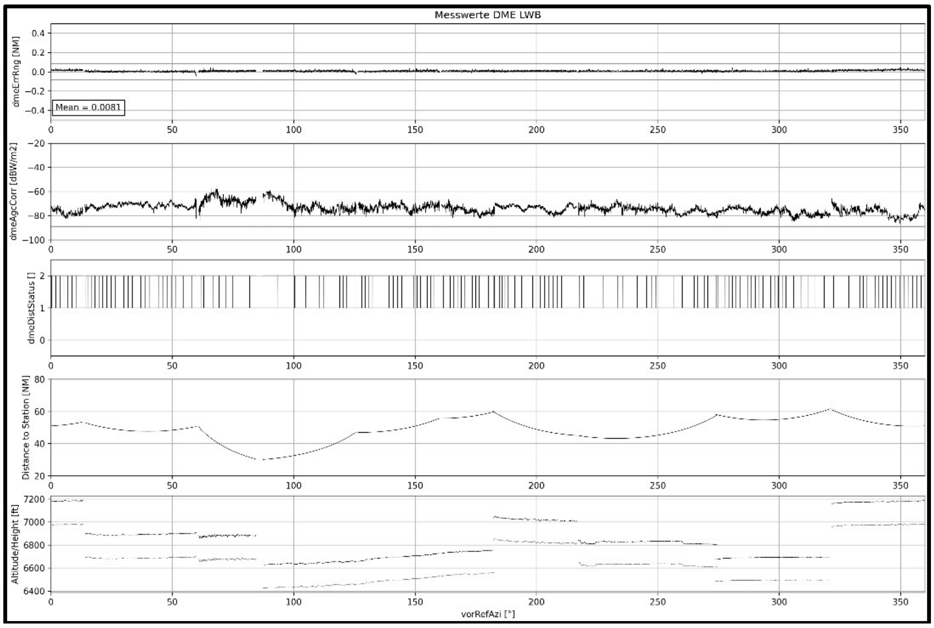
The second most common combination is *0010 0000*. According to Table 1, this indicates that one of the VOR modulations is out of tolerance. However, as described in previous chapters, this combination can be treated as secondary, as the modulation is not meaningful given the sometimes very slight elevation and high impact of the vegetation on the received signal.

Rare combinations include *0100 1001* or *0100 1000*, indicating that there are few measurement points at which only the respective component-specific error is large enough to result in an RNAV PEE violation.

Another frequently occurring ErrorCodes are *0111 1111* and *0111 1101*, which most likely indicate that the VORDME was not operational at that time of the inspection. Such cases must be excluded from the percentage calculations and more importantly the inspection should be repeated to achieve a more realistic overview over the RNAV-Capability. Furthermore, these ErrorCodes amplify the effect of the VOR field strength on the overall analysis.



a. VOR Component of the orbit-like Inspection for DVORDME LWB



b. DME Component of the orbit-like Inspection for DVORDME LWB

Figure 7. Orbit-like Inspection for DVORDME LWB (Löwenberg) composing of multiple PBO Routes. The Figure is split into two Subfigures, a. presents the VOR Component, while b. presents the DME Component. Both Subfigures also include the Distance from the navaid and the Altitudes.

ORBIT-LIKE INSPECTION

The Figures 7a and 7b and show the composite PBO routes for the DVORDME LWB (Löwenberg) for the orbit-like inspection. In Figure 7a, the parameters for the VOR component are plotted from top to bottom: VOR azimuth error, PFE, CMN, received field strength (AGC-corrected), distance to the navaid, and flight altitude in AMSL and above the station, each shown as a function of the azimuth angle of the navaid. In Figure 7b, the corresponding DME component parameters are displayed: DME distance error, received field strength (AGC corrected), unlock status, distance to the navaid, and flight altitude in AMSL and above the station, likewise plotted over the azimuth angle of the navaid.

It can be observed that the field strength does not always remain above the conventional tolerance limits for VOR and DME. This is because the PBO routes were planned, where possible, to follow the previously simulated coverage range in order to determine the actual, realistic operational coverage of the navaid. Nevertheless, all measurement points from the orbit-like inspection are used and included in the computation of mean values. For subsequent inspection cycles, the PBO routes were adjusted where possible to ensure that the field strength no longer falls below the conventional tolerance threshold.

Mean values are computed for the VOR azimuth error, the VOR 30Hz- and 9960Hz-AM-modulation depth, and the DME distance error. A comparison between the composite measurements and the actual orbit flights shows a good correlation between the respective values. Therefore, the so far periodical orbit flights for VORs in Germany will be replaced by these composited PBO routes. Nevertheless, orbit flights will still be used for commissioning flights or for the alignment of the navaid.

CONCLUSION

A comprehensive concept for the measurement and assessment of RNAV 5-capability has been presented. This included the necessary and extensive planning of a route network, along with the key considerations required during the planning phase. The operational measurement process was briefly outlined. Subsequently, based on the PBN Manual Doc 9613, the RNAV 5 requirements were applied to the facilities, defining both individual components and combined performance criteria. The evaluation of each measurement is performed using the introduced ErrorCode, which consolidates the individual components and combined requirements and is assessed using a 40-second sliding window, corresponding to the 95%-criterion. The analysis of an individual route was demonstrated using an example, and the ErrorCode was applied accordingly. Building on the evaluation of individual routes, RNAV 5-capability was then extended across an area and subsequently combined into a nationwide overview for Germany.

A beneficial by-product of these measurements is the generation of orbit-like inspections, which, similar to a conventional orbit, inspect all azimuth angles of a navaid and thus provide a comprehensive overview of its characteristics. In addition, mean values for trend monitoring are derived, which correlate well with those obtained from actual orbit flights.

FUTURE WORK

The next step is to expand the analysis to DME/DME navigation so that a corresponding coverage map can be created, depicting the realistic service ranges of the DME facilities. With the continued reduction of VOR installations, it will be increasingly important to regularly assess the remaining stations and classify their RNAV capability.

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