Emulation of Radius-to-Fix legs in Departure Routes via Fly-By Turns

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Abstract: *The results of a preliminary study on the emulation of radius-to-fix legs in turning departures by means of standard track-to-fix legs are presented in this technical note. While radius-to-fix equipage rates keep gradually increasing over time, a traffic mix containing aircraft with and without this navigation capability can impede an optimal management of the traffic flows whenever precise and repeatable curved flight paths are required. After test-flying various sequences of track-to-fix segments to emulate a reference constant-radius arc in a typical departure environment, the deviations to the desired flight path and the flyability aspects were assessed. The first results for a given scenario and aircraft type show an adequate path conformance for a navigation specification RNAV/RNP 1 within a certain range of aircraft performances and weather conditions. However, the reduced predictability of the roll steering when transitioning between track-to-fix segments and the high frequency in the oscillations of the bank angle may pose a problem to flight crews and passengers, respectively.*

Key Words: *Radius-to-fix (RF), Standard Instrument Departure (SID), Multiple-TF Turn (MTT), track adherence, fly-by*

1. INTRODUCTION

Performance-Based Navigation (PBN) has revolutionized aviation in the last two decades. Amongst the many PBN elements that have strongly improved navigation accuracy and integrity, one of the most outstanding ones is the Radius-to-Fix (RF) path terminator or RF leg [1]. Its technical capability to transfer the concept of straight-segment lateral protection to a curved segment is its inherent advantage over conventional or Area Navigation (RNAV) turns, where wind effects must be considered and lead to somewhat "bulky" wind spiral protection areas [2]. As these wider buffers can be avoided with RF legs, they therefore provide excellent opportunities for terrain avoidance and flight path consistency. While this feature has originally seen its primary use in demanding terrain as part of so-called Required Navigation Performance (RNP) Authorization Required (AR) approach procedures [3] or RNP departure routes, it has now also found its way to less safety-critical noise abatement and track mile reduction initiatives, i.e. procedures with a clear environmental impetus. However, all these applications only make sense from a capacity and Air Traffic Control (ATC) planning perspective when the number of airspace users for such procedures is sufficiently high. While most modern medium-range single-aisle and larger long-haul aircraft are equipped with RF capability, this navigation feature is still less common in many regional aircraft which, however, often represent a considerable portion of flights at hub airports. In order to tackle this problem, the idea was born to find ways to "emulate" RF-capability with normal Track-to-Fix (TF) RNAV path-terminators (as featured by the lesser-equipped avionics) for its application in non-safety-critical (i.e. environmentally motivated) procedures. The initial concepts for this were developed by the Federal Aviation Administration (FAA) in the United States and Austro Control's Instrument Flight Procedure (IFP) office could learn from these initiatives during an exchange program with their American counterparts in 2015 and 2016. While previous FAA work has focused mainly on the arrival segment and, in particular, lead-in procedures to final approach, the work presented here was limited to Standard Instrument Departure (SID) procedures. The reason for this choice is the ever-growing necessity for hub airports around the world to alleviate surrounding communities from noise emissions produced in the departure segment of flight. For this purpose, enhancing flight track accuracy and reproducibility by means of RF legs has already become the measure of choice for many airports. However, the strategy poses problems when there is no homogenous RF-capability in the local fleet which is why this is an interesting area to apply RF-emulation. The basic idea behind RF-emulation is the replication of "RF-like" track keeping accuracy in curved flight segments by means of a skilfully selected sequence of standard fly-by turns which resulted in the name "Multiple-TF Turn" (MTT) for this concept. It must be stressed that the MTT concept is outside of any current International Civil Aviation Organization (ICAO) regulatory framework such as PANS-OPS [2] and aims purely at a technical analysis of avionics and flight response to a given Flight Management System (FMS) coding of fly-by turn segments to emulate an actual RF leg.

Thus - inspired by previous FAA work - the study performed by Austro Control's IFP team together with their partner Novair pursued several promising waypoint sequences which were then coded and test-flown in a Level D full-flight simulator to analyse system response with the goal to make these RF emulations usable for a wider range of aircraft (with lower navigation performance) and thereby facilitate the roll-out of environmentally friendly and cost-saving procedures without equipage-induced capacity limitations to airports and ATC. The details on this study are presented in the following sections.

2. USE OF RADIUS-TO-FIX LEGS

The so-called RF functionality enables the FMS to compute arc paths around a given centre point [4]. Unlike standard fly-by turns, RF legs ensure a consistent and repeatable ground track within the nominal design parameters despite the speed variability. Typically, differences in the ground speed due to changing wind conditions and flight performances can be compensated by the flight control computer by means of roll steering. A detailed description of the RF application can be found in the industry standards RTCA DO-236C / ED-75 [5] and RTCA DO-283B [6]. Several studies have confirmed that not even functional differences in the performances of different FMSs generate significant deviations between designed and flown aircraft path [7, 8]. Due to the high precision and predictability associated to RF legs, the applicable protection areas defined in procedure design criteria [2, 9] could be substantially be reduced. This makes RF legs a powerful tool to avoid obstacles [10] as well as environmentally sensitive areas and restricted airspace [11]. Today, flight procedure design criteria [2, 9] incorporate RF legs for non-AR RNP procedures, extending the use of this technology significantly. Furthermore, RNP 1 with RF functionally has been mandated in Europa as part of the navigation strategy for the near future [12] and identified as a key enabler for the future development of the National Airspace System (NAS) in the United States [13].

Over 80% of the aircraft operating from and to main European hub airports are reported to be RF-capable [14]. In the United States, the forecast is that similar equipage rates will be reached around 2020 [13]. However, the installation of certified RF equipment and the subsequent operational approval [15, 16] still poses a financial challenge for regional operators and general aviation.

This kind of operations, such as feeder and business flights, contribute significantly to the overall amount of movements at many hub airports worldwide. At this point, it must be stressed that the mixed use of RF and non-RF operations can create capacity bottlenecks when RF track adherence is required for operational or environmental purposes and cannot be directly controlled by Air Traffic Control (ATC) because of variations in local fleet equipage. This can be compared to the situation where RNAV SIDs are in place alongside conventional departure routes and the preferred assignment by ATC can be impeded by aircraft capabilities. This therefore represents a planning variable leading to occasional re-planning and, consequently, capacity reduction. Hence the interest to develop solid methods to properly emulate RF tracks.

In order to best accommodate operators without RF capability in contexts where ground track adherence has been deemed necessary, the Performance Based Operations Aviation Rulemaking Committee (PARC) has recently published a series of recommendations and guidance material on RF-TF concurrent operations in the United States [17]. This material also tackles charting and database creation and builds upon previous operational recommendations on approach procedures with transitions from RNP to Instrument Landing System (ILS) or equivalent ILS look-alike guidance, thus enabling the extension of the so-called “Established on RNP” concept to a wider range of users [18].

Part of these recommendations are being gradually incorporated into FAA orders and directives such as the U.S. Standard for PBN Instrument Procedure Design [9]. One of the principle recommendations with respect to procedure design, suggests that three 60-degree TF-TF fly-by turns should be used for 180-degree transitions between downwind and final (see Fig. 1). The Distance of Turn Anticipation (DTA) determines then the minimum length of the TF segments.

Whereas the PARC recommendations and resulting FAA design criteria address the approach phase to support the “Established on RNP” concept, no specific study on RF emulation for SID procedures has yet been released.

Some ANSPs have introduced new RF arcs as overlays to existing standard fly-by turns in an attempt to concentrate the flight trajectory distribution of the SIDs at strategic hub airports. Some examples are Vienna, Amsterdam, Zurich [19] and Hong Kong. These designs have usually been driven by the need to tightly control noise footprints around the airport. However, the resulting benefit is again highly dependent on the traffic mix as aircraft without RF capability will still generate a noteworthy dispersion of the flight tracks that may not meet the noise protection requirements. A proper RF-emulation technique for operators without RF capability could counteract this undesired effect regardless of the RF equipage rate.

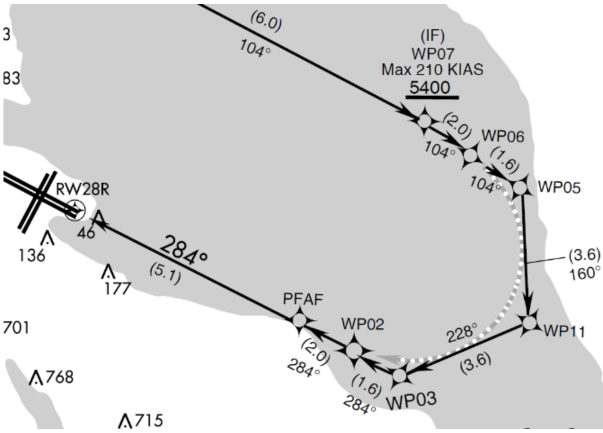


Fig. 1 – Established-on-RNP overlay approach based on TF legs [17]

3. PROBLEM STATEMENT

Previous research efforts to emulate RF legs by means of MTT basically focus on approach operations. On the other hand, airports served by SIDs with RF overlays to conventional fly-by turns cannot achieve an optimal ground track concentration if the RF equipage rate is not high enough. In this note, we investigate the optimal design strategy to emulate RF legs during departure routes based on MTT. Relying on data collected during flight simulation trials, various design options are compared with the original emulated RF leg from a technical feasibility and fly-ability point of view. It shall be noted that the described problem is clearly one resulting from a technical transition phase, where a valuable navigation capability like RF finds wider use in the community but cannot be expected from every airspace user, which causes procedure inconsistencies and planning deficiencies. This can be seen as a small-scale analogy to the overall situation of procedure design which since the turn of the millennium deals with a duality of rules and performances due to the co-existence of conventional navigation and performance-based navigation (PBN). This duality also oftentimes carries the burden of insufficient equipage rates which prevent technologically advanced solutions from becoming a default because the lesser-equipped airspace user cannot be left behind. The proposed RF emulation is therefore an interesting option to apply an advanced element of PBN while at the same time respecting the necessary “backward” compatibility with lesser equipped aircraft types that, nonetheless, still play an important role in the overall fleet mix. But even a perfect RF emulation does not come without a cost. In order to keep the required safety levels, additional efforts must be made. Not only with respect to chart usability and coding, but also regarding ATC procedures, as for instance, there is no specific code to indicate RF stand-alone capability in the flight plan to facilitate the management of the departure clearances. In summary, RF emulation can be seen as an interim solution to enable TF-RF concurrent operations until the RF equipage has become commonplace.

4. PROCEDURE DESIGN

In order to explore possible RF emulation solutions for turning departures, a series of MTT sequences were designed to be test-flown by experienced pilots in a full-flight simulator. Resulting relevant flight parameters were recorded, allowing for post-simulator comparative analysis.

Vienna international airport (ICAO designator LOWW) was selected for the definition of the test scenarios given the increasing pressure to reduce the noise footprints around the airport by concentrating the flight tracks away from noise-sensitive areas. In some cases, very precise flight track conformance with an agreed designed route is necessary even during the turns. For the operational scenarios a total system error of not more than 1 NM (95% of the flight time) was assumed. This corresponds to an RNP/RNAV 1 navigation specification based on Global Navigation Satellite System (GNSS). Fig. 2 shows an overview of the designed MTT departure routes.

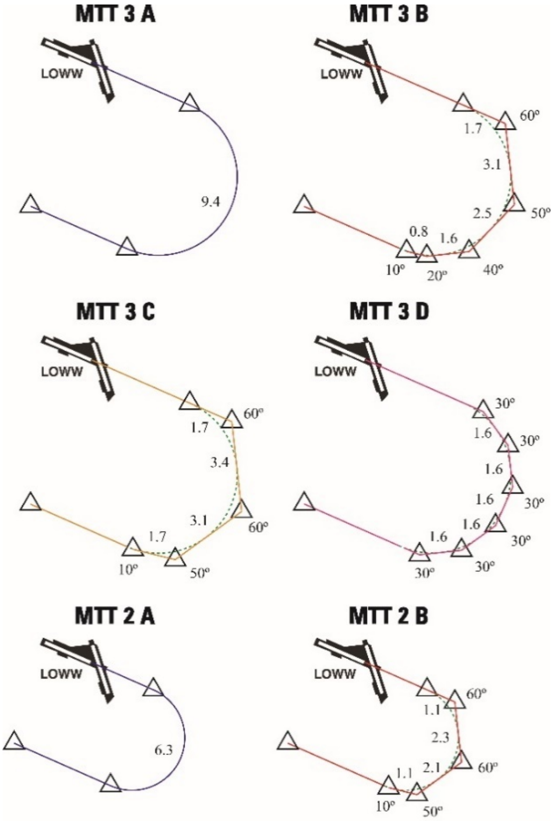


Fig. 2 – MTT sequences with the corresponding track changes (segment lengths are shown in NM)

The design of the SID routes is based on 180°-turn waypoint sequences used for the evaluation of lead-in approach procedures with 3 NM turn radius during a previous phase of the project. The main parameters that were modified among the designs were the number of TF segments, segment length, and consequently the track change between segments, as depicted in Fig. 2.

In addition, the sequence that showed the most promising results for lead-in approach procedures (MTT 3C) was used to test the influence of a smaller turn radius - and therefore shorter segment length - on the results. This is the sequence MTT 2B, which has a turn radius of 2NM. This turn radius was consciously chosen as it represents an extreme case and as such, would be worth testing. The minimum turn radius as per the design criteria should be twice the RNP, which in this case yields 2 NM.

For both design versions, with 2 and 3NM turn radii respectively, the corresponding RF arc was added to the MTT set as a reference to compare the results with (see sequences MTT 3A and 2A in Fig. 2).

Although current ICAO procedure design criteria [2] were considered to a great extent to design the MTT sequences, some short segments would infringe the minimum stabilization distance between waypoints. This design requirement was promulgated to ensure that the turn can be accommodated for a wide range of RNAV systems even in the worst-case scenario. Nevertheless, the worst-case scenario assumption entails five-second bank establishment time, a bank angle of 15°, and in addition, track-changes under 50° are considered as track-changes of 50° for the calculation. These assumptions proved to be too conservative in view of the specific aircraft and flight settings used.

Given a radius for the reference arc (RF leg) to be approximated by the MTT sequence, segment lengths are limited by the DTA. The DTA is the distance required to geometrically allow the tangential interception of the next segment and can be calculated as follows,

$$DTA = r \cdot tan\left(\frac{\theta}{2}\right) \tag{1}$$

where θ denotes the track change and r the turn radius, which can in turn be expressed by the following expression assuming uniform stationary turn,

$$r = \frac{V^2{}_{GS}}{g \cdot tan\,\alpha} \tag{2}$$

where V_{GS} is the ground speed, g the gravitational acceleration and α the bank angle.

The MTT sequences were designed on the premise that an insufficient DTA can trigger unexpected reactions from the FMS and should be avoided. The DTA, and therefore the segment length, is in the end a function of V_{GS} since θ and g are constant, and α can be determined by investigating the behaviour of the local fleet at typical turn altitudes for the specific procedure in normal conditions. This is necessary because of the high variability of FMS equipment implementing different roll control algorithms. The Flight Management Guidance Computer (FMGC) normally calculates the required bank angle as a linear function of the true airspeed (V_{TAS}) up to a limit that is not only aircraft-specific, but also depends on the flight mode and situation. In case of a local fleet with heterogeneous bank performance, the lowest bank limit should be used. In the frame of this project, only one aircraft type was considered, the Airbus 320 (A320). This aircraft type is one of the most popular single-aisle short- to medium-range airliner. Even though the A320 can be equipped with avionic systems compatible with RF functionalities, most of the A320 fleet flying for regional operators to and from Vienna international airport are not RF-equipped or do not have the corresponding operational approval. For this aircraft a maximum bank angle of 30° was identified for normal operations [20]. However, the roll limit is normally 25° in managed mode with the FMS/FMGC providing lateral guidance. This limit is increased by 5° only if the engaged leg cannot be captured [21]. For that reason and given that the lower bank limit represents the more conservative design option, a bank angle of 25° was used for the procedure design.

The maximum V_{GS} for which the design will accommodate the TF-TF fly-by turn can be obtained from Equation (2) if r takes the value of the reference RF arc to be approximated.

The reference arc with 3 NM turn radius yields a maximum V_{GS} of 310kt. This corresponds, for instance, to a turn at 6000 ft Above Mean Sea Level (AMSL) under International Standard Atmosphere (ISA)+15° conditions with a Calibrated Air Speed (V_{CAS}) of 200kt and a maximum tailwind component of 85kt. For a turn at 12500ft at the end of the MTT and under the same conditions, the maximum tailwind would decrease by 25kt. This clearly reflects an important particularity of the MTTs when applied to departure routes. The available buffer to allow for wind components decreases as the aircraft climbs during the turn because of the altitude on the True Air Speed (V_{TAS}) if V_{CAS} remains constant. This has to be considered during the design phase by making conservative assumptions regarding the maximum climb gradient and wind components that can be expected.

The reference arc with 2 NM turn radius yields a maximum V_{GS} of 253kt, which constrains even more the allowance for wind at high altitudes if the bank angle limit of 25° cannot be exceeded. Nevertheless, a V_{CAS} of 200kt still seems to be sufficient for the performances of the A320 and meteorological conditions expected in the actual environment.

The final MTT coding information was lastly arranged in tabular form to facilitate the coding into ARINC 424 format [4]. One example of the coding tables produced can be seen in Fig. 3.

RNAV SID Coding Table of MTT 3 C										
Path Terminator	Waypoint			Course/ Track ° MAG (° True)	DIST NM	Turn Direction	Constraints		Navigation Specification	Remarks
	Identifier	Flyover	Coordinates				Crossing ALT	Speed		
CF	NOT56	no	N480444.24 E0163959.78	112° (116.2°)			A1430+	K200-	RNAV 1	
TF	TRY54	no	N480357.91 E0164219.48	112° (116.3°)	1.7			K200-	RNAV 1	
TF	TRY59	no	N480031.73 E0164239.12	172° (176.3°)	3.4	right		K200-	RNAV 1	
TF	TRY60	no	N475848.17 E0163847.60	232° (236.3°)	3.1	right		K200-	RNAV 1	
TF	TRY58	no	N475915.96 E0163625.92	282° (286.3°)	1.7	right		K200-	RNAV 1	
TF	TRY52	no	N480108.70 E0163046.19	292° (296.3°)	4.2	right		K200-	RNAV 1	

Fig. 3 – Example of coding table for the MTT SID 3C

5. SIMULATOR AND FLIGHT TRIALS

A full-flight simulator (level D) of an A320 fitted with a Honeywell Pegasus FMS with the software release 1A was used to perform the flight validation exercises on 29 August 2018 at the CAE training premises in Copenhagen, Denmark. All MTT procedures were coded into an ARINC 424 navigation database [4]. Even though the simulator used is capable of flying RF legs, the lack of this capability can be easily forced by not using RF path terminators in the coding.

True aircraft position along with key aircraft performance parameters, such as speed, bank angle, and altitude were recorded at a sample rate of 4 Hz. These data enabled the post-simulation analysis presented in Section 6.

The MTT SID scenarios selected for the simulator trials comprise a straight-out departure from runway 11 at LOWW to a turn waypoint followed by a 180º right turn, with a radius of 3 NM (MTT 3A, 3B, 3C and 3D) and 2NM (MTT 2A and 2B), respectively, to establish the aircraft on the downwind (see Fig. 2). Apart from the still-air scenario under ISA+15° conditions, a second meteorological scenario with a wind component of 40 kt from 024° was also considered to study the effects of high crosswind right after departure and subsequent tailwind during the turn with a maximum at the midpoint of the MTT/RF paths. The designs MTT 3A and 2A, which are the baseline SIDs with RF legs instead of MTTs (see Fig. 2), were flown only under wind conditions since the lateral deviation or Cross-Track Error (XTE) in still air was considered negligible for the purposes of this study. All scenarios were flown in the managed mode of the auto fight guidance with auto-thrust activated and a speed limit of V_{CAS} = 200 kt, as considered during the design of the procedures. The take-off weight was set to 65000 kg for all departures.

6. RESULTS

Fig. 4 shows the flight tracks recorded during the simulations for the MTT scenarios with 3 NM turn radius. If the tracks are compared with the procedure reference RF arc, it seems at first sight that the RF path-emulation capabilities of all MTT designs are generally good under all conditions with lateral deviations from the desired path well within the Cross-Track Tolerance (XTT) for RNAV/RNP 1 (1852 m).

The design MTT 3D achieved the best approximation to the reference RF arc without wind influence, whereas the MTT 3C produced the best results under wind conditions. This is confirmed by the distributions shown in Fig. 5, as well as in the box-and-whiskers plots depicted in Fig. 6.

Note that the design MTT 3C is the only one for which the effect of the wind improved the RF-path adherence. This pattern can be observed again for the corresponding design with 2 NM turn radius (MTT 2B) in Fig. 7, 8 and 9. This is due to the longer segments with greater track changes. They are an unnecessary extension of the flight path in still-air conditions but can better accommodate larger DTAs under strong wind conditions. On the other hand, the SIDs MTT 3B and especially the MTT 3D generated higher XTE under wind influence due to their shorter segments with smaller track changes.

These shorter segments cannot always allow for the DTA calculated by the FMGC and caused the aircraft to deviate outwards from the calculated curved path (see Fig. 4) during the simulation session, thus generating a Flight Technical Error (FTE) that is displayed to the crew if it becomes significant.

This undesired effect becomes more evident during the roll-out to complete the turn as the aircraft has considerably gained more V_{GS}. The effects of the altitude and the wind component on V_{GS} are well reflected on the speed plots in Fig. 10. This figure provides a graphical representation of some key aircraft performance parameters for a better understanding of the phenomena observed during the simulations.

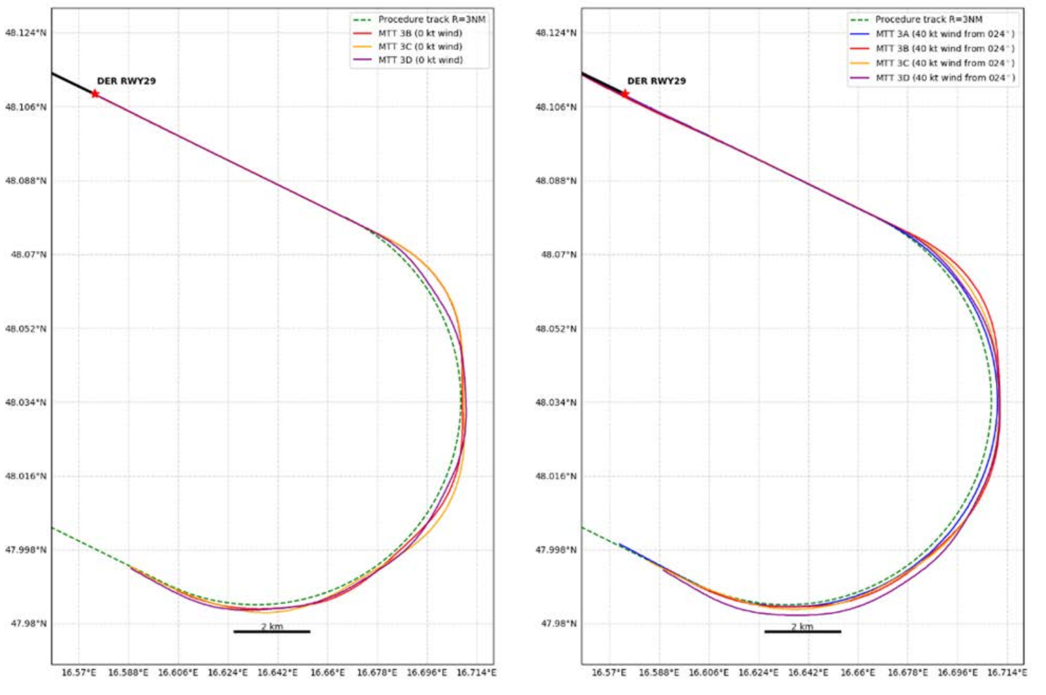


Fig. 4 – Flight tracks for the SIDs with 3 NM turn radius under wind and still-air conditions

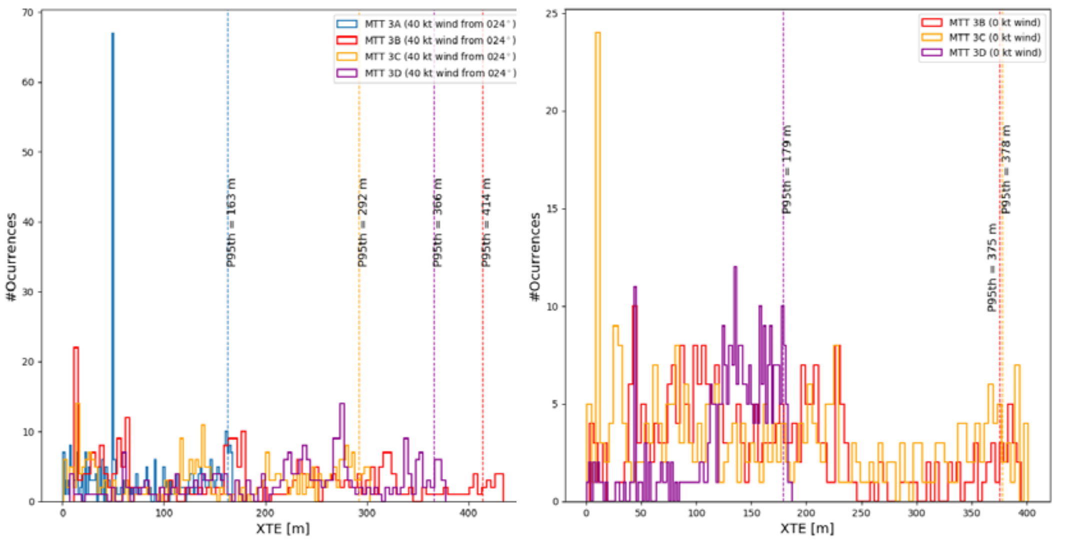


Fig. 5 – XTE histograms (P95) for the SIDs with 3 NM turn radius in still air (right) and with wind (left)

If only the maximum values of the XTE distributions are considered for both cases, with and without wind influence, the design MTT 3D gives the best results.

It must be stressed that all references to wind effects in the present analysis relate to the wind scenario defined for the flight trial (40 kt cross- and tailwind).

In light of the results, a better reaction of the designs MTT 3B and 3D to headwind components along the turn could be expected because of the resulting reduction in the DTA. Headwind components would however negatively affect designs like MTT 3C for which the length of the TF segments is somewhat over-dimensioned under still-air conditions.

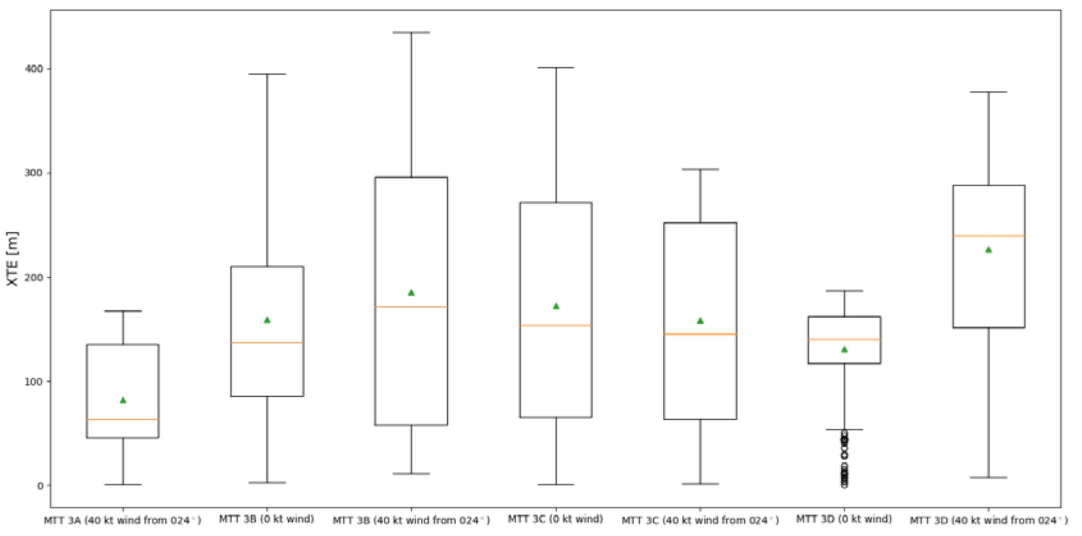


Fig. 6 – Box-and-whiskers plot showing range, quartiles and mean for the distribution of XTE values during the test flights of the SIDs with 3 NM turn radius under wind and still-air conditions

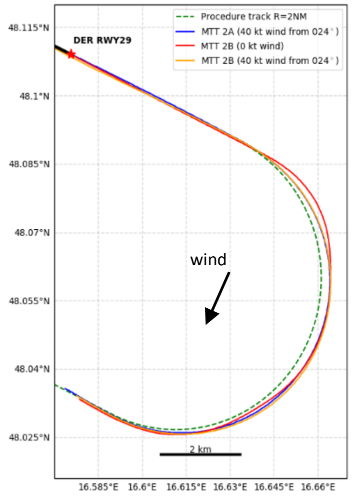


Fig. 7 – Flight tracks for the SIDs with 2 NM turn radius under wind and still-air conditions

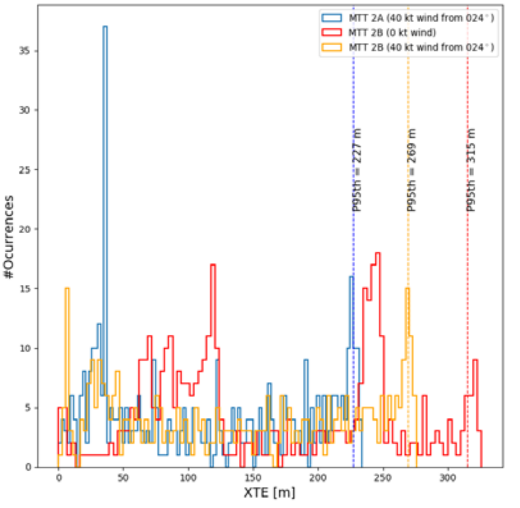


Fig. 8 – XTE histograms (P95) for the SIDs with 2 NM turn radius in still air and with wind

By comparing the results of the 3 NM-radius MTTs with those obtained with the corresponding 2 NM-radius version, where the MTT sequence 60-60-50-10 was selected for the 180° turn (see Fig. 2), it can be seen that the maximum values of the XTE distributions are lower for the MTTs with 2 NM under both still-air and wind conditions. Note that the best approximation to the reference RF arc under wind conditions was observed during the simulations with the design MTT 2B (see Fig. 10). This is due to a nearly perfect match between the theoretical DTA (segment length) used for the design and the actual DTA calculated by the FMGC under the specific conditions of the flight trials. The turn radius plot of the MTT 2B in Fig. 10 shows how a value around 2 NM (target radius) is maintained throughout the turn. Obviously, this also applies to the bank angle, which quite resembles the roll behaviour of the aircraft while flying the RF baseline design (MTT 2A).

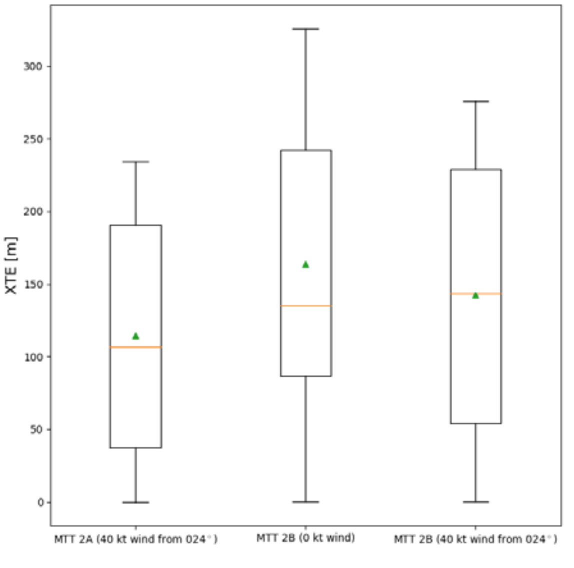


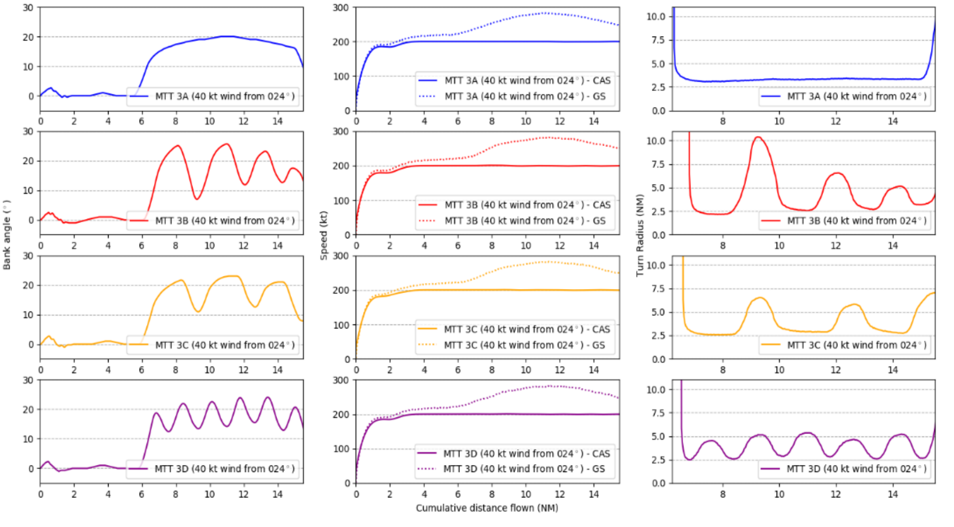
Fig. 9 – Box-and-whiskers plot showing range, quartiles and mean for the distribution of XTE values during the test flights of the SIDs with 2 NM turn radius under wind and still-air conditions

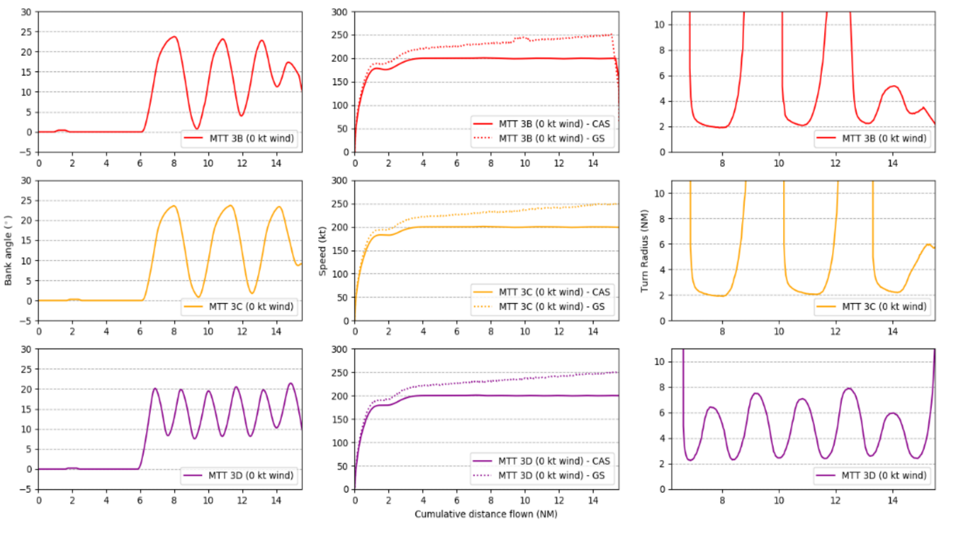
From the flyability and cockpit point of view, the MTT designs were compared by the flight crew with the performance of the baseline RF design (MTT 3A and 2A). As expected, the baseline scenarios were considered smooth and consistent with RF-leg performance, i.e. stable and predictable.

The oscillations in the bank angle produced by the rest of the MTT designs were considered acceptable, with the highest frequency in the oscillations caused by the SID MTT 3D because of the higher number of segments and track changes. The amplitude of the bank variations is however lower than for the rest of the scenarios.

The flight crew reasoned that the somewhat excessive intermittence of the roll steering could be comparable with multiple consecutive radar vectors and should therefore not impose more workload than that accepted by most flight crews. However, two issues were further discussed:

1. It is questionable whether the high number of variations in the bank angle can be considered acceptable from a passenger comfort perspective. These continuous roll variations during the turns may particularly affect more sensitive passengers if conducted on a regular basis.





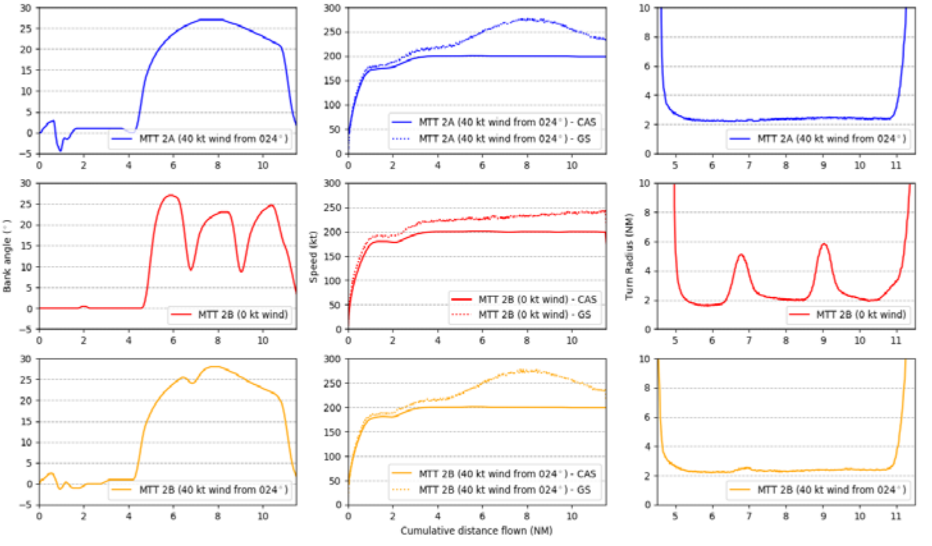


Fig. 10 – Actual turn radius, speed and bank angle for the SIDs under wind and still-air conditions

2. The behaviour of the roll steering throughout the MTT, especially before and after the various waypoints of the sequence, lacks the predictability linked to an RF leg. Flyability was considered acceptable though – as the overall turn was still predictable in general terms – but it was concluded that some familiarization with the turn behaviour will probably be needed among flight crews to gain more confidence in the concept.

7. CONCLUSIONS

In this technical note, the results of a preliminary study on RF emulation for turning departure routes by means of Multiple-TF Turns (MTT) are presented. During the transition phase in which RF capability is being phased in until reaching complete implementation, RF-emulation can support flight operations where RF look-alike path containment and predictability is required. From the simulation study conducted to test various MTT designs for departures routes in one particular scenario and using one specific aircraft type, it can be concluded that all designs satisfied the containment requirements that the equivalent RF path would impose in an RNAV/RNP 1 environment. However, the path-following ability of the MTTs to approximate a constant-radius arc is very sensitive to wind components. Even though conservative designs with long TF segments are recommended to account for extreme, but still realistic aircraft performances and weather conditions, modern FMSs may enable the continuity of the track guidance without disengagement of the autopilot if the length of the segments does not suffice to accommodate the fly-by transition. In these cases, MTTs with a larger number of reduced TF segments can provide good results during departures for a broader range of performances and weather conditions, whereas this application is not recommended for approach lead-in procedures due to the high risk of overshooting the final approach track. Nevertheless, the conclusions exposed here are only valid for the scenario and the specific aircraft type used in the simulations. Thorough and exhaustive analyses of the local fleet and environment should always be carried out prior to the design phase of the MTTs to determine which kind of design is required to accommodate as many operators as possible.

This may include flight trials to explore the behaviour of the specific FMSs to be used. Although the flight crew considered acceptable the use of MTTs to emulate RF legs from the flyability point of view, some concerns were raised regarding the reduced predictability of the turn behaviour when transitioning between fly-by waypoints and the impact of the periodic bank oscillations on passenger comfort. These aspects require further research efforts to ensure the feasibility of the RF-emulation technique for all stakeholders involved. Additional flight trials with a wider group of aircraft representative of the local fleet should be conducted to determine whether the observations of this aircraft-specific study can be generalized

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REFERENCES

[1] * * * ICAO, *Performance-Based Navigation (PBN) Manual (Doc 9613), 4rd* ed., Montreal: International Civil Aviation Organization, 2013.

[2] * * * ICAO, *Procedures for Air Navigation Services - Aircraft Operations (PANS-OPS, Doc 8168)*, 6th ed., vol. **2**, Montreal: International Civil Aviation Organization, 2016.

[3] * * * ICAO, *Required Navigation Performance Authorization Required (RNP AR) Procedure Design Manual (Doc 9905*), 2nd ed., Montreal: International Civil Aviation Organization, 2016.

[4] * * * ARINC, *Navigation System Database – ARINC 424-21*, Annapolis, MD: Aeronautical Radio, Inc., 2016.

[5] * * * RTCA, *Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation (ED-75/DO-236C Chg. 1*), Washington DC: RTCA, 2014.

[6] * * * RTCA, *Minimum Operational Performance Standards for Required Navigation Performance for Area Navigation (DO-283B)*, Washington DC: RTCA, 2015.

[7] A. A. Herndon, M. Cramer, and K. Sprong, Analysis of advanced flight management systems (fms), flight management computer (fmc) field observations trials, radius-to-fix path terminators, In *2008 IEEE/AIAA 27th Digital Avionics Systems Conference (DASC)*, pp. 2-A, 2008.

[8] A. A. Herndon, M. Cramer, T. Nicholson, S. Miller, and L. Rodriguez, Analysis of advanced flight management systems (FMSS), flight management computer (FMC) field observations trials: Standard instrument departure with radius-to-fix (RF) path terminators, In *2012 IEEE/AIAA 31st Digital Avionics Systems Conference (DASC)*, pp. 5B2-1, 2012.

[9] * * * FAA, *United States Standard for Performance-Based Navigation (PBN) Instrument Procedure Design. Federal Aviation Administration Order 8260.58A FAA*, U.S. Department of Transportation, March 14, 2016.

[10] B. Masson, M. Bain, J. Page, *Engine-Out Takeoff Path Optimization out of Terrain Challenging Airports*, AIAA Guidance and Navigation Control, Portland, Oregon, USA, 8-11 August 2011.

[11] T. Dautermann et al., Design, implementation and flight testing of advanced RNP to SBAS LPV approaches in Germany, *Aerospace Science and Technology*, **47**, pp. 280–290, 2015.

[12] * * * European Commission. *Implementing regulation (EU) No 716/2014 of 27 June 2014 on the establishment of the Pilot Common Project supporting the implementation of the European Air Traffic Management Master Plan*, Brussels, 2014.

[13] * * * FAA, *Performance-Based Navigation - Navigation Strategy 2016 (PBN-NAS)*, Federal Aviation Administration, U.S. Department of Transportation, 2016.

[14] * * * SESAR, *Guidance Material for SESAR Deployment Programme Implementation - Monitoring View 2017*, Single European Sky ATM Research (SESAR) Joint Undertaking, Brussels, December 20, 2017.

[15] * * * FAA, *Approval Guidance for RNP Operations and Barometric Vertical Navigation in the U.S. National Airspace System and in Oceanic and Remote Continental Airspace (AC 90-105A) - Appendix 1*, U.S. Department of Transportation, March 7, 2016.

[16] * * * EASA, *Revision of operational approval criteria for performance-based navigation - Air operations - AMC and GM to Part-SPO - Amendment 5. Annex to ED Decision 2016/021/R*, European Aviation Safety Agency, July 29, 2016.
[17] * * * PARC, *RF/TF Concurrent Operations Recommendations*, Performance-Based Operations Aviation Rulemaking Committee (PARC), July 5, 2018.
[18] * * * PARC, *RNP to ILS TF/RF Design and Operational Guidance Recommendations.* Performance-Based Operations Aviation Rulemaking Committee (PARC), October 5, 2015.
[19] M. Troller, M. Scaramuzza, and R. Germann, *RF Leg for Departures: One Year of successful experience*, Proceedings of the International Symposium on Precision Approach and Performance-Based Navigation (ISPA) 2013, DGON, Berlin, Germany, 2013.
[20] * * * Airbus, *A318/319/320/321 Flight Crew Operating Manual*, Airbus Industries, Blagnac, France, 2018.
[21] * * * Honeywell, *Flight Management System (FMS) Pegasus Step 1 for the Airbus A318/319/320/321 - Pilot's Guide*, Honeywell International, Phoenix, Arizona (U.S.A.), 2009.