European PBN Route Spacing Handbook

PBN HANDBOOK No. 3

SUPPORTING EUROPEAN AVIATION

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NETWORK MANAGER

This document is one of a series of inter-related PBN publications, each of which can be used independently. Handbooks 1 & 3 are mainly aimed at ATM/operational audiences, whilst the EUROCONTROL Guidelines for RNAV 1 Infrastructure Assessment (EUROCONTROL - GUID – 0114) and Handbook No 4 primarily target Infrastructure Managers. Handbooks 5 & 6, provide the link between the two audiences on subjects of shared importance.

This document is Handbook **No 3.**

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DOCUMENT CONTROL

The following table records the complete history of the successive editions of the present document.

Edition Number	Edition Date	Reason for Change	Pages Affected
0.1	28.X. 2014	Creation of the document	All
0.2	07.XI.2014	Proposed issue for review at ERS-TF/2	All
0.3 – 0.6	III—V 2015	Internal review	Nav Unit (limited)
0.7	15.VI.2015	Revisions for review at ERS-TF/3	All
0.8 and 0.9	5.VII.2015	Revisions for review at ERS-TF/3	All
1.0 – 1.1	14.VII.2016	Mature draft for Internal EUROCONTROL review	All
1.2	17.VII.2016	Mature draft for ERS-TF review	All
1.3	12.IX.2016	Final Corrections	Highlights + Executive Summary, para 4.4 + Annexes 1&2
1.4	27.X.2016	Submission to NETOPS	Title and final finish
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V.1.a	10.II.2021	Updated to reflect CP 1	Chapters 3 & 5

EXECUTIVE SUMMARY

This document addresses the **spacing of proximate flight procedures;** it specifically focuses on **terminal and extended terminal areas** in European **Radar surveillance environments**. Important conclusions are drawn in the closing chapter of this document. Examples of route spacings are provided in the Annexes. The Guidance Material presented in this document is closely related to the *European Airspace Concept Handbook for PBN Implementation*, (Ed. 4) which is undergoing a significant consequential update. In particular, this document replaces the Handbook's Attachment 5 (Strategic De-confliction of RNAV and RNP Routes in a Radar Environment) and provides updated information regarding PBN and free routes.

Audience

Intended primarily for airspace planners and their supporting PBN specialists, this document is not a technical reference manual but rather a source of guidance, capturing some best practice. The need for this document stems from regulatory requirements to implement PBN SIDs/STARs within the EU. A particular aspect of this implementation is the route spacing between SID and STAR procedures that can be achieved in congested airspace with radar surveillance.

Overview

Chapters 1 and *2* set out to contextualise **PBN** (performance-based navigation with its emphasis on aircraft certification and flight crew qualification), and then connect PBN to the **Airspace Concept** (including ATS Routes, SIDs/STARs and instrument approach procedures). *Chapter 3* explains how PBN supports certain **Operational Concepts** by enabling the **strategic de-confliction of routes** and *Chapter 4* reveals how spacing of routes is calculated. *Chapters 5* & *6* present Challenges and Options as regards PBN implementation, and *Chapter 7* draws conclusions from the analysis.

Conclusions

The sample spacing distances using the ICAO/EUROCONTROL Collision Risk Model, shown in Annex 1, suggest that navigation performance is not the prevalent factor in route spacing determination today. Indeed these spacing examples, which are based on data samples from three major European terminal areas, as well as the results based on London's terminal area using the Loss of Separation Model (see UK CAA CAP 1385), could suggest that the limiting factors in drawing routes closer together include other factors. These are: the Radar separation minima of respectively 3 and 5 NM in terminal and en route operations as well as human factors such as the controller's screen resolution and ATC sector size. The examples shown in these Annexes also indicate that aspects like route configuration, procedure complexity and flyability have an important effect on achievable route spacing minima.

Recommendations

Although this document shows *sample* route spacings, it cannot be over-emphasised that these *sample* spacings are linked to particular spacing methodologies using particular traffic samples. As such, their inclusion in this document does not mean that these sample distances are ready-made for implementation. An implementation safety case would need to determine the relevance of this document's examples to the intended terminal area of application. Furthermore, post implementation lateral navigation performance monitoring would need to confirm the achieved navigation performance.

This document has been produced under the auspices of the Enhanced Route Spacing Task Force (ERS-TF) of EUROCONTROL's Network Operations Team (NETOPS).

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<u>Annexes and Attachments</u>

ABBREVIATIONS

4D	4-dimensional
ADS-B	Automatic Dependent Surveillance- Broadcast
ADS-C	Automatic Dependent Surveillance-Contract
ARINC	Aeronautical Radio, Incorporated
APV	Approach Procedure with Vertical Guidance
APV-Baro	Approach Procedure with Vertical Guidance with Barometric Vertical Guidance
APV-SBAS	Approach Procedure with Vertical Guidance with Satellite Based Augmentation
AR	Authorisation Required
ARN	ATS Route Network
A-RNP	Advanced Required Navigation Performance
Baro-VNAV	Barometric Vertical Navigation
B-RNAV	Basic Area Navigation (RNAV 5)
CCO	Continuous Climb Operation
CDFA	Continuous Descent Final Approaches
CDO	Continuous Descent Operation
CFIT	Controlled Flight Into Terrain
CS-ACNS	Certification Specification for Airborne Communication, Navigation and Surveillance Systems
DCT	Direct Track (in context of European Free Routes)
D/D	DME/DME
DME	Distance Measuring Equipment
DO	RTCA Document
Doc	Document
EGNOS	European Geostationary Navigation Overlay Service
ETSO	European Technical Standard Order
EU	European Union
EUROCAE	The European Organisation for Civil Aviation Equipment
EUROCONTROL	European Organisation for the Safety of Air Navigation
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FAS	Final Approach Segment
FL	Flight Level

FMS	Flight Management System
FRT	Fixed-Radius Transition
GBAS	Ground Based Augmentation System
GNSS	Global Satellite Navigation System
GPS	Global Positioning System
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IRU	Inertial Reference Unit
JPALS	Joint Precision Approach and Landing System
KPI	Key Performance Indicator
LOA	Letter of Acceptance
LNAV	Lateral Navigation
LNAV/VNAV	Lateral Navigation/Vertical Navigation
LP	Lateral Precision
LPV	Lateral Precision with Vertical Guidance
MASPS	Minimum Aviation System Performance Standards
MC	Multi Constellation
MF	Multi Frequency
MLS	Microwave Landing System
MoC	Means of Compliance
MOPS	Minimum Operational Performance Standards
NAV	Navigation
NAVAID	Navigation Aid
NM	Nautical Mile
NPA	Non Precision Approach
NPR	Noise Preferential Routes
NSA	National Supervisory Authority
PA	Precision Approach
PANS	Procedures of Air Navigation Services
PBN	Performance-Based Navigation
PBN SG	Performance-Based Navigation Study Group
PIRG	Planning and Implementation Regional Group
P-RNAV	Precision Area Navigation (≈ RNAV 1)
PRB	Performance Review Body

PRC	Performance Review Commission
RF	Radius to Fix
RNAV	Area Navigation
RNP	Required Navigation Performance
RNP APCH	Required Navigation Performance Approach
RTA	Required Time of Arrival
RTCA	Radio Technical Commission for Aeronautics
SARPS	Standards And Recommended Practices
SBAS	Satellite Based Augmentation System
SID	Standard Instrument Departure
SIS	Signal In Space
SPA	Specific Approval
SPI	Surveillance Performance and Interoperability
STAR	Standard Instrument Arrival Route
TBO	Trajectory Based Operations
TMA	Terminal Control Area
TOAC	Time of Arrival Control
TPO	Tactical Parallel Offset
TSO	Technical Standard Order
US	United States
VOR	Very-High Frequency (VHF) Omni-directional Radio Range
VORTAC	Very-High Frequency (VHF) Omni-directional Radio Range/Tactical Air Navigation System
VNAV	Vertical Navigation
WG	Working Group
xLS	Precision landing system such as ILS, GLS, MLS (but excludes RNP precision operations)

DOCUMENT REFERENCES

Document Full title	***Short title used in document text***
European Airspace Concept Handbook for PBN Implementation, Edition 4, PBN Handbook No. 1	*Airspace Concept Handbook*
European Navaid Infrastructure Planning Handbook including Minimum Operational Network (MON), PBN Handbook No. 4	*Infrastructure Planning Handbook.*
European GNSS Contingency/Reversion for PBN Operations, PBN Handbook No. 6	*GNSS Reversion Handbook*
Eurocontrol Guidelines for RNAV 1 Infrastructure Assessment (EUROCONTROL - GUID – 0114).	*RNAV 1 Infrastructure Guidance*
ICAO Annex 11, Air Traffic Services	*Annex 11*
ICAO PANS-ATM, Doc 4444	*PANS-ATM or Doc 4444*
ICAO Manual on Testing of Navigation Aids, (Doc 8071).	*Doc 8071*.
ICAO Performance-based Navigation Manual, ICAO, Doc 9613, Edition 4, 2013	*PBN Manual*
ICAO, ATS Planning Manual, Doc 9426	*ATS Planning Manual*
ICAO, Manual on the Use of Performance Based Navigation (PBN) in Airspace Design (Doc 9992, 2013 Edition);	*Doc 9992*
ICAO Quality Assurance Manual for Flight Procedure Design, (Doc 9906 Vol 1-6)	*Doc 9906*
Eurocontrol Terminal Airspace Design Guidelines (Ed. 2.0, 2005);	*Terminal Airspace Design Guidelines*
European Route Network Improvement Plan Part I	*ERNIP Part I*

Note: More detailed route spacing reference publications are listed in Attachment B to this Handbook.

1. INTRODUCTION

Systemisation of the air traffic flows together with the **strategic de-confliction** of ATS routes is used in the European network to safely improve the efficiency of air traffic operations in a fixed route environment. One of the enablers is Performance-based Navigation (PBN), which allows the placement of routes independent of ground-based NAVAIDs. An important element of the systemisation concerns the spacing of parallel and non-parallel routes and, consequently, the safety assessment methodology used to determine the minimum spacing consistent with a pre-defined level of safety.

The aim of this document is two-fold. On the one hand, the document provides some examples of the different levels of systemisation / strategic de-confliction applied in European States and, on the other hand, it explains the corresponding safety assessment methods utilised. To put the examples in context, a framework is provided in Chapters 2 – 5 of this document and this is supported by State examples in Annex 2.

Chapter 2 provides an outline of Performance-based Navigation (PBN), emphasizing that PBN provides a level of guarantee of an aircraft's ability to navigate along a fixed published and designated ATS route's prescribed path. **Chapter 3** expands on that by linking that guarantee with the airspace concept and the intended operations. The chapter concludes that PBN facilitates route network systemisation and flight path de-confliction. Variations in the level of application in European airspace are also discussed.

Chapter 4 then focuses on the spacing between proximate flight procedures, particularly the ICAO methodology for the determination of safe route spacing. This chapter starts off with the relationship between strategic de-confliction, separation and spacing; it is followed by a very brief summary of the ICAO collision risk methodology for determining separation and spacing. This methodology, adapted with regard to navigation performance and controller intervention has also been utilized in EUROCONTROL route spacing studies. Emphasis will be put on the fact that the use of generic or conservative assumptions leads to generic or conservative spacing values. Put differently, the more specific the assumptions, the more specific the calculated spacing values are expected to be.

Chapter 5 details a number of implementation realities challenging the implementation of PBN, airspace systemisation, flight path de-confliction, and minimum route spacing in Europe. **Chapter 6** provides some implementation options.

The last Chapter, **Chapter 7,** draws conclusions and indicates recommendations.

The document concludes with a couple of Annexes, which provide an example of the route spacing methodology together with examples of route spacings applied in certain states following implementation safety assessments. In addition, the reader is encouraged to review UK CAA CAP 1385 that details a new methodology employed by the UK with sample route spacings.

2. PBN AND ATS ROUTES

2.1 Introduction

Flight paths, including both ATS Routes and 'DCT' tracks, are the backbone of the European Network and its Airspace Concept which includes RVSM, FUA, Class C airspace, parallel route networks, SIDs/STARs and Free Routes.

When aircraft operate on a route, ATC and pilots need confidence that the aircraft will remain on the route, both laterally and vertically.

Performance-based Navigation (PBN) is key to providing this confidence in navigation performance for both controllers and pilots. Based exclusively on the use of area navigation systems (see Attachment A), PBN has become the **N** in C-N-S (Communication, Navigation and Surveillance), in all flight phases, excluding cases where GLS, MLS and ILS are used in the final approach segment.

PBN's basic premise is that both the aircraft and flight crew must be qualified to navigate along a flight path requiring the use of an RNAV or RNP system. Flight paths flown by the RNAV or RNP system can be either of the following:

a) Fixed, published designated[1] routes including Instrument Approach Procedures (IAP) and/or designated ATS Routes[2] (incl. SID/STAR);
b) Predicated Free Routes as one kind of non-designated Free Routes. Whilst technically the organised track system in the North Atlantic (known as the NAT OTS) could fall into this category, it is usually accepted as being 'outside' the 'free route' description and falling more into the description of 'user preferred trajectories'.
c) DCT's such as those inside the European Free Route Airspace. Whilst their point-to-point availability is published in the State's AIP and/or the Route Availability Document (RAD), DCT 'tracks' are not 'designated' as per ICAO Annex 11;

A commonality between (a) and (b) is that when these routes are strategically positioned, it is often with a view to enabling traffic de-confliction, environmental mitigation, parallel runway operations, etc. To these ends, a navigation performance is needed to operate on the routes. As regards (c) there is a need for a performance requirement to be set within the airspace to 'guarantee' the lateral track accuracy along the path defined by the aircraft for point-to-point DCT navigation between two waypoints.

This document focuses on the *strategic de-confliction of fixed, published, designated ATS Routes, particularly SIDs/STARs,* designated by the shaded cell in the second column in the following table.

[1] *In this context, designated refers to following the route naming convention in ICAO Annex 11, Appendix 1 and 3.*

[2] *PANS-ATM's definition of ATS routes includes advisory routes, airways, controlled and uncontrolled routes as well as designated arrival and departure routes (which are also instrument flight procedures). The use of the expression 'ATS Routes' as a stand-alone term in this context is intended to include designated airways and arrival and departure routes (which are also instrument flight procedures).*

Table 1 – ATS Routes, SIDs, STARs, IAPs and Free Routes use PBN

➔ 'Flight Path' ➔	Strategic Drivers affecting PBN path placement or route configuration
Instrument Approach Procedures (IAP)	— Safety; vertical path defined — Environmental requirements — Parallel runway operations needs in final and intermediate approach segment.
Fixed, published, and designated ATS Routes (particularly. SID/STAR) *Note: Designation is as per ICAO Annex 11 Appendix 1 or 3.*	— Safety & Efficiency — Environmental requirements — **Strategic de-confliction of ATS Routes incl. SID/STARs**
'DCT' Tracks & Free Route Airspace	— **Efficiency: Meteo advantage (e.g. Jetstream)**

2.2 Navigation Performance

In PBN, navigation performance refers to the **accuracy** of position/path steering to be achieved on a route; the need to navigate properly for a continuous period (**continuity**) and some form of alerting if the aircraft can no longer navigate as well as it should (**integrity**).

KEY POINT: The importance of 'accuracy' is sometimes over-inflated to the detriment of path steering. There is a mistaken belief that an excellent positioning capability leads to perfect path steering. Reality is different: the major challenge facing the use of the navigation computer, which is the enabler for PBN, is the aircraft's ability to follow the *intended, charted path*; this is commonly referred to as FLYABILITY. With PBN implementation, *flyability* of procedures is the focus of significant effort and can involve flight simulations and live trials. Ironically, the aircraft/crew may be qualified, the procedure perfectly charted and deviations from the route might occur, not because of poor navigation accuracy but for other reasons such as challenging procedure geometry (for example short segment lengths in between waypoints, high track angle changes, the use of fly-over waypoints, etc.). This challenge can also often be traced to the navigation data base coding used by the RNAV or RNP system. There are many navigation computers in use, each with their own algorithms and different interpretations of the route coded into their database.

2.3 PBN review

The confidence PBN provides to pilots and controllers that the aircraft will adhere to its cleared flight path is crucial where aircraft are expected to self-navigate along pre-determined, planned ATS routes. This 'performance' assurance stems from PBN's three components, one being the aircraft's **positioning** capability provided by the **NAVAID Infrastructure**; the second being the on-board navigation system's **path steering** (spelt out in the **Navigation Specification**) and finally the design/placement of **routes** **(**known as the **Navigation Application**).

- **NAVAID Infrastructure** ⇨ positioning;
- **Navigation Specification** ⇨ path steering,
- **Navigation Applications** ⇨ routes/procedures.

The quality of the **positioning** provided by the **NAVAID Infrastructure** (GNSS, DME, and VOR) or aircraft's inertial reference system (IRS) to the on-board navigation system is critical to achieving the performance requirements detailed in the **Navigation Specification**. The latter spells out how well an aircraft must estimate its *position* in space (position estimation is normally enabled by the **NAVAID Infrastructure**) and to *steer along a defined path*. **Navigation Application** is PBN shorthand for an ATS Route, SID, STAR or Instrument Approach Procedure, which, when published, must include navigation performance requirements based on a specific **Navigation Specification.**

** Note: The better the positioning source used by the on-board RNAV system, the better an aircraft's ability to determine its position. VOR is the least accurate navigation aid recognized within PBN and only supports one Navigation Specification (RNAV 5) used primarily for ATS Routes (excluding SID/STAR); GNSS, which today is based on GPS with appropriate augmentation, and DME/DME both enable more accurate position estimation. If no external navigation signals are available, then the use of an Inertial Reference System (IRS) could provide an autonomous position estimation capability; however, as this functionality is not required by most Nav Specs it is therefore an operator's choice whether or not to fit this equipment in the aircraft.*

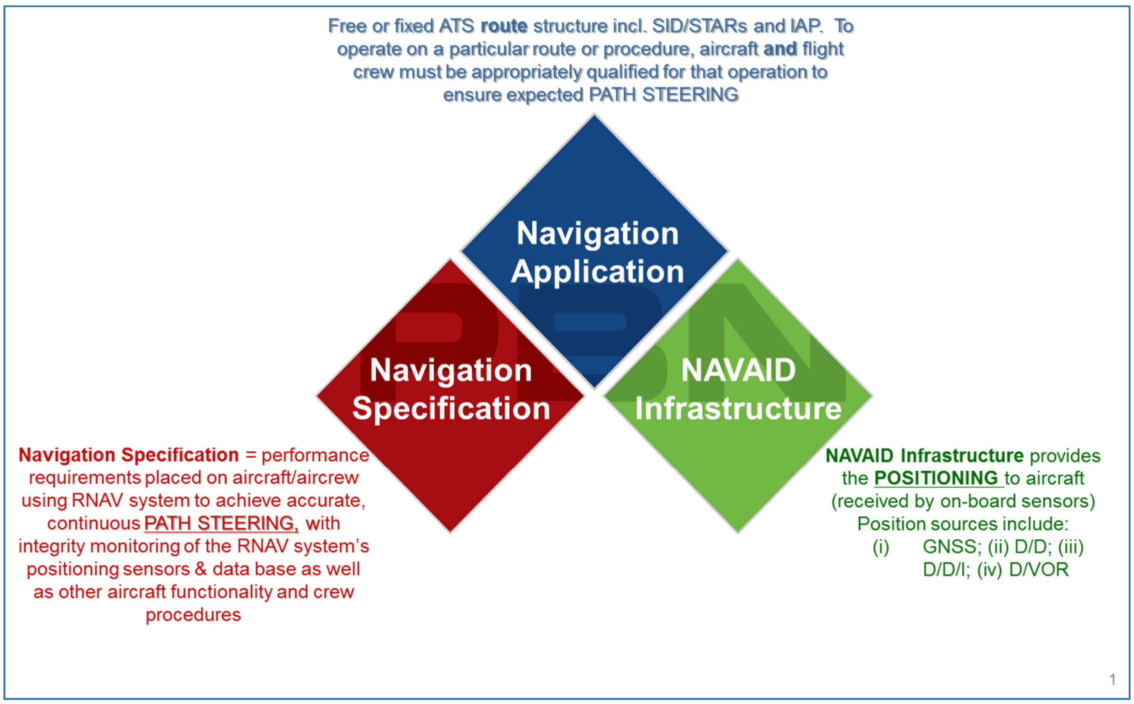


Figure 1: PBN's three components

The **Navigation Specification can be viewed as the 'control point' of PBN: it sets out all the** technical and operational 'performance requirements' to be achieved by aircraft and flight crew for a particular Navigation Application in a particular flight phase. The **Navigation Specification** identifies flight crew operating requirements, required performance/functionalities of the area navigation equipment and associated aircraft avionics as well as acceptable navigation positioning sources; logically, there must be an appropriate **NAVAID Infrastructure** to support the positioning capability. All this aims to meet the operational needs identified in the Airspace Concept. **These Navigation Specifications provide the basis for** States or regions to develop their certification and operational approval documentation.

2.4 ICAO's Navigation Specifications

ICAO has identified two kinds of **Navigation Specification:** RNAV specifications and RNP specifications. Older specifications are RNAV specifications (with avionics which can date from 1970s generation). Most post-1995 aircraft qualify for RNP specifications, which generally have more demanding requirements. One additional requirement that RNP specifications have over RNAV specifications is the requirement for on-board performance monitoring and alerting. Furthermore, higher performance requirements are usually integral to RNP specifications; and advanced functionalities such as **Radius to Fix** (RF) and **Fixed Radius Transition** (FRT) transitions can only be associated with RNP 'aircraft' that can qualify for an RNP specification; (RF and FRT enable predictable and highly repeatable turn performance). As a rule of thumb: an aircraft certified with RF is very likely to be eligible for RNP operations. On the other hand, an aircraft that 'qualifies' for RNP on the basis of only on-board performance-monitoring and alerting will not necessarily be eligible for any RNP operation, as those operations might require specific performance and functions associated with the RNP specifications (e.g. Radius-to-Fix).

Each navigation specification in the PBN Manual Volume II, is roughly 20 pages in length and contains core and contextual material. Core material relating to the navigation specification includes descriptions of the performance (accuracy, integrity and continuity) required from the navigation computer, the functionalities demanded to meet the requirements of the Navigation Application, the approval process, aircraft eligibility and operational approval, as applicable.

More contextual material within the Navigation Specification relates primarily to Air Navigation Service Providers (ANSP) considerations and includes requirements concerning the Navigation, Communication and Surveillance Infrastructures, air traffic controller training, ATC support tools, ATS system monitoring, aeronautical publication, etc.

ICAO has no intention of creating any more RNAV specifications as it is intended to deploy only RNP applications in the future. Therefore, in the longer term, the withdrawal of RNAV specifications by ICAO is to be expected.

Figure 2 provides an overview of the PBN navigation specifications with the required navigation accuracy expressed in NM per flight phase and the required or optional PBN functions (e.g. RF, FRT, …) associated to each navigation specification.

Navigation Specification	Flight Phase – Navigation Application and Lateral Navigation Accuracy (NM)								Additional Functionalities (Required or Optional)					
	ATS or User Preferred Routes		Arrival Procedures	Approach				Departure Procedures						
	En route oceanic / remote	En route Continental	Arrival	Initial	Intermediate	Final	Missed[1]	Dep	RF	FRT[c]	VNAV (Final Segment)	Parallel Offset[d]	Holding	TOAC
RNAV 10	10													
RNAV 5[2]		5	5											
RNAV 2		2	2					2						
RNAV 1		1	1	1	1		1	1						
RNP 4	4									O		R[d]		
RNP 2	2	2								O		O[d]		
RNP 1[7]			1	1	1		1	1	O[a]	O				
Advanced RNP	2[3]	2 or 1	0.3	0.3	0.3		1[9]	0.3	R[a]	O		R[d]	R	
RNP APCH[4]				1	1	0.3[5]	1[8]		O[a]		O (Baro or SBAS)			
RNP AR APCH				1 – 0.1	1 – 0.1	0.3 – 0.1	1 – 0.1	1 – 0.3	R[b]		R[e] (Baro or SBAS)			
RNP 0.3[6]		0.3	0.3	0.3	0.3		0.3	0.3	O[a]					

Refer to PBN Manual, Vol II, Table II-A-1-1 for Notes

Refer to PBN Manual, Vol II, Table II-A-1-3 for Notes
Letters used instead of numbers for clarity

Source: Advanced draft of Edition 5 of the PBN Manual due for publication in 2020 {Edition requires ICAO endorsement}.

Figure 2: ICAO PBN Specifications with Optional and/or Required functions

Note: PBN Manual Edition 4 currently shows Advanced RNP with a 1 NM lateral navigation accuracy in the arrival, initial, and intermediate approach. The 0.3 NM shown in this table is based on a high expectation of a change in Edition 5.

European regulatory requirements for RNAV and RNP

Europe's airspace concept is foreseen to undergo a PBN change. The PBN Implementing Regulation (2018/1048) calls for the implementation of RNAV 1 SIDs and STARs (with the option to use RNP 1 with RF), as well as RNP final approaches with vertical guidance (RNP APCH with LNAV, LNAV/VNAV and LPV minima).

2.5 Summary

This chapter has shown that PBN 'guarantees' navigation performance along an ATS route (or SID/STAR/IAP) as long as two conditions are met:

- The PBN ATS route (or SID/STAR/IAP) is fixed, published, designated and coded in the aircraft navigation database, and the level of performance is specified by a navigation specification; AND
- The aircraft and flight crew have demonstrated their qualification to the required level of navigation performance (certification and operational approval).

3. AIRSPACE CONCEPTS

3.1 Europe's Airspace Concept

At a very generic level, Europe's airspace concept (which extends across many disciplines) can be summarised as having the following characteristics:

- The use of Reduced Vertical Separation Minima (RVSM) between FLs 290 and 410.
- Airspace Classification Class C above FL195.
- Extensive use of the "Flexible Use of Airspace" concept;
- Evolution from State managed upper airspace to Functional Airspace Blocks (FABs).
- A Free Route system in higher airspace where DCT tracking between waypoints is permitted, with tactical conflict resolution using Radar surveillance and direct pilot-controller voice communication. *(Note, that although dependent surveillance is increasingly being introduced as the second layer of surveillance, all European route spacing studies have thus far assumed Primary or Secondary Surveillance Radar i.e. the navigation and surveillance position solution are not shared)*.
- A parallel network of mainly uni-directional RNAV 5 (B-RNAV) ATS routes, connected to the free route system, are knitted around major terminal areas and linked to the conventional or RNAV 1 SIDs/STARs where Radar vectoring is also used. These routes are organised flows which sometimes include a flight level allocation schema. They are spaced at a certain distance to minimise the Radar Controller workload for a given traffic density.
- ATM procedures comprising separation minima, spacing distances, flight planning procedures as well as factors including conditions associated with use of reserved areas as well as airspace classification.

KEY POINT: An Airspace Concept is made up of many components including several enablers, some of which are provided by C-N-S. It is crucial to keep in mind that PBN is only *one* of those enablers. On its own, PBN's advantages are limited. **Intelligent use *and exploitation of synergies between C-N-S-ATM systems,* makes PBN a powerful tool.**

3.2 Intended Operations within an airspace concept

Together, the operational requirements and Airspace Concept provide the framework of *intended operations* within an airspace – mindful that the steps and iterations between Strategic Objectives → Operational Requirements → Airspace Concept → Enablers is critical to meeting performance objectives.

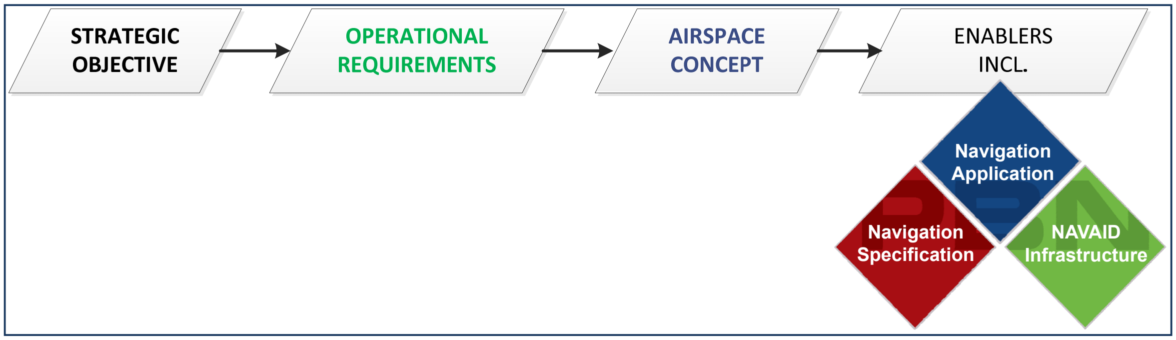


Figure 3: Flow and Iterations from Strategic Objectives to Enablers

By way of example: taking a capacity increase within an ATC sector as a strategic objective -> the operational requirement can be closely spaced routes. As such, the airspace concept could be to develop a route configuration architecture where, for example, the relation between risks associated with RVSM and those associated with closely space routes must be assessed. If it is decided to use closely spaced routes, PBN would be ***one*** of several enablers making this possible. Of course, there are many route configurations possible – crossing, merging, parallel, diverging, and so forth.

Given the above, PBN allows flows of traffic to be designed and the placement and spacing of these ATS routes (fixed, designated and published) will rely on the 'guaranteed navigation performance' amongst other factors. Importantly, the configuration of the routes could determine, for example, the best way to manage transit flows, where to create spurs to link SIDs/STARs, enable the segregation of certain tracks from each other, all with a view of safely ensuring flight efficiency and meeting Network performance targets. Two fundamental concepts underlie most strategic objectives related to capacity enhancement: **systemisation** and **strategic de-confliction.**

Systemisation & Strategic de-confliction

In terminal operations outside the final approach segment, PBN is used for the systemisation and strategic de-confliction of fixed, designated ATS Routes, SIDs/STARs and Instrument Approach Procedures.

Table 2 – PBN Supporting Strategic De-Confliction

↓ 'Flight Path' ↓	PBN's Main Purpose	Strategic Drivers affecting	Additional considerations affecting
		PBN path placement or route configuration	
Instrument Approach Procedures (IAP)	3D Path adherence to ensure Obstacle Clearance	— Safety; vertical path defined — Environmental requirements — Parallel runway operations needs in final and intermediate approach segment.	— COM/SUR and ATM System capabilities/requirements — Pilot and ATC Procedures
Fixed, published, designated ATS Routes (particularly. SID/STAR) *Note: Designation is as per* ICAO *Annex 11 Appendix 1 or 3.*	2D Path adherence with minimum altitudes to ensure obstacle clearance or climb/descent with altitude 'windows' for traffic management.	— Safety & Efficiency — Environmental requirements — **Strategic de-confliction of ATS Routes incl. SID/STARs**	— COM/SUR and ATM System capabilities/requirements — Pilot and ATC Procedures
'DCT' Tracks & Free Route Airspace	Path adherence in 2D	— **Efficiency: Meteo advantage (e.g. Jetstream)**	

Systemisation affects the route design function where any route is designed and placed as part of a greater plan, viewing the total Route network's traffic flows (viewed as a system from cruise to feeding airports in the network). These routes form a system catering for major trans-continental and spur flows which in turn connect from/to the IFPs, allowing routes to be repetitively/systematically used by populations of aircraft because the route has been located in the optimum place in relation to other routes or airports. 'Entry' and 'Exit' points from terminal areas are typical indicators of a systemised traffic flow and route structure. Even a Radar vectoring environment can be systemised, where controllers repetitively use the same Radar vectoring tracks to position aircraft from an arrival point onto the final approach.

Strategic de-confliction is linked to systemisation. When creating a systemised route configuration, a key design objective is to prevent conflicting routes (or to *strategically* de-conflict the routes) and to de-conflict routes from holding patterns. Strategic de-confliction is achieved by building enough space between the routes – based on a prescribed minimum lateral and/or vertical distance - so that the need for ATC to intervene to ensure adequate separation is either reduced or eliminated. Thus, strategic de-confliction can be two or three-dimensional (2D or 3D).

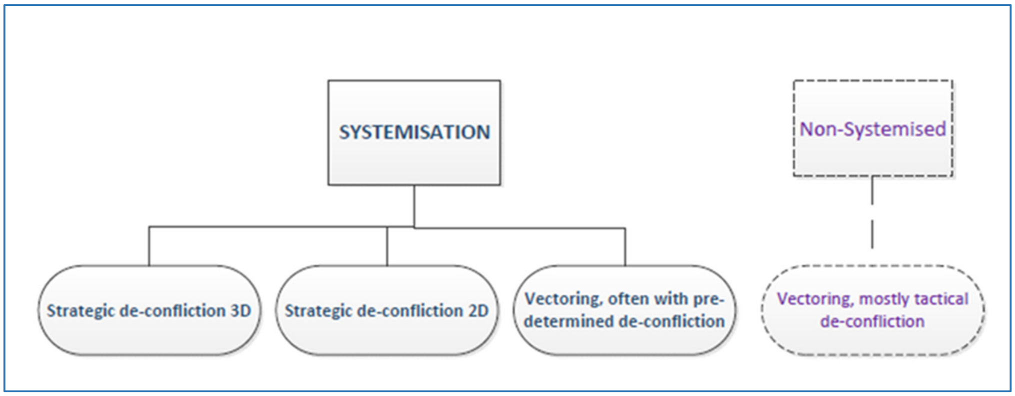
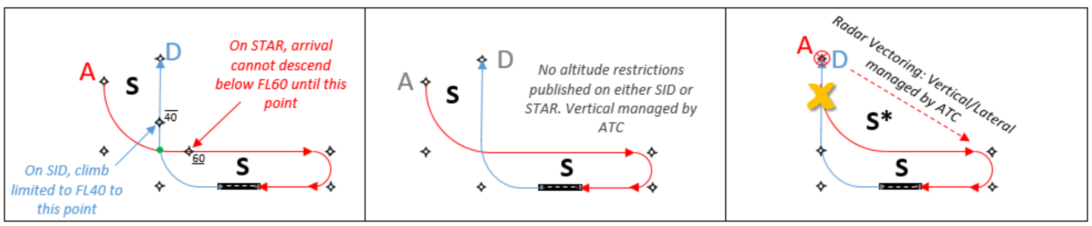


Figure 4: Systemisation and Strategic de-confliction

The advantages to be gained by systemisation and strategic de-confliction relate to network efficiency, flight efficiency and capacity. One potential disadvantage is the potential de-skilling of controllers, discussed later on in this document. The next two Figures show examples of strategic de-confliction in terminal and en route airspace respectively.

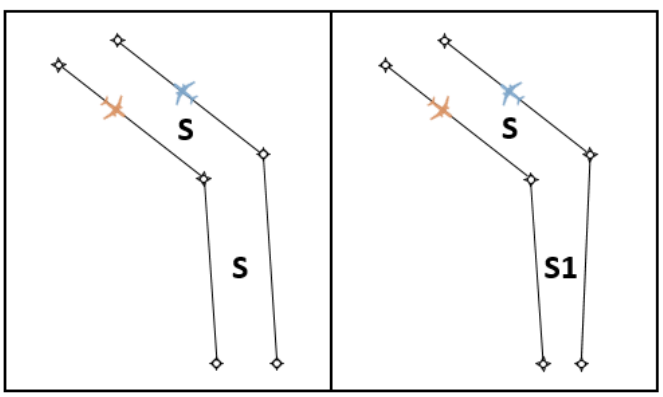


*Both Lateral and vertical strategic de-confliction designed (lateral element at **S**)*

*Lateral strategic de-confliction at **S**. Design allows for easy tactical management of vertical dimension*

*Limited strategic de-confliction at **S***; Lateral strategic de-confliction at **S**. None at ✗*

Figure 5: Examples of strategic de-confliction between SIDs/STARs



*Lateral and vertical strategic de-confliction designed at **S** (adequate spacing ensures that safe separation is assured in normal operations)*

*Lateral and vertical strategic de-confliction designed at **S** Strategic placement at **S1** means that there ATC must assure safe separation by de-conflicting traffic vertically*

Figure 6: Examples of Strategic de-confliction/Placement between ATS Routes (en route)

KEY POINT: PBN makes systemisation and strategic de-confliction possible because route placement is no longer constrained by the location of ground-based NAVAIDS. **Coupling this flexibility to the confidence in track keeping performance means that all published ATS Routes, SIDs/STARs and IAPs can be systemised and strategically de-conflicted**. In the horizontal plane, a natural way of de-conflicting routes is the use of parallel or diverging routes so that traffic on one route 'interferes' minimally (and preferably not at all) with traffic on the other. If this is not possible, then the (lateral) flexibility of route placement enabled by PBN is used when designing crossing tracks, particularly SIDs/STARs. Here, PBN's flexibility allows the airspace designer to determine the most appropriate location for the crossing point between designed tracks so as to create the greatest vertical spacing possible which should ensure minimal vertical interaction or 'interference' between, for example, aircraft climbing and descending on crossing SIDs/STARs. (This is explained in more detail in Activity 7 in the European Airspace Concept Handbook for PBN Implementation Handbook 1).

The systemisation and strategic de-confliction of routes within an airspace concept is planned for normal operations. i.e. where all airborne and ground systems enabling day-to-day operations are serviceable and functioning normally.

However, the airspace concept designed as per PBN Handbook No. 1 requires that the route design cater for contingency procedures.

Such procedures could account for the loss of communications, loss of surveillance layers and low visibility operations (LVO). Because 95% of the ECAC fleet is GPS equipped and because GNSS is required for RNP operations (mandated by EU 2018/1048) the airspace concept, which is built on systemisation and strategic de-confliction of ATS routes and is used for free route navigation, must include contingency procedures for the loss of GPS. For more information, please refer to the European GNSS Contingency/Reversion Handbook for PBN Operations (PBN Handbook No. 6).

3.3 Existing European variations

Although generically, Europe's Airspace Concept appears homogenous, there are some national variations in airspace concepts and navigation applications.

- In those parts of Europe having free route airspace, FL305 is the level above which FRA is mandatory effective 31 December 2022, following the publication of the CP1 IR (Common Project One Implementing Regulation);
- Some countries use fixed route structures whilst others use Radar Vectoring;
- STARs are not always deployed in the same way.
- The navigation application used in the final approach segment can vary significantly.
- Some SID/STARs require RNAV 1 qualifications, whilst others – the large majority – are still conventional SID/STARs. Effective January 2024, RNP 1 with RF may be used on SIDS/STARs, on a needs basis.
- Some countries have published SID/STAR systems – which remain unused, whilst others systematically use their SID/STARs.
- Some countries rely exclusively on Radar vectoring.

Fixed Route Structures vs. Tactical Radar Vectoring

Almost everywhere in Europe, a mix of fixed route structures and Radar Vectoring exists to some degree; these combinations can involve any kind of trajectory combination whether it be straight or turning route segments, holding patterns, trajectories within reserved airspaces and/or Radar vectoring trajectories. The extent of PBN's influence on airspace efficiency in terms of spacing of proximate flight procedures is determined by the Airspace Concept selected and associated concept of operations. Three variants can be identified:

1) An airspace concept containing a *minimal PBN route structure* and the concept of operations envisages a *tactical operation where controllers mainly Radar vector* ➲ PBN serves little purpose as far as the ATM benefits to be gained (though it could be beneficial in terms of environmental benefits regarding route placement to avoid noise or in terms of safety for terrain avoidance). – See Note 1
2) An airspace concept containing an *extensive PBN route structure* which relies on *lateral strategic de-confliction* of proximate flight procedures and the concept of operation envisages *some tactical intervention and management* of the vertical plane by the controller, ➲ the potential ATM benefit provided by PBN is significant. – See Note 2
3) An Airspace Concept containing an *extensive PBN route structure* which relies on *lateral and vertical strategic de-confliction* of proximate flight procedures (using vertical and lateral navigation performance) and the concept of operation envisages *minimal tactical intervention by the controller*, ➲ the benefit provided by PBN can be maximised. – See Note 1

Whilst the ideal end-state is (3), above, flight efficiency may not always make it possible, and very often a pre-dominance of (2) which includes some Radar Vectoring and some strategic de-confliction in three dimensions is the end result with the current tools available to controllers. A migration path towards (3) will probably be assisted with new controller tools, but the overall need to balance conflicting stakeholder requirements often poses a significant challenge.

Note 1 – The European Airspace Concept Handbook for PBN Implementation distinguishes between open and closed procedures (where open procedures generally terminate somewhere on downwind and require Radar vectoring for the transition to the final approach segment). The use of open procedures is an example of a minimum use of Radar vectoring. Where procedures are closed providing a predicated track to the ILS intercept or other Final Approach Segment, PBN is the standard for the transition to the final approach segment. In this instance, the use of Radar vectoring can be non-existent and PBN is extensively relied upon for separation and spacing. Generally, pilots prefer closed procedures because it allows the FMS to properly 'manage' the flight. In the ATC community, however, preference is divided as regards open vs. closed procedures.

Note 2 – Care needs to be taken that the runway throughput is not affected when choosing the extent of tactical intervention as some flexibility is needed for aircraft sequencing.

KEY POINT: The above does not suggest that PBN is a standalone enabler in enabling operations along strategically de-conflicted ATS Routes/procedures. Assurance of the route being correctly flown is determined by the flyability of the route which is affected by proper procedure design, appropriate data base coding, appropriate consideration being given to different type of FMS algorithms, use of level and speed constraints, climb/descent performance of the aircraft, etc.

Considering PBN's capability to exploit the potential to strategically de-conflict traffic – in (currently) three dimensions but ultimately in four – it follows that in a medium to high-density high-complexity operating environment, scenario 3 above has a lower ATC (intervention) workload than scenario 1 or 2. Whilst ATC tools could be used to alleviate some of the workload in scenarios 1 or 2, balances need to be determined, along with attendant costs, risks and mitigations.

STARs … are not all the same.

The next two diagrams show that there is no common, systematic European switch from free route airspace to a fixed ATS Route network leading to a STAR and ultimately an Instrument Approach Procedure.

In Figure 7 below, STARs begin at the TMA boundary or holding pattern (not shown) and end at the Intermediate Fix whereupon the IFPs couple to the Final Approach Segment. However, Figure 8 has STARs 'terminating' at a nominal TMA boundary where holding may be required after which aircraft are either cleared on an IFP or Radar Vectored to final approach. *Note: ICAO's definition of ATS Routes includes airways, advisory routes, arrivals/departure routes (which can be designated as SIDs/STARs). 'Transitions' do not exist in ICAO terminology, even though they are sometimes used on Instrument Approach Charts as a nomenclature for RNAV STARs or initial and intermediate segments of Final Approach Procedures.*

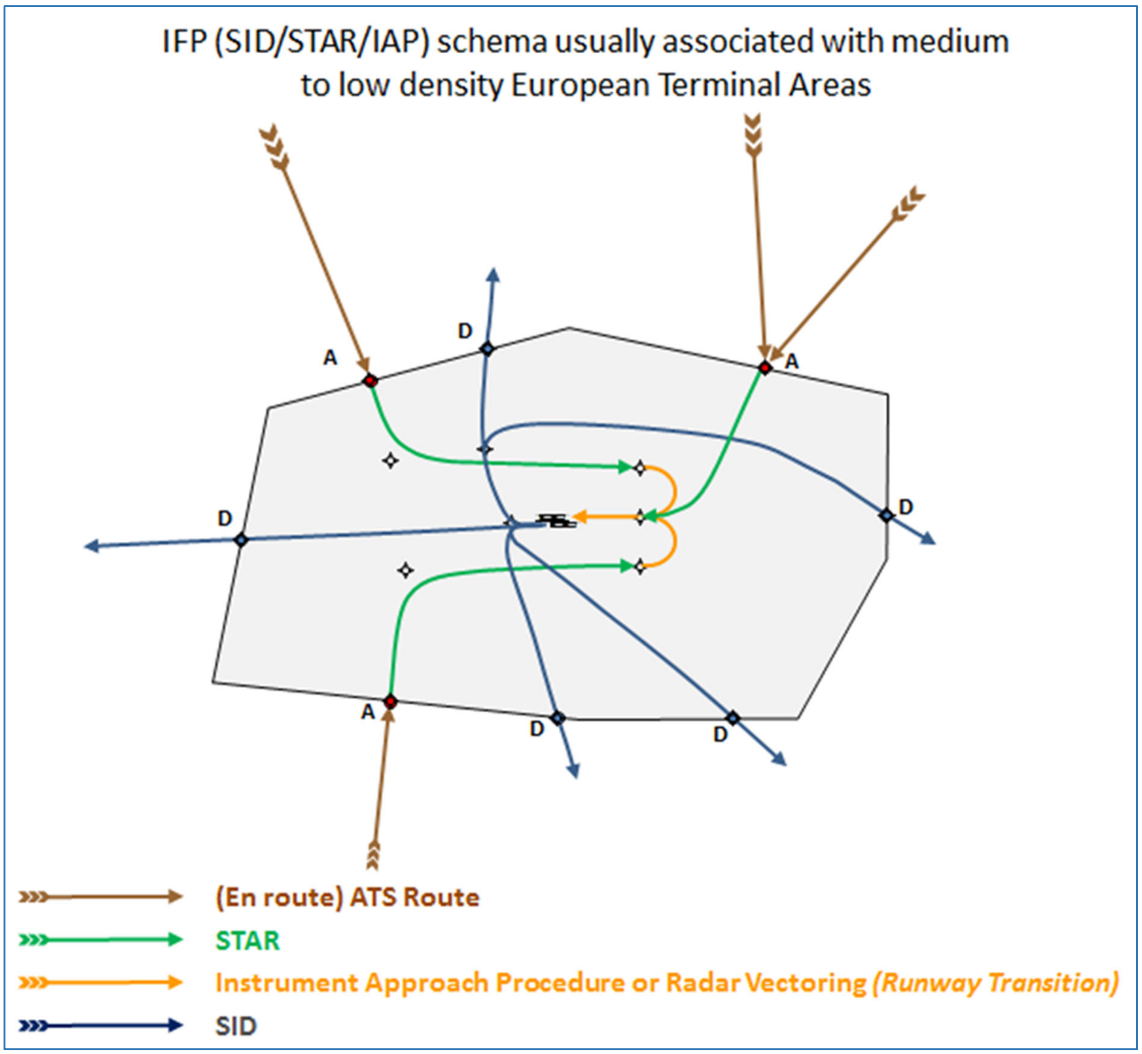


Figure 7: STARs/IAPs – usually lower density airspace

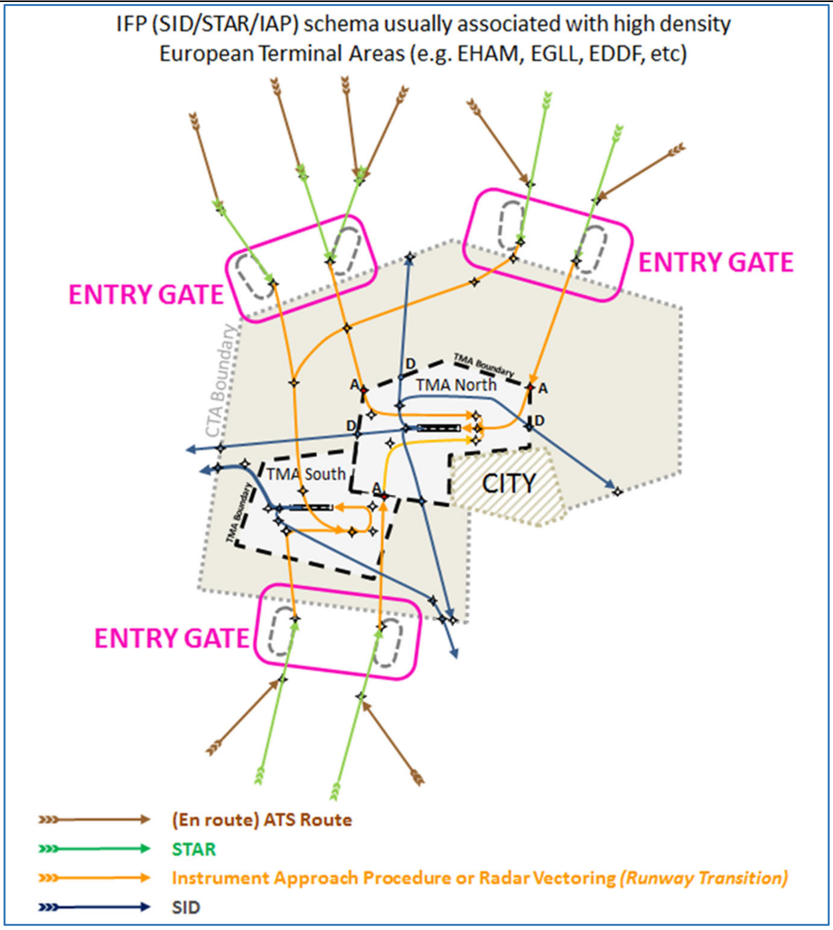


Figure 8: STARs/IAPs – usually higher density airspace

The above differences also have an impact on the connectivity between the fixed and free route environment. Where STARs 'terminate' at the nominal terminal area boundary or in a holding pattern, upstream, connectivity must be assured between the free route environment and the STAR. In the case of STAR's beginning at the nominal terminal area boundary, connectivity must be assured between the free route environment and the ATS Route preceding the STAR. Connectivity, in this context, speaks not only to the airspace design aspect but also to the compatibility of navigation specifications along respective flight segments.

European Variations in transition to final approach.

The final approach can be 2D, 3D, based on PBN or using a non-PBN landing system. One of the more challenging aspects from airspace operations perspective is ensuring that the transition to final approach addresses the need to maintain runway throughput. Key to this is ensuring controller and pilot acceptance of the procedures, thus establishing the link between traffic flow, sequencing technique, route design and flyability of the procedures. Whilst this aspect is not within the scope of this document, what is of relevance for PBN is ensuring that the link between flight phases is seamless, particularly when there is a switch in technology required between different flight segments. Examples of such a switch in technology are the connection of an intermediate approach segment using an RNAV1 or RNP1 navigation specification to a Final Approach based on ILS or GBAS (which uses a Multi-Mode-Receiver and not an RNAV system). This is often referred to as PBN transition to xLS (where x can be either "I", "M" or "G" referring to any of the precision approach landing systems). There are also scenarios where an aircraft is Radar Vectored and then sent direct to a waypoint on an initial or intermediate segment of an approach procedure. This technique is often used to line up the aircraft on the Final Approach Segment of a PBN final approach procedure (RNP

APCH). From a PBN perspective (the scope of this document), Transition to Final Approach means a PBN intermediate approach linking through to any other kind final approach segment using the same or different technology. See Figure 9.

A change over from one PBN application to another (e.g. RNP 1 STAR to RNP APCH) is usually less complex as regards the on-board technology. Recent research has shown that when there is a switch in technology between the intermediate and final approach segment, seamless technology switching needs to be safeguarded, usually in terms of procedure design and flight crew procedures.

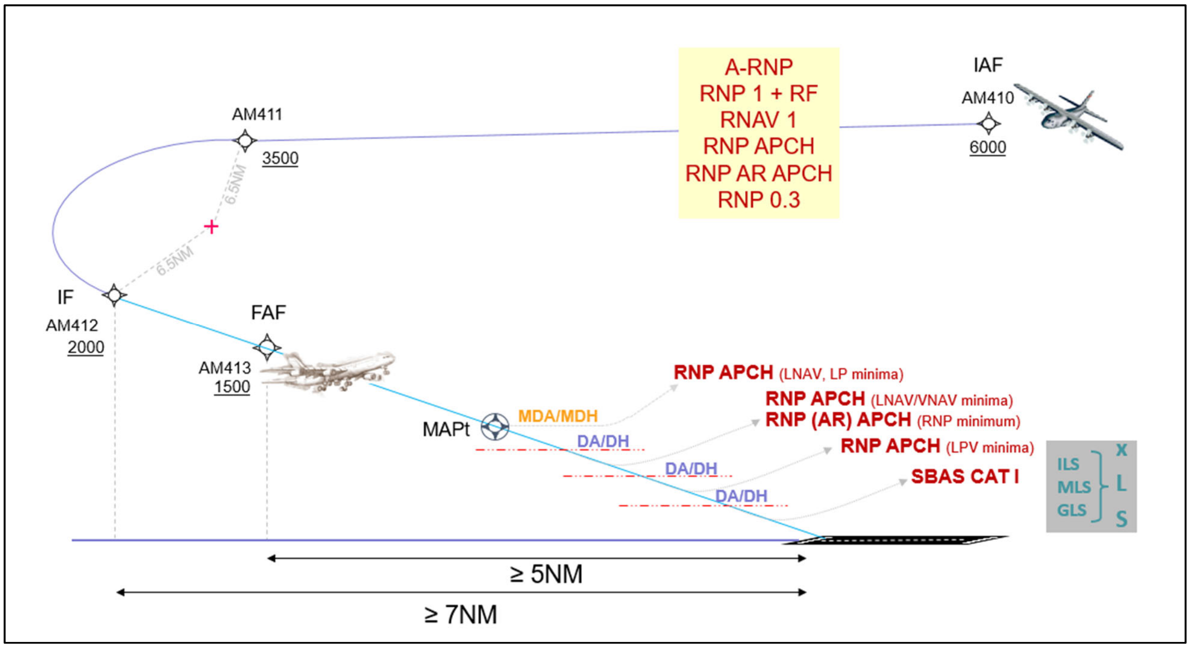


Figure 9: Transition to Final Approach - potential variations

The spacing between IAPs in the final approach segment (FAS) relates directly to Simultaneous Operations to Parallel or near-Parallel Operations whose provisions in Chapter 6 of PANS-ATM are currently limited to ILS, MLS, GLS or RNP AR parallel approaches using ATS surveillance. On-going work in various ICAO Panels is addressing the numerous permutations of parallel or near parallel runway operations using PBN and different xLS technologies.

3.4 Foreseen changes to Europe's Airspace Concept

It is clear that in designing fixed, published and designated ATS Routes, SIDs, STARs and Instrument Approach Procedures (the backbone of the airspace concept), reliance is placed on area navigation techniques and on systemisation and strategic de-confliction. Although the free route environment also requires the use of PBN, systemisation and <u>strategic</u> de-confliction *are not* part of the free route operational concept.

Various changes are foreseen to this Airspace Concept in the next decade.

Airspace regulated by the European Commission's CP 1 IR ([EU] 2021/116) stipulates the use of Free Route Airspace in a two-stepped approach with December 2022 and December 2025 milestones. Within the designated FRA, users select their flight path between any of the WPT's published as entry/exit points to the FRA.

The PBN Implementing Regulation (EU 2018/1048) requires all Instrument Runway Ends (IREs) to have a RNP APCH deployed by 25 January 2024. Furthermore, it also requires all EU Member States to deploy

RNAV 1 SID/STARs as the minimum requirement to support those IREs, with dates of 25 January 2024 for limited deployment and full deployment by 6 June 2030. The Table below summaries the implementation dates for the PBN IR [EU] 2018/1048.

PBN IR Article 4 & 7 Applicability with AUR.2005		Applies 03/12/2020	Applies 25/01/2024	Applies 06/06/2030
Art 4	Transition Plan *(or significant updates)* approved *(living document)*[1]	X[1]	X[1]	X[1]
AUR.2005 1/2/3	RNP APCH at IREs without Precision Approach (PA)	X		
	RNP APCH at all IREs (with PA)		X	
AUR.2005 4/5	RNAV 1 or RNP 1 (+ RF if required) SID and STAR - one per IRE		X	
	RNAV 1 or RNP 1 (+RF if required) for all SID and STARs			X
AUR.2005 6	RNAV 5 ATS Routes (excl. SIDs/STARs) at and above FL150[2]	X		
	RNAV 5 ATS Routes (excl. SIDs/STARs) below FL150		X	
AUR.2005 7	Helicopter RNP 0.3 or RNAV 1 or RNP 1 (+RF if required) SID/STAR - one per IRE		X	
	Helicopter RNP 0.3 or RNAV 1 or RNP 1 (+RF if required) for all SID/STAR			X
	Helicopter RNP 0.3 or RNAV 1 or RNP 1 ATS Routes (excl. SIDs/STARs) below FL150		X	

Note 1 - The transition plan will have several iterations; Article 4 requires that the draft/significant updates to the plan must be approved by the competent authority ***early enough*** *to provide sufficient time for the ANSPs to meet the identified implementation date. (Sufficient time would include accounting for the AIRAC cycle dates, publication and regulatory approval and compliance with other national requirements - see the PBN Portal for an example of the implementation scheduling and time required: https://pbnportal.eu/epbn/main/PBN-Tools/Planning-Estimation.html). The planned implementation dates detailed in the transition plans should be commensurate with the target date obligations.*

Note 2 - CP 1 requires FRA to be implemented with two milestones: 2022 & 2025. FRA is associated with RNAV 5 through the ICAO EUR requirement for RNAV 5 published in ICAO Doc 7030. (CP 1's revised FRA requirements replace previous requirements in the PCP IR).

Updated 10FEB2021

Figure 10: Summary of the PBN Implementation Regulation

At enabler level, another shift is foreseen with the gradual inclusion of ADS-B or Wide-Area Multi-lateration (WAM) as secondary or tertiary layers of surveillance in areas having radar coverage, or as primary surveillance means in non-radar airspace. This will affect the relationship between PBN, ATC intervention and the surveillance enabler in terms of safety methodologies and implementation realities.

3.5 Summary

This Chapter has focused upon the Airspace Concept with its backbone of ATS Routes, SIDs/STARs and Instrument Approach Procedures and the intended operation of systemisation and strategic de-confliction. **Its key message is that PBN's point-to-point navigation permits a route network to be systemised and flight paths to be strategically de-conflicted.** Although systemisation is widespread in Europe, the use of strategic de-confliction varies.

The next question is *if* one seeks to strategically de-conflict routes, how close can any two routes or a route and holding, be placed to each other? But first, how can that answer be established? Is there a method?

4. SPACING METHODOLOGIES

4.1 Introduction

This chapter discusses methodologies used to determine spacing between PBN ATS routes and instrument flight procedures to accommodate their strategic de-confliction to achieve the efficiency and safety objectives whilst ensuring a manageable workload for controllers. What is the minimum distance or spacing that can exist between two proximate flight procedures when strategic de-confliction is the intended operation?

Note: Traditional route spacing work has concentrated on the spacing between two parallel routes in procedural upper airspace. Terminal area requirements are being identified to determine the spacing between combinations of routes, holding patterns, reserved airspace boundaries and vectoring paths.

4.2 Separation and Spacing for strategic de-confliction

PANS-ATM Chapter 5 contains sensor-based separation minima for procedural application. This is usually achieved in a tactical manner by ATC. For example, when both aircraft are established on different outbound VOR radials diverging by at least 15 degrees and at least one aircraft is at a distance of 28 km (15 NM) or more from the facility, the aircraft are laterally separated. In this case, both aircraft can be cleared (tactically) to the same flight level. Generally, ATS routes coinciding with these two radials are not published though may be created strategically to accommodate traffic management. Historically, numerical separation minima were derived by technical/operational safety considerations rather than Collision Risk Modelling (CRM).

PANS-ATM Chapter 5 also includes PBN separation minima which are not sensor based. Using the 15° example above, ATS routes with a subtended angle of 15° or more apart from a waypoint would be published with, for example, waypoints denoting the conditional distance after which both aircraft could climb or descend to their respective flight levels. With PBN, this common waypoint from which two routes diverge could be 'anywhere' which means that the separation minima can be used where such a common waypoint and its diverging routes has been published. Thus the traditional 'tactical' nature of separation provision is no longer in evidence because the separation has been strategically designed and built into the design of the airspace in optimum places, where needed. Numerical values for this kind of separation minima have been derived by Collision Risk Modelling (CRM) supported by technical/operational safety considerations (including hazard identification).

(Route) Spacing has traditionally referred to the spacing between fixed, designated and published parallel routes. Thus, the strategic element has always existed with route spacing: In a Radar environment where PBN routes have been strategically spaced to ensure de-confliction, aircraft operate along a published route and ATC monitors the aircraft's progress through ATS surveillance. Using PBN's flexibility to strategically separate traffic (previous paragraph) has effectively blurred the line between separation (which once was exclusively tactical), and route spacing which was more strategic.

4.3 ICAO Methodology for determining separation and spacing

Note: the Note at paragraph 4.1 is applicable.

ICAO, in its Manual on Airspace Planning Methodology for the Determination of Separation Minima (Doc. 9689), identifies two ways in which safety may be evaluated: one is called the relative method, the other the absolute or 'threshold' method[3]. In the former, two systems resembling each other are compared. In the latter, a target level of safety is identified as an absolute threshold, and mathematical collision risk modelling is used to demonstrate that this target has been achieved. The absolute method is used primarily by ICAO when determining separation minima and the spacing between routes.

Collision risk modelling used for the absolute method includes assessment of risk and identifying viable mitigations. This collision risk model (CRM) is known as the Reich model. The 'ingredients' included in a CRM include the Navigation Performance, Exposure to Risk and ATC Intervention.

In CRM calculations, the model assumes ATS routes to be parallel or intersecting lines which one or more pairs of aircraft are trying to follow along the route centreline. The original Reich model or extensions thereof, are basic tools of collision risk modelling. These models link the separation minimum or route spacing to the level of collision risk on a pair of parallel or intersecting routes. They have been used by mathematicians to determine the minimum spacing between parallel ATS Routes (incl. SIDs/STARs and instrument approach procedures) as well as intersecting routes lateral separation minima.

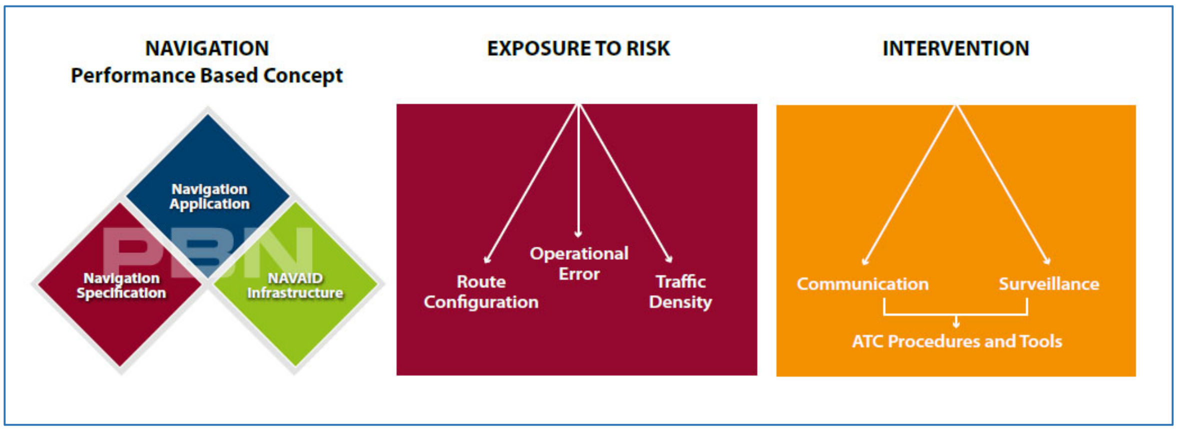


Figure 11: Ingredients of the Reich Model

Collision risk modelling relies on specific **assumptions** concerning the three boxes in Figure 11. Starting with the left-hand box in the diagram, which is the navigation performance of the aircraft operating along the route: in PBN, this is described in the Navigation Specification in terms of accuracy, integrity and continuity (along with the functionalities and other requirements to be satisfied to achieve the performance). The middle box identifies the errors which could cause aircraft to collide and thus depicts exposure to risk. The basic elements of this are the route configuration (Are the routes parallel or intersecting? Are aircraft travelling in the same or opposite direction on parallel routes? Are they in level flight or climbing/descending?), and how many aircraft are anticipated to operate along the routes i.e. what is the traffic density? Apart from exposure to the technical collision risk due to navigation performance, there are potential risks engendered by the occurrence of operational error e.g. a pilot selecting a wrong route or an incorrect waypoint along an assigned route. The right-hand box is how ATC can prevent a collision by intervening and this is achieved using Communication and Surveillance *with* ATC

[3] *This does not imply the absence of other methodologies – e.g. UK CAA CAP 1385.*

support tools capable of monitoring track deviations from a route centreline. As a consequence of the coupled surveillance and track deviation monitoring tool, ATC Intervention is achieved by ATC communicating corrective action to an aircraft.

Assumptions in all three boxes may be subdivided into assumptions on how the system works and assumptions on the numerical values of parameters characterizing the system. The reasonableness of the former type of assumptions can often be demonstrated. The latter type of assumptions can be supported by data.

As the values change in the three boxes, the separation minima and route spacing change. Thus, for one navigation specification (i.e. one navigation performance defined in the navigation specification), various route spacings can be achieved based upon 'changes' to the traffic density or the ATC intervention capability or the existence/removal of ATS surveillance. Further variations can be introduced: most route spacing studies assume that all aircraft operating along the routes are in the same ATC sector, i.e. the spacing of X-NM between two routes has assumed that the intervention capability (the right-hand box) is the same for both aircraft. If a sector line is to be drawn between two parallel routes at implementation, this may affect the spacing between the routes, i.e. it may be necessary to increase the spacing between the routes.

Assumptions and data are key to aircraft collision risk modelling

One of the key assumptions included in the Reich Model is navigation performance i.e. the ability of the aircraft population to respect the flight path (the mathematical 'line') vertically and/or laterally. To determine how good aircraft's navigation performance is, two approaches can be taken:

The first approach places reliance on the *required* lateral performance (accuracy) prescribed in the navigation specification as the 'fixed' numerical value in the CRM related to Total System Error (TSE – See Attachment 1). In this case, for an RNP 1 specification, the assumed navigation performance is +/-1 NM TSE 95% of the flight time with RNP functions as well as on-board performance monitoring and alerting providing some form of guarantee that this accuracy requirement is met in normal operating modes (without an alert being generated). Note that this approach means that outside the 95%, assumptions need to be made as regarding the 'tails' of the distribution. Put more simply, for the remaining 5% of the time, the aircraft can (theoretically) be anywhere.

The second approach is to collect data on the *actual* navigation performance (accuracy) of aircraft operating within the area of intended operation (see Attachment 1). This is a costly and very expensive task and can take a considerable amount of time. Until 2015/16, the most recent 'high quality' data set of navigation performance data dated from the 1980s. The latest data collection exercise took place in 2015/2016, and unsurprisingly, the lateral navigation performance of aircraft is significantly improved compared to that of 30 years ago and the spacing results derived by CRM are encouraging. Furthermore, the up-to-date *actual* navigation performance shows a marked difference to *required* performance. In the EUROCONTROL data collection of 2015/2016, tail data was also collected but assumptions still needed to be made in some cases, to refine the distribution tails.

Because the Reich Model relies on the attribution of (**assumed**) numerical values and data, changes in values (changes in **assumptions)** can alter the route spacing that results. *Thus producing a universal spacing answer applicable to all scenarios is highly improbable*.

Some critical characteristics of generic European route spacing studies

From a European perspective, two key assumptions used in the Reich Model are different compared to studies done by ICAO: Aircraft navigation performance and ATC Intervention.

Whilst ICAO studies traditionally rely upon the required performance (i.e. prescribed) in the navigation specification, EUROCONTROL studies have relied upon collected **aircraft navigation performance data** fed into the CRM. This approach has an advantage in that the actual performance is being recognised (and this is often better than the required performance). There are two potential disadvantages however: (i) an aircraft meeting only the required performance might *legitimately* penetrate the airspace – and so upset the calculations. (ii) data collection is extremely expensive. These remarks pertain to any model utilising *actual* navigation performance.

Although the Reich Model can account for **ATC intervention**, its use in ICAO SASP collision risk studies tends to be limited to a procedural environment as this is considered the lowest common denominator globally. EUROCONTROL studies provide a variation in that ATC intervention using **Radar surveillance** is factored into the Reich Model. Rather than using a theoretical approach to controller intervention modelling, EUROCONTROL collision risk modelling studies use controller intervention failure probabilities based on (validated by) real-time-simulations. What becomes obvious when these simulations are run is how influential and nuanced certain surveillance factors can be. This point is resumed in paragraph 4.4

Because EUROCONTROL studies traditionally use worst-case scenarios in the collision risk model – assuming e.g. that States using the results would not undertake any implementation assessment (which is not permitted) – EUROCONTROL's route spacing studies have previously returned conservative spacing figures. However, the 2015/16 data analysis has changed this, as it is glaringly obvious how excellent the actual navigation performance – and path steering – actually is.

Annex 1 shows how EUROCONTROL uses the ICAO Methodology when it undertakes generic route spacing studies. The use of this methodology is based on several key assumptions, amongst which is the assumption that an independent form of ATS surveillance, namely radar, is used for ATC intervention. The studies' findings are validated by Real-Time Simulation (RTS) and implementations to date have further validated the model with post-implementation safety assessments – as was done for B-RNAV six or seven years after implementation.

KEY POINT: A limitation of using radar surveillance as a mitigation of risk is that the spacing between two routes with aircraft operating at the same flight level cannot be the same or less than the Radar separation minima (thus if the Radar separation minima is 3 NM, the spacing between routes cannot be 3NM or less). This is because a lateral deviation could instantly cause a separation infringement. As such, allowing for sufficient time for the controller to detect and correct a deviation and for the pilot to respond correctly has tended to convert into a minimum route spacing of 4-5 NM in an environment using 3NM Radar separation minima.

Additional 'characteristics' included in generic European route spacing studies

Typically, the following characteristics have been included in the European operating environment when determining route spacing.

- Actual vs. required (prescribed) navigation performance;
- Conservative traffic density (tending to worst case, see above);
- Radar coverage with monitoring continuity – see Note 1;
- Dual radio with backup frequency;

- For RNAV 5 (B-RNAV), turns limited to 20 degrees with extensive availability of VOR and DME (for en route coverage) and en route radar separation minimum of 5 NM;
- For RNAV 1, terminal radar separation minimum of 3 NM – see Note 2;
- All route spacing scenarios have assumed the aircraft to be in the same ATC sector (the responsibility of one controller);
- Before the route spacing studies undertaken in 2015/16, all preceding RNAV route spacing studies in ECAC addressed only straight parallel tracks with a need to increase the spacing between the tracks on the turns. In contrast to the previous RNAV studies, previous RNP studies included turning segments with constant radius turns (requiring FRT or RF capability) thereby not requiring increased spacing between routes on the turn.

Note 1: All route spacing studies undertaken in Europe have assumed (independent) radar surveillance and not ADS-B. If these route spacings were intended for implementation in airspace within which only ADS-B surveillance is provided, the route spacings may need adjustment due to GPS being a common point of failure. Notably, however, Europe has two ADS-B application streams, one intended for non-Radar areas and another for a radar environment and reversion strategies would be different in each case.

Note 2: The generic collision risk assessment undertaken in 2003 to determine RNAV 1 route spacing (9 NM between straight en route parallel tracks) is a good example. It is interesting to note that when a 'sub-study' for the Paris-London tracks was done after the generic study, a 7 NM spacing was found to meet the TLS of $5 * 10^{-9}$ fatal accidents per flight hour along those tracks. This was found to be due to the Paris-London traffic density being lower than the traffic density assumed for the generic study.

4.4 Can derived route spacing be universally applied?

Given the significant role played by assumptions and data in any mathematical modelling, it follows that the assumptions used, determine the outcome of the mathematical modelling. Any 'generic' or 'regional' spacing study undertaken with one set of assumptions pertaining to a particular environment, *cannot be universally applied without an implementation safety assessment for another environment.* Perhaps the only potential exceptions are route spacing studies done for oceanic operating environments as these tend to be more 'uniform'.

KEY POINT: Any published table showing route spacing values determined by particular studies must be seen in this light. No published spacing results for continental application (or study supporting these results) can be considered universal norms. Results are valid only for the assumptions and data used, the particular operating environment and airspace and operational concept envisaged. It is also stressed that a route spacing value supported by extensive data, statistical analysis, mathematical modelling and airspace design 'guarantee' that the aircraft will adhere to the route to ensure that the route spacing is maintained. Flyability is critical to flight operations and ensuring the aircraft is capable of path adherence is necessary, as are the proper coding of routes, procedures design, account being taken of FMS algorithms, etc. Therefore, <u>there is no single universal applicable value for route spacing</u>.

It is therefore to be expected that published results from a CRM study may lead to States determining a different spacing following their own implementation safety assessment and/or validation by RTS; a specific environment with its own operational realities affects the spacing. Examples of operational realities include procedure design of arrivals/departures, FMS algorithms, pilot and ATC procedures, aircraft types, and database coding.

Attention is drawn to the fact that assumptions used for all route spacing studies undertaken before 2015 by EUROCONTROL using collision risk modelling include aircraft navigation performance data from the 1980s. Aircraft navigation performance has improved significantly since then: not only with the increased use of GPS for positioning and the removal of Selective Availability by the US DoD, but also with the increased presence in the European fleet of modern generation aircraft. Thus, newer up-to-date data has been collected to improve the realism of the collision risk modelling approach and results of the latest CRM undertaken in 2015/16 are shown in Annex 1.

4.5 How close?

EUROCONTROL traditionally uses real-time simulations to validate 'theoretical' route spacing values derived by CRM. Over the years, it became predictable that the RTS findings would simply confirm the CRM values. This is no longer true: the 'predictability' of the RTS is no longer a given: two key simulations stand out in marking the shift from the 'dominance' of navigation performance to the increasing importance of 'human performance' in the route spacing 'equation'.

One simulation was held in Malmö in 2004, the other in Budapest in 2011. Whilst the Malmö simulation dealt with strategic de-confliction of crossing tracks, the Budapest simulation concerned parallel and converging tracks in en route and terminal operations .

RNP 1 SID/STAR crossing simulations held in Malmö in 2004.

Terminal Routes invariably have to cross one another at some point. Because an arriving aircraft's rate of descent is usually shallower than a departing aircraft's climb gradient, those routes crossing closer to the airport generally require the departure to cross beneath the arrival, whilst when routes cross further away it is often possible for the departing aircraft to climb above the arriving aircraft before the crossing point. In the Malmö simulations, a variety of crossing angles were used, with careful attention paid to the vertical profiles to minimise level offs for climbing and descending aircraft. Three key observations (over and above the actual investigation) were made by controllers during the RTS de-brief:

i) Crossing angles of less than 45° between tracks caused aircraft to appear 'dangerously close' to controllers, even though there were no separation infringements. Probable cause: screen resolution, label size/orientation.

ii) Certain geometries and relative position between aircraft on crossing tracks could trigger nuisance TCAS alerts.

iii) Where the SID crossed below the STAR, controllers asked for 2000 feet interval to be required for altitude constraints points, so that it would not be possible for converging aircraft on maximum rates of climb/descent to appear as if they would not level off.

Thus although the theoretical distance calculated for these crossing tracks in the calculations had been considered safe, the practical application during a RTS resulted in controllers wanting a greater distance due to the apparent 'closeness' of targets based on the resolution used on the situation display.

The Advanced RNP Simulation in Budapest 2011

This real time simulation dealt with parallel and converging tracks in en route and terminal operations where respectively, 5 and 3NM radar separation minima are applied. The CRM result based on 1980s data provided a 6-7 NM route spacing for terminal operations, and 7-8 NM for en route airspace. The RTS demonstrated that terminal controllers could manage a route spacing of 5 NM between SIDs/STARs despite the CRM result, but in en route, the case was different. Here the practical RTS 'validation' supported the more conservative figures of 7-8 NM of the CRM. Although controllers were asked to manage a 6 NM en-route spacing on straight parallel tracks, they proposed that a spacing of no less than 7 NM be considered in en route for Advanced RNP (1 NM accuracy) – for that specific environment due to the ATS surveillance systems and set up parameters (look ahead time and threshold of alert) being used. Furthermore, controllers asked that the spacing be no less than 7 NM, if turns were included on the parallel tracks. During debriefs, it became evident that the size of the ATC sector and the scale of the Radar Map allied with the relative aircraft speeds was the reason for this controller request: on a particular scale (quite a typical scale used by en route controllers), the spacing of 7 NM looked 'acceptable' and 6 NM appeared 'too close'. Thus, a question has arisen whether human factors and the scale of the Radar display do not risk becoming the limiting factor in en route spacing between parallel routes.

KEY POINT: the resolution of the radar display (a function of ATC sector size) has very clearly become a determining human factor which forms part of the post-CRM implementation safety analysis to determine the acceptable (final) route spacing. Included in considerations are items such as label size and algorithm affecting label orientation both of which affect the potential for label overlap, as well as the aircraft 'target' size and so forth.

It is stressed, that these observations and the above Key Point do not preclude implementation of a route-spacing smaller than the CRM determined value being used where human factor interfaces so permit e.g. a different situation display scaling is used, as long as the spacing is not equal to or less than the Radar separation minima. Furthermore, in a terminal environment, due to the scaling of the map and the (slower) speed of the aircraft, the distance between the radar targets usually appears larger than in an en route environment, so human factor interfaces are different.

4.6 Summary

Chapter 2 showed that PBN 'guarantees' navigation performance along an ATS route as long as two conditions are met:

- The PBN ATS route (or SID/STAR/IAP) is fixed, published, designated and coded in the aircraft navigation database, and the level of performance is specified by a navigation specification; AND
- The aircraft and flight crew have demonstrated their qualification to the required level of navigation performance (certification and operational approval).

Chapter 3 focused upon the Airspace Concept with its backbone of ATS Routes, SIDs/STARs and Instrument Approach Procedures and the intended operation of systemisation and strategic de-confliction. Its key message is that PBN's point-to-point navigation permits a route network to be systemised and flight paths to be strategically de-conflicted. Variations in Europe show that although the extent to which systemisation is employed is wide spread, the extent to which strategic de-confliction is used seems to vary.

This Chapter followed the thread of systemisation and strategic de-confliction, explaining the ICAO collision risk modelling methodology for determining the spacing between routes that are being strategically de-conflicted. The collision risk model is based on assumptions concerning the specific operational environment under consideration, which effectively means that the 'result' does not necessarily have universal application. The question as to how close routes can be spaced was also discussed.

5. EUROPEAN SPACING CHALLENGES

5.1 Introduction

Whilst Chapters 2, 3, and 4 have discussed the theory of PBN, the airspace concept and the ICAO collision risk modelling methodology for spacing of proximate flight procedures, this chapter steps into the reality of European PBN implementation, particularly in terminal and extended terminal operations. It identifies and explains clear challenges facing ANSPs in particular and other stakeholders such as flight crew, airports, airport neighbours and air traffic control. The issues are clustered into those related to:

- Spacing;
- ATC Operations, Airspace and Enablers;
- Flight Operations & Aircraft;
- Consultation & Fragmentation.

SPACING

5.2 General applicability of route spacing values

The PBN Manual as well as other documents include published route spacing results from a wide range of studies. Many of these studies have been undertaken using the ICAO Collision Risk Modelling (CRM) methodology and usually validated by real-time simulation (RTS). Most of these studies have been undertaken with a regional application in mind. As explained in Chapter 4, this means that universal applicability of published route spacing values is not possible. This is less so for spacings established for oceanic or remote areas as these can be more universally applied because the fleet composition, infrastructure/operating environment tends to be more homogenous in these areas than in varying continental environments.

A State is at liberty to use route spacing studies as a benchmark i.e. a place to start. Two options are available to the State at this point.

(i) Either the State/ANSP can 'deconstruct' the reference study to uncover all assumptions used, understand the analysis that led to the conclusion and then test their own statistical data to reach conclusions applicable to their specific fleet performance and likely implementation possibilities by RTS, or

(ii) A State can check the relevance to their fleet of the reference lateral navigation performance distributions and can undertake their own RTS to demonstrate that their output meets their performance and safety targets. RTS has been used successfully in many cases to this end: in this scenario, a careful analysis is done of the assumptions to see if they are pertinent to the environment used to build the RTS. See Figure 14 at Page 41.

In no instance is there a short copy/paste from a previous study to obtain route spacing in a different environment

5.3 ICAO CRM Methodology

Over time, several States have questioned the applicability of ICAO's collision risk modelling methodology to a radar Surveillance environment, particularly because of the large spacing minima that CRM tended to return. For this reason, some States developed alternative methodologies to determine applicable spacing in a radar environment.

Figure 12 attempts to show a high level depiction of conceptual differences in models/methods used to determine spacing between routes. Whilst the ICAO and EUROCONTROL models are conservative, the Loss of Separation Model (see UK CAA CAP 1385) and Empirical step-by-step model are more optimistic, taking greater credit for controller capability i.e. the ATCO's performance is central to the risk budget. The two pink boxes (containing the HAZID, etc.) are key to any methodology: this is where in-depth analytical work is done before finding the 'final' spacing minima to be tested through a RTS. It is clear that these different models may return different spacing minima, which is to be expected because they use different assumptions.

This amplifies the reasons why route spacing values cannot be universally applied – unless the most conservative value (worst case) is used as the norm, which is probably too inefficient for airspace operations

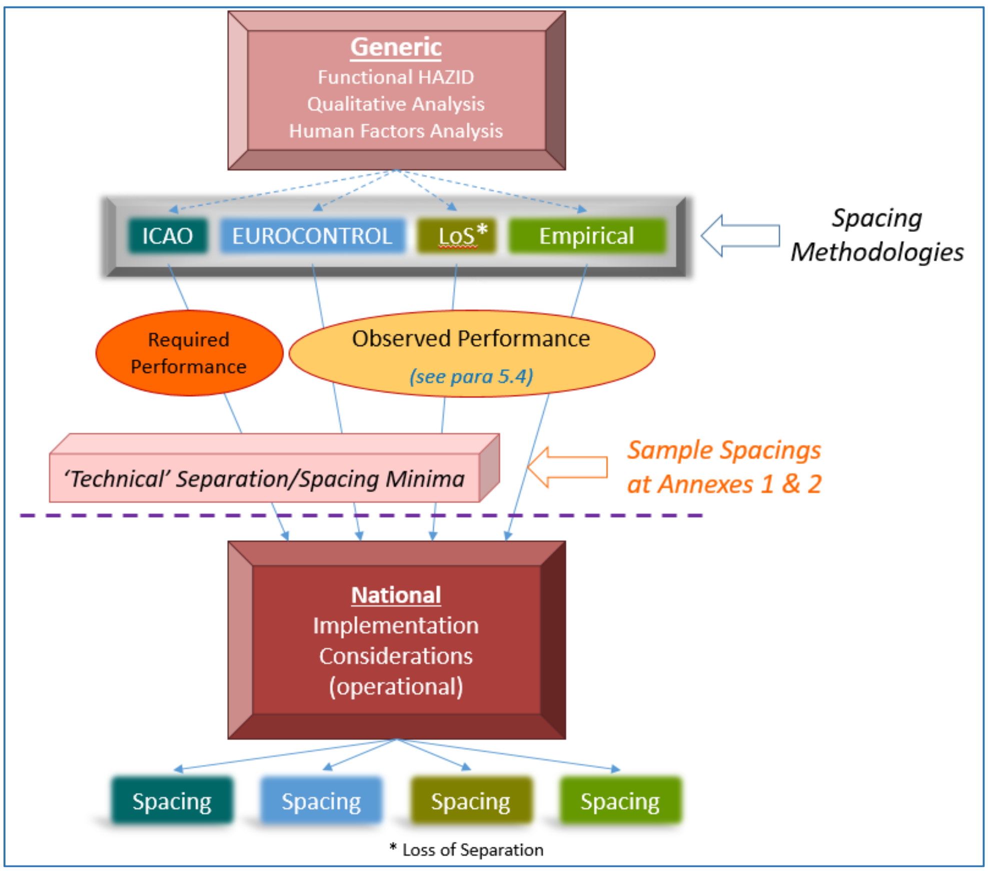


Figure 12: Simplified comparison of the ICAO CRM, EUROCONTROL CRM, Loss Of Separation Model (see UK CAP 1385) and Empirical method for determining route spacing.

Note: The Loss of Separation Risk Model (LSRM) is substantially different to the traditional ICAO CRM method which uses a Target Level of Safety as the reference baseline for comparison with the collision risk associated to the existing spacing minima. The LSRM supports the controller and can be viewed as controller 'centric' whereas the ICAO/EUROCONTROL more traditional CRM methodology tend to start from the Navigation Performance (the positive), then 'diluted' by the risk (the negative), which are mitigated by the controller.

The 2015/2016 EUROCONTROL CRM study and the UK 2015/2016 LSRM Study both used 21st century data. In the EUROCONTROL study, data was provided by three major ANSPs. If Annex 1 and UK CAP 1385 were to be compared, the 'answers' from these two considerably different methodologies, would be very similar. This suggests that the lateral navigation performance data, rather than the model, drives the spacing deduced.

5.4 Use of observed navigation performance in statistical analysis

Several points are to be noted when using *observed* navigation performance (as is the case in the EUROCONTROL CRM and the LSRM) as opposed to *required* navigation performance following the traditional ICAO CRM methodology:

- In a radar environment, observed performance is proof of the good navigation performance and provides evidence that the actual performance is better than the required performance. Whilst the ICAO Navigation Specification spells out the required performance, it reveals little outside the 95 percentile, which is where observed performance becomes particularly relevant, allowing determination of what happens for the remaining 5% (the tails of the distribution).
- This means that post-implementation checks need to be undertaken to ensure that the actual navigation performance achieved by aircraft during implementation is the same or better than the observed performance utilized as the basis for route spacing determination.
- Data collected to determine lateral navigation performance as the basis for route spacing determination for either an RNAV or RNP specification will effectively feature the same traffic sample and, therefore, the same lateral track keeping accuracy along straight tracks. Thus, if 95% of the fleet is comprised of new generation aircraft, the traffic sample will effectively reflect a navigation performance of an RNP fleet even if the intent is to implement RNAV 1. This level of observed navigation performance could tempt the implementation team to design a closer route spacing for that environment. The design team should consider two factors in spacing between RNAV 1 ATS routes.
    - Firstly, whilst the predominant observed navigational performance may be that of RNP 1 capable aircraft with very accurate track keeping, older generation aircraft certified to RNAV 1 can legitimately fly on these ATS routes and their performance might not match that of the majority of the fleet.
    - Secondly, whether it is a RNAV 1 or RNP 1 environment, the loss of GNSS will impact all aircraft (because over 95% of the ECAC fleet uses GNSS as the primary positioning source). Therefore, any ANSP planning their navigation application on a GNSS infrastructure must consider mitigation measures in case of GPS loss. Refer to the European GNSS Contingency/Reversion Handbook for PBN (PBN Handbook No. 6) for further guidance on this issue.
- The use of observed performance therefore means that on-board performance-monitoring and alerting (the 'theoretical' distinction between RNP from RNAV specifications) holds less relevance for applications using a modern fleet, as the aircraft in this fleet would meet RNP1 performance as a common baseline in both RNAV and RNP applications.

5.5 Evolution of the Controller

In many European terminal areas, an extensive use of radar vectoring by controllers remains. In some instances, the Radar vectoring 'tracks' are systemised, and in others, there is little systemisation of repeatable radar vectoring tracks which has given rise to airspace user complaints of the lack of predictability and poor flight efficiency.

As PBN's main driver in en-route and terminal operations is enabling the **strategic de-confliction of traffic flows**, it follows that the controllers' role will change as less radar vectoring is required to resolve conflicts on a tactical basis. Importantly, the controller's responsibility does not change as he/she remains responsible for maintaining separation between aircraft, but the controller's role does evolve; this role includes *more* monitoring of the aircraft as they 'self-navigate' and less radar vectoring. As the controller retains responsibility for separating aircraft, the monitoring role is as critical as radar vectoring which it begins to replace. It is important when making operational decisions, to ensure that efficient traffic sequencing remains possible in more systemised environments where controllers apply less radar vectoring.

Particular care must be taken regarding the controller's 'evolution' regarding the transition to final approach as indicated in Chapter 3, para 3.3 page 21, particularly as regards increasingly complex parallel runway operations. The operational requirement – of efficient traffic sequencing – remains a consistent need, despite any evolution of controller role.

This said, mitigations in the event of avionics problems have to be prepared for i.e. issues that would require controllers to resort to radar vectoring. Reasons for this could range from a single aircraft losing its RNAV or RNP capability, to a full area outage of GPS. Therefore, local competency of radar vectoring skills must be maintained; this could be ensured by a mix of recurrent training and the implementation of an airspace concept that retains some element of radar vectoring. Reversion in the event of a GPS outage is discussed in Chapter 6, as is the connected topic of the use of dependent surveillance.

5.6 Mixed Mode operation

In PBN, mixed mode refers to an ATM environment where the procedures designed and operations permitted accommodate more than one kind of navigation capability. Examples include:

- RNAV 1 SIDs/STARs + Advanced RNP SIDs/STARs
- RNAV 5 + RNAV 2 + Conventional ATS Routes
- RNP AR APCH procedures + RNP APCH (APV SBAS) procedures + ILS
- RNP APCH (APV Baro) procedures + GLS

The notion of mixed mode is analogous to terms such as BEBS (Best Equipped Best Served) or MCBS (Most Capable Best Served). The reason why mixed mode operations arise usually relates to Cost (too expensive to retrofit a fleet), physical limitations of older aircraft which cannot be upgraded, or the mixture of different type of operators (General Aviation, Airline Operations, Military Operations) in the same airspace.

Airspace mandates for PBN equipage are not popular with airline operators primarily due to retrofit costs. Operations not regulated with mandatory PBN requirements may find itself operating with mixed PBN modes or with a mix of conventional and PBN traffic. In medium to high-density operations, mixed mode operations are not successful especially if the mix is present during peak traffic times. Many simulations undertaken over the years have demonstrated this consistently.

The reasons behind mixed mode operation often has to do with what can be described as the avionics gap between general aviation (GA), business aviation (BA), regional aviation (RA) and airline operations (AO). In reality, the PBN concept and the associated navigation specifications have focused almost exclusively on airline operations (modern, large commercial jets) and consequently the gap between different end users becomes an issue where general, business and regional aviation cannot comply with navigation specifications due to the reasons given above. ICAO's PBN Study Group is trying to redress this imbalance.

5.7 ATC Flight Plan – PBN coding

There are two challenges with current PBN codes in the ATC Flight Plan: the first is their complexity and the second is that they are inserted in Item 18 of the ATC Flight Plan. In many FDP/RDP systems, these fields are truncated or even deleted and may not be displayed to the controller. Even if these codes were included, it is arguable that a controller could check that information, given his/her other duties (potential workload issue). This is particularly problematic where there is an intention to utilise mixed mode operation where knowledge of the aircraft qualification is critical. It is to be noted that new navigation specifications and new PBN functions included in the 2013 edition of the PBN Manual do not currently (February 2020) have any ATC Flight Plan Codes.

5.8 Uncertainty regarding implementation safety assessments

Many ANSPs struggle to know how to undertake ***implementation*** safety assessments. Whilst, the design of each procedure (for obstacle clearance, using PANS-OPS) includes requirements for validation and the provision of safety evidence for each procedure, the (total) airspace safety evaluation of the operation (including interaction between all procedures and routes i.e. the core of the airspace concept) must also demonstrate that safety criteria are met. For individual procedure design, challenges seem to be stakeholder needs for a standardised 'template' which ICAO and EASA are trying to address. As regards the interaction of procedures/routes within the airspace concept, the safety evaluation is more related to scale, where the airspace safety evaluation has to examine the integrated picture of risk/enablers melded into the total airspace operation in which the PBN 'based' airspace design plays a substantive role.

States have normally developed their own methodologies for validating procedure design. For the (total) airspace safety evaluation, some states have developed their own methodologies whilst many use the one described in the *European Airspace Concept Handbook for PBN Implementation*, often as a starting point from which they find their own way. This Handbook provides a structure on a step-by-step basis. As components of the airspace concept become more integrated (such as CNS enablers relying on a common technology (GNSS)) the art of operational airspace safety evaluation will become supremely important and perhaps more complex.

5.9 Multi-disciplinary approach

Inasmuch as PBN route developments in one airspace need to fit with those in an adjacent airspace – adjacent means laterally or vertically – the different disciplines involved in a PBN implementation need to coordinate, discuss and learn to speak each other's language because they rely on each other. Unfortunately, many examples exist where engineers and controllers/airspace designers fail to communicate effectively and do not understand each other's issues and often the planned 'seamless' transition from one airspace concept to another is not achieved. In PBN, the inability to cooperate/collaborate across different disciplinary cultures can – and has – caused PBN implementations to fail.

5.10 Flyability

Whether or not PBN routes are designed for the purpose of ATS route spacing, it is imperative to ensure that a designed IFP is flyable i.e. that the track can actually be flown with the level of precision envisaged. The non-flyability of routes may not appear 'dramatic' for aircraft-to-aircraft separation when routes are spaced by 10 to 15 NM, but the importance of flyability increases when they are spaced by 4-5 NM, or for parallel runways.

Although most aircraft can navigate very well independently whether they are RNAV or RNP, large deviations often occur as a consequence of poorly designed IFPs. Of particular reference are the navigation anomalies observed in the initial departure phase of flight. The flyability of a procedure is influenced by the aircraft's performance, particularly groundspeed (including the effects of adverse wind) and its ability to maintain a path within the available bank angle authority. Establishing a design that accounts for these factors is essential and may lead to use of speed constraints, especially in turns. In order to ensure the flyability of PBN procedures, ICAO Doc 8168 Volume II provides criteria for the minimum length of a segment limited by two waypoints. Very often, flight validation is also undertaken before procedure publication to ensure that the published procedure is indeed flyable.

Issues with flyability arise for a variety of reasons that all broadly stem from either the aircraft RNAV/RNP system's interpretation of a published IFP, or the actual design of the procedure. Related issues include:

- The way conventional procedures are coded in an aircraft's database may vary depending on interpretations of the database coder. This leads to variations in the flight path when the RNAV system is used to fly these procedures.
- Differences in aircraft performance and the interaction of vertical performance and lateral navigation performance may influence the resulting flight path. Examples are turns at a prescribed altitude whereby the altitude is reached at various positions by different aircraft having different climb performances.
- Fly - over points and the way that an aircraft's RNAV/RNP system is designed to continue the published procedure may influence the resulting aircraft flight paths. Depending on the situation, the use of the RF function could be a potential better alternative for fly - over waypoints.
- Environmental pressure to design a route 'poorly' so as to avoid noise sensitive areas. There are known cases where published procedures satisfy political pressures but are physically unflyable.
- Aircraft groundspeeds significantly affect fly-by turn performance and speed constraints do not suit all aircraft or elicit the same performance from all aircraft during fly-by turns. This is in contrast with the use of the RF function whereby the aircraft's ground track is predictable and controlled by the RNP system varying the bank angle during the turn. To further limit the risk of path deviations due to high groundspeeds and aircraft bank angle limitations, AT or BELOW speed constraints could be coded at the last waypoint of an RF leg in a departure procedure and at the first waypoint of an RF leg in an arrival procedure.

Whether a controller action (intervention) is required to rectify an observed flyability issue, will depend upon the degree of difficulty the aircraft has in achieving the nominal path, its speed and trajectory, the radar display resolution and the proximity of other aircraft or the edge of controlled airspace.

The flyability of a procedure therefore needs to be considered ahead of making any analysis of route spacing as assumptions can be undermined through poor path adherence.

It is noted that the above points relating to flyability effectively complement the Key Point made in Chapter 2 related to the mistaken tendency by PBN users to inflate the importance of navigation accuracy.

(i) It does not automatically follow that because an aircraft can accurately fix its position, it will navigate with the same accuracy.

(ii) Even if aircraft can navigate accurately, depending on how the procedure is coded, it might not always fly the procedure exactly as intended by the procedure designer.

This is because PBN relies on the use of a navigation database containing routes that are used by the area navigation system (called an RNAV system), on which PBN relies. There is a vast variety of RNAV systems in use, each with their own algorithms. Depending on the complexity of the route, database coders may sometimes have to 'adapt' the coding to suit the aircraft performance in order to ensure that the procedure is flyable and that the procedure will be flown as intended. This is why procedure design practice and flight validation are critical to ensure flyability.

5.11 Fleet capability vs fleet qualification

Certification costs are considerable in Europe as well as elsewhere. Therefore, operators are often reluctant to have capable aircraft certified without a clear indication that there will be a return on investment. In addition, the type of operation can influence whether and when the aircraft are certified as the length of time deemed acceptable for the payback on the investment plays a role. This is linked to the issue above regarding aircraft navigation performance observed through data collection. The argument used is that seeing as the performance is so good – RNAV 1 can be used and RNP 1 is not needed. However, this is a skewed reality in effect because the fleet is clearly an RNP 1 fleet (albeit without RNP certification).

CONSULTATION & FRAGMENTATION

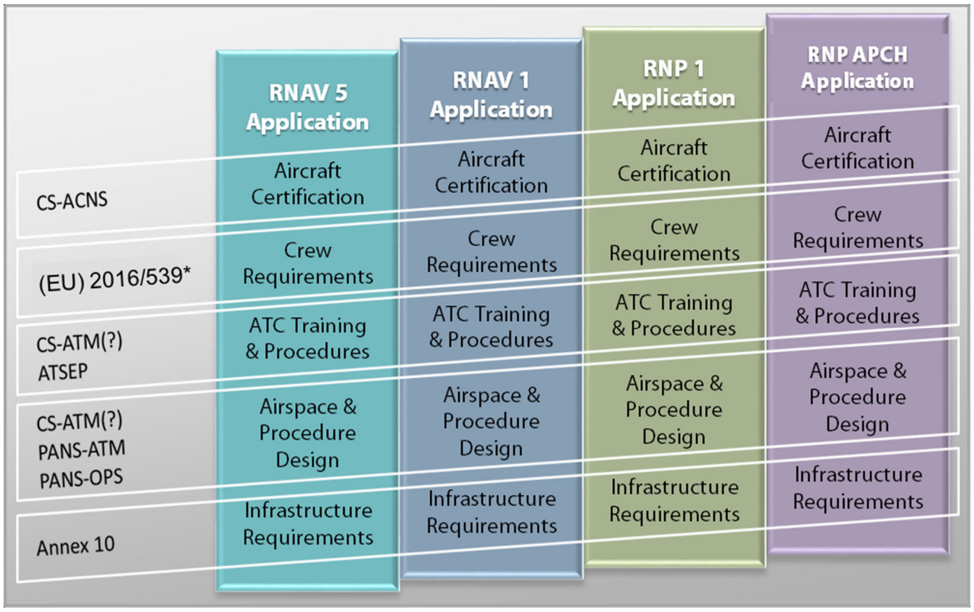
5.12 Environmental consultation

Pressures relating to the need to undertake environmental consultation and satisfy environmental sensitivities often mean that it can take an extensive period of time (sometimes many years) to go through the entire process needed to introduce a new schema of SIDs/STARs. This reality sometimes proves to be a serious challenge to PBN implementation particularly as regards the placement or design of new PBN SIDs/STARs.

A major debate during the last ten years – and still on-going – discusses whether to concentrate tracks or to disperse them as a strategy for noise mitigation. Track concentration tends to limit (actually target) a part of the population to be disturbed by aircraft noise as all aircraft systematically follow the same track. In contrast, track dispersion means that the noise is distributed across all communities, which may result in annoying all airport neighbours. In reality, both of these approaches have their critics, and the success of one or the other appears to depend on local circumstances. Understanding local issues and good communication with the local communities are key to PBN implementation and may alleviate environmental challenges.

5.13 Institutional Complexity

Europe's regulatory landscape has become increasingly complex. Regulation emanating from the European Commission in the form of Implementing Regulations (such as the PBN IR) or EASA's regulatory packages (as indicated on the diagram below) highlights this challenge. Whilst ICAO's PBN Manual has packaged the navigation applications in the vertical view (the entire operation for RNAV 5, for example, being contained in one Navigation Specification), the EASA regulatory framework – and that of other regulatory authorities – develop regulations and qualification documentation horizontally where, for example, certification material is banded together from all navigation specifications. This can make it difficult for implementers to connect all the packages of legislation for the implementation of a particular RNAV or RNP application.



* Only 'special' ops approvals will remain for RNP 0.3 and RNP AR APCH

Figure 13: ICAO norms (vertical), European Regulation (horizontal)

5.14 Summary

Chapter 2 showed that PBN 'guarantees' navigation performance along an ATS route as the aircraft and flight crew have demonstrated their qualification to the required level of navigation performance.

Chapter 3 focused upon the Airspace Concept with its backbone of ATS Routes, SIDs/STARs and Instrument Approach Procedures and the intended operation of systemisation and strategic de-confliction. Its key message is that PBN's point-to-point navigation permits a route network to be systemised and for flight paths to be strategically de-conflicted. Examples in Europe show that the extent to which systemisation is employed is wide spread but the extent to which strategic de-confliction is used seems to vary.

Chapter 4 followed the thread of systemisation and strategic de-confliction – explaining the ICAO collision risk modelling methodology for determining the spacing between routes that are being strategically de-conflicted. The collision risk model is based on assumptions concerning the specific operational environment under consideration, which effectively means that the 'result' does not necessarily have universal application. The question as to how close routes can be spaced was also discussed.

This Chapter has highlighted implementation realities that ANSPs face in Europe: the challenges they face are varied and complex. The following Chapter considers implementation options.

6. IMPLEMENTATION OPTIONS

6.1 INTRODUCTION

Chapter 5 identified implementation realities broadly clustered into four groups. This Chapter seeks to tackle each group as a whole and provide potential ways to progress.

6.2 FINDING SOLUTIONS

RESOLVING SPACING ISSUES

A major issue identified is the non-universal applicability of published route spacing values. **Realistically, there are no short-cuts around differences in operating environments which makes applied spacing values dependent on specific (non-universal) assumptions, thus *always* necessitating an implementation safety assessment.** Accepting that this caveat is clearly understood, the Annexes in this document show spacing values derived in various studies/implementations. The source of each study is also indicated.

Annex 1 provides an overview of the difference between the ICAO and EUROCONTROL CRM Methodology, and then provides sample route spacing configurations determined by EUROCONTROL using the adapted ICAO CRM Methodology with actual navigation performance data collected from three major terminal areas in Europe in 2015.

Annex 2 lists spacing values derived by several ECAC States through implementation safety assessment for their specific environments.

KEY POINTS: There are distinct differences between Annexes 1 and 2.

First, the methodologies used are different: Annex 1 is based on existing ICAO accepted practice and Annex 2 shows actual implementations applied by certain ANSPs/States following a *local implementation safety assessment*. In addition, the UK CAP 1385 shows a new methodology developed in the UK and validated by their CAA.

Second, Annex 1 presents spacing values obtained from a generic collision risk analysis using observed navigaion perfromance obtained through data collection in three major terminal areas in Europe in 2015. The data is location specific and the results have not undergone a specific implementation safety assessment.

Third, Annex 1 provides a generic range of spacing values which provide a starting point for ANSPs' implementation safety assessments which must be undertaken; Annex 2 shows *final values of* implemented spacing distances used in certain states, *after* an implementation safety assessment; UK CAA CAP 1385 provides a specific range of spacing values applicable in the United Kingdom which still need to be subjected to an implementation safety assessment.

THEREFORE, no spacing value shown in this document can be used without a local implementation safety assessment.

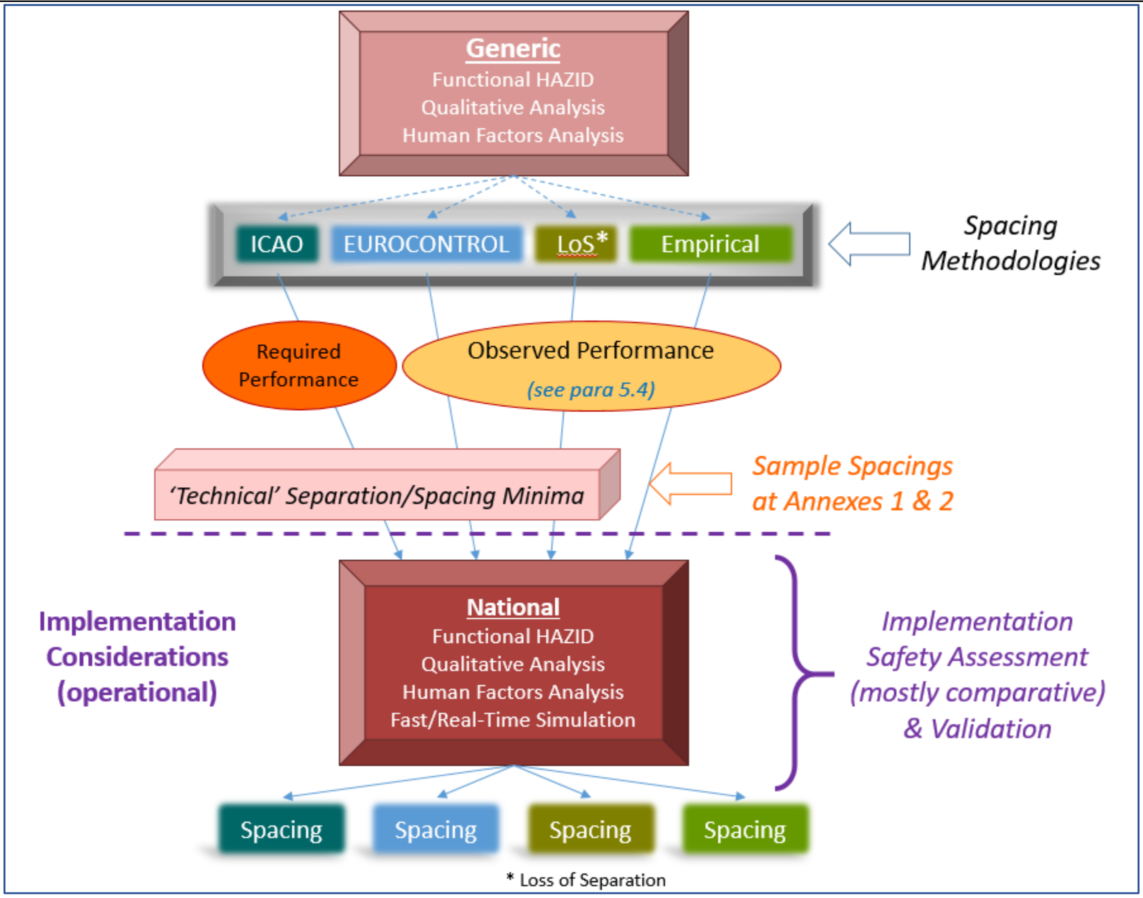


Figure 14: Using this document as a starting point for Implementation Safety Assessment

KEY POINT: The purpose of spacing values for strategic de-confliction is to ensure separation that controllers can work with; these do not suggest that ATC is expected to do nothing.

RESOLVING ISSUES RELATED TO ATC OPERATIONS, AIRSPACE/ENABLERS

Evolution of the Controller: Chapter 5 indicates a changing role for the controller when strategic de-confliction of PBN routes is implemented. With the increased reliance upon GNSS across COM/NAV/SUR, the failure of the critical GNSS positioning source must be managed. There are two potential failure situations that must be considered – one being where a single aircraft loses GNSS positioning due to an on-board avionics failure and with no other positioning capability. The other is where there is a GPS constellation outage affecting a wide area where specific aircraft may no longer be able to navigate as they have lost their only positioning source. In either situation, ANSPs should develop contingency operating scenarios for GPS failures (such as may exist for Low Visibility Procedures, or Radar Maintenance periods), and ensure frequent recurrent training for these situations.

Two scenarios need to be considered in either of these failure situations: first, 'what if' GNSS provides *only* the navigation positioning solution because surveillance is being supported by a cooperative independent capability? Secondly, 'what if' in either of the above situations, GNSS provides both the navigation and surveillance positioning due to the simultaneous use of GPS to support navigation positioning and cooperative *dependent* surveillance with ADS-B. In European high-density areas, most States are retaining cooperative independent surveillance with ADS-B as a secondary or tertiary layer of surveillance, making this single point of failure less probable. In lower density areas, known as non-Radar Areas (NRAs) GNSS may be used for ADS-B surveillance (which could include space-based ADS-B) and RNP operations simultaneously.

Reversion in the event of a GPS outage

Given the advanced functionalities that can be used with an RNP specification and the improved guarantee of navigation performance, it becomes potentially possible to reduce the route spacing with an RNP specification on straight and turning segments. This means that safeguards must be put in place to cater for an aircraft's inability to maintain RNP and one of the causes for this can be the loss of GPS. Of particular significance is a wide-area outage of GPS which could affect a population of aircraft operating in an airspace.

In case of dependent surveillance based on GNSS, it may be possible to revert to procedural control in some low complexity/density environments after loss of GNSS, provided the controllers have been procedurally trained and are not de-skilled.

As regards alternative means of obtaining position, several possibilities exist if GPS were to fail where RNP was deployed across a terminal or extended terminal area.

(i) Reversion to Radar vectoring in some medium to low density Radar environments;

(ii) Reversion to DME/DME positioning with a degradation from RNP to RNAV;

(iii) Reversion to DME/DME positioning maintaining RNP capability.

It is to be noted that (i) to (ii) are usually considered viable options for short-term GPS outages, but that (iii) is considered the only viable option for longer-term outages if the operation is dependent on the RNP capability of the aircraft.

For positioning, DME is an acceptable substitute to GPS. It should be noted that a high percentage of the European fleet is equipped with a DME/DME (D/D) capability, possibly with an integrated inertial system (this is referred to as D/D/I). As such, the loss of GPS does not equate to a total navigation failure on board the aircraft. Indeed, all of the navigation functions except on-board performance monitoring and alerting would continue to be available, i.e. a high percentage of the European fleet does not suddenly get 'reduced' to a state where aircraft are unable to navigate. With the loss of GNSS, minor degradations in the navigation accuracy will occur however. This means that if the area is systemised relying on RNP capability, this might lead to reductions in capacity as spacing might be temporarily increased and/or traffic loads on certain routes/procedures reduced. As a side effect, on-board performance monitoring and alerting in certain aircraft types will be lost when GNSS fails (though all the other functions remain). This means that the pilot will not any longer be alerted when the reliance on the navigation positioning accuracy cannot be guaranteed by the aircraft system. Still this is very different for that part of the fleet that are only GNSS equipped (i.e. without DME/DME and/or inertial): these aircraft would be rendered unable to navigate in the event of a GNSS outage, and they would need to be conventionally managed primarily by radar vectoring.

The probability of a GPS area outage affecting several states or ATCUs is notoriously difficult to estimate and in a recent study undertaken by EUROCONTROL, the probability of an area outage was set to between one event per year to one event every 10-15 years. A consequence of this inability to determine the probability of the outage is the tendency to focus on the severity – and to eradicate the risk completely. This is not necessarily a good approach as it could result in an expensive reversion requirement being put in place in order to manage a rare event.

During 2013-2014, SESAR tackled this question in the context of the NAVAID Infrastructure requirements for RNP using the route spacing figures determined for Advanced RNP and with conditions. A first step was a theoretical study which identified that the loss of GPS did not compromise safety (as long as certain safeguards were put in place) using a 7NM spacing in en route airspace and 5 NM in terminal airspace with the full suite of Advanced RNP functionalities available. This result was largely confirmed by a real time simulation held in Budapest in the summer of 2014 that identified certain additional safety requirements to manage the risk of closer route spacing

What the study suggests is that the advanced functionalities contributed to the feasibility of the reversion scenario if only the navigation accuracy was slightly degraded and on-board performance monitoring and alerting is lost.

Use of dependent surveillance

All of EUROCONTROL's route spacing studies have assumed the availability of cooperative independent surveillance i.e. radar. This is to ensure that the means of surveillance remains fully independent from the navigation positioning source. In recent years, there has been an increasing interest to deploy ADS-B surveillance, which relies upon GPS for aircraft position determination – upon which RNP specifications also rely. What this development means is that a single potential point of failure (GPS) exists. This means that the mitigation provided by independent (radar) surveillance has to be re-considered as a co-dependence on GPS has been created through the use of ADS. The impact of using ADS as the surveillance source could translate into route spacing distances greater than those with independent surveillance. Furthermore, although Wide Area Multilateration (WAM) is considered another form of independent surveillance, consideration must be given to its timing source; if it is using GPS time then the loss of the signal could equally impact this surveillance technique.

As such, the probability of area outage (e.g. of GPS) needs to be established and the implementation safety case's HAZID and mitigation strategies need to fully account for this weakness being introduced into a system with the use of dependent surveillance.

Impact of Mixed Mode

There are several ways of minimising the mixed mode effect in *medium* to *high* density airspace:

(i) Lower the navigation specification required for flight on all ATS routes/SIDs/STARs so that all airspace users can achieve it (RNAV 5 is an excellent example). This 'lowest common denominator' approach effectively removes mixed mode. There are downsides to this approach:
   a. High-end carriers are frustrated by the lack of use of their equipment (after considerable investment costs made by them).
   b. Low-end navigation specifications seldom return the sort of performance required to achieve benefits in medium to high density airspace.
   c. Opportunities to rationalisation the NAVAID infrastructure are reduced.

(ii) Another way is to dictate time periods during which mixed mode operations are acceptable (such periods would be when there is a low traffic density).

Activities 10 & 11 of the *European Airspace Concept Handbook for PBN Implementation, Ed 4*, provides examples of mixed mode 'models' in use. In many cases, the downfall of the mixed mode operations stems from ATC flight plan issues in the flight – or radar data processor *or* human factor elements whereby reaching a certain workload controllers 'revert' to simpler instructions i.e. radar vectoring.

Meeting the challenge of multi-disciplinary cooperation

Issues related to a multi-disciplinary approach can be resolved with a multi-disciplinary view of operations and, for PBN implementation purposes, a multi-disciplinary team acting in concert. This need is stressed in the Planning phase of the *European Airspace Concept Handbook for PBN Implementation, Handbook 1.* Inasmuch as an airspace change cannot be undertaken in isolation without the input of a multi-disciplinary team, it is the same for PBN implementation, with its many issues.

RESOLVING CONSULTATION ISSUES

EUROCONTROL's Environmental Unit has developed a Collaborative Environmental Management processes that provides a solid starting point for environmental consultation. That said, environmental pressure remains a clear political blocking point in the deployment of PBN.

From an ATM/CNS perspective, one clear mitigation is to ensure that a multi-disciplinary approach is used for the implementation of PBN. This means ensuring that environmental managers and consultation points of contact usually affiliated to Airport Operators, are inside the PBN deployment process from the outset. This need is stressed in the Planning phase of the *European Airspace Concept Handbook for PBN Implementation, Handbook 1.*

A PACKAGED SOLUTION: EUROPEAN PBN IMPLEMENTATION SUPPORT

Mindful of the implementation issues and of stakeholder needs, EUROCONTROL in a full partnership approach is developing a PBN website to support PBN implementation. The objective of the PBN Portal is to facilitate PBN implementation particularly to ensure regulatory compliance in Europe. Significantly, the intended approach is the provision of a 'Toolkit' developed in partnership with stakeholders through, and in full concert with, existing institutional arrangements such as the SESAR Deployment Manager, the Network Manager, ICAO and EUROCONTROL stakeholders. Duplication is to be avoided (it is one of the main objectives of the PBN Portal), with the expectation that pooled knowledge/resources will facilitate PBN and particularly RNP implementation in ECAC given the shortage of resources and accompanying PBN expertise in all domains. In short, the PBN Portal aims to facilitate sharing knowledge and will allow States, ANSPs and other PBN stakeholders to benefit from lessons learned.

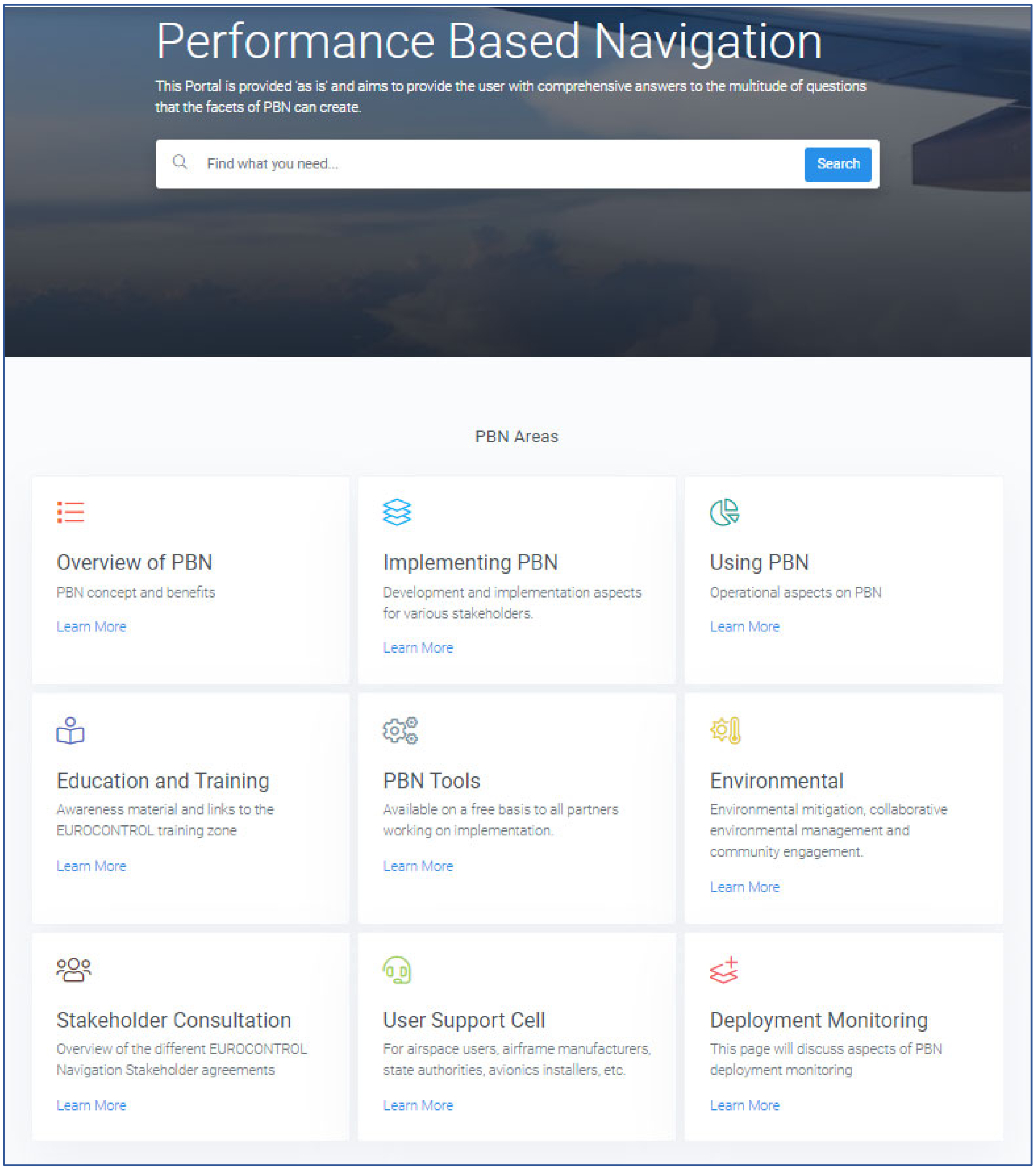


Figure 15: EUROCONTROL's PBN Portal

https://pbnportal.eu/epbn/home/home.html

6.3 SUMMARY

There are considerable challenges facing PBN implementation, not the least of which is the complexity of ensuring partnership participation in the overall implementation initiative. As Communication, Navigation and Surveillance evolve and the role of the controller adapts with new concepts and technologies, the partnership approach that is key to PBN's success, will become all the more important.

7. CONCLUDING REMARKS

This document has provided some examples of the different levels of systemisation / strategic de-confliction in European States and the corresponding safety assessment methods. With the objective to improve the efficiency of air traffic operations whilst maintaining safety, a framework has been provided centred around Performance-based Navigation (PBN), the airspace concept, the spacing between proximate flight procedures, and implementation realities in Europe.

An outline of Performance-based Navigation (PBN) has been provided in which it was emphasised that PBN provides a level of guarantee of an aircraft's ability to navigate along an ATS route provided that the aircraft and flight crew have demonstrated their qualification to the required level of navigation performance.

Linked to the Airspace Concept and the intended operations, a key conclusion is that PBN's point-to-point navigation permits a route network to be systemised and flight paths to be strategically de-conflicted. It has also been concluded that examples in Europe show that the extent to which systemisation is employed is wide spread, but the extent to which strategic de-confliction is used seems to vary.

An introduction to the ICAO/EUROCONTROL collision risk modelling methodology for determining the spacing between strategically de-conflicted routes was provided. New, up-to-date navigation performance data, collected from three major Terminal Areas in Europe in 2015, has been included in the CRM. This new performance data has dramatically affected the spacing results. It has also indicated that with the smaller route spacing distances provided by the CRM, the effect of human performance (affected for example by radar display resolution) is becoming increasingly important in the determination of route spacing. The collision risk model is based on assumptions concerning the specific operational environment and is fed by location-dependent data. Therefore, the 'result' does not necessarily have universal application. Generally, the use of generic or conservative assumptions will lead to generic or conservative spacing values. However, the more specific the assumptions used in the model, the more specific the calculated spacing values are expected to be.

Finally, a number of realities challenging the implementation of PBN, airspace systemisation, flight path de-confliction, and minimum route spacing in Europe have been examined, leading to the conclusion that the challenges faced by ANSPs in Europe, are varied and complex.

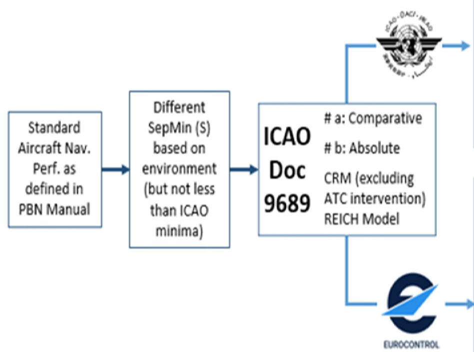
The document concludes with a set of Annexes, which provide examples of various route spacing methodologies including input from the United Kingdom and, to a lesser degree, other countries.

Annex 1 Parts A, B & C

Tables

Figures

ANNEX 1, PART A – COMPARISON OF ICAO/ EUROCONTROL CRM



PROCEDURAL ONLY

Criteria	PBN Specification	Spacing Oceanic (Lateral/Longitudinal)
Required Performance + Assumptions re tails of distribution	RNP 10/4	With ADS-C 50NM/50NM
	RNP 4	With ADS-C and CPDLC 23NM/30NM
	MNPS	60NM/150NM
		Spacing Terminal Lateral on Adjacent IFPs
V. small data collection (Terminal)	RNAV 1/RNP 1/RNP APCH	7NM
	RNP 1/RNP APCH	5NM with RF

C R M

***RADAR** ENVIRONMENT: Radar SepMin – 5NM (ENR); 3NM (TERM)*

Criteria	PBN Specification	Route Spacing (1998 to 2016)	
Observed Performance + Data Collection re tails	RNAV 5 (B-RNAV) ENR	16.5NM - Same direction 18NM - Bi direction	Comparative
		10-15NM	ATC Intervention
	RNAV 1 (P-RNAV) ENR	9 – 10NM	CRM (confirmed by RTS)
	RNAV 1 (P-RNAV) TERM	7 – 8NM	CRM (confirmed by RTS)
	RNP 1 RNAV ENR	7NM	CRM (confirmed by RTS)
1982-84 'Gold Standard' Data Set En Route	A-RNP 1 ENR	7NM	CRM (confirmed by RTS)
	A-RNP 1 TERM	7NM	CRM (RTS = 5NM)
	A-RNP 0.5 TERM	6 – 7NM	CRM

Tails modelled using 1) + 2) + 3):

1) 1982-1984 'Gold Standard' updated by expert judgement from Boeing/Airbus;
2) Use of very small traffic sample from SASP;
3) ATC intervention using data from earlier simulations. Note, these intervention rates used to script in the deviation rates to the RNP simulations (which included RAM + CLAM)

Annex 1 Part C shows the EUROCONTROL route configurations and spacings determined in 2016 using up-to-date performance data

EUROCONTROL ROUTE SPACING STUDIES (1998-2016): HIGH LEVEL VIEW OF SALIENT CHARACTERISTICS

- *Radar environment = Independent surveillance (Radar not ADS-B to avoid common mode failure)*
- *Radar surveillance = as per EUROCONTROL Surveillance Standard*
- *Spacing (S) cannot be equal to Radar SepMin because for adjacent aircraft at the same level, a deviation immediately results in a loss of separation. If S = Radar SepMin, there may even be conflict without deviation*
- *Estimates conservative (worst case) to cater for possibility of individual ANSPs not undertaking local implementation safety assessments.*
- *As per ICAO Doc 9689, Target Level of Safety (TLS) pre 2000 = 1 x 10^{-8} fatal accidents / flight hour (fa/fh) and post 2000 = 5 x 10^{-9} fa/fh.*
- *In the European case, Radar SepMin assumed in EUROCONTROL studies to be 5NM in ENR and 3NM in Terminal (though values can be different)*

Remarks:

1. *If generic safety assessment (CRM except for B-RNAV) returns S significantly larger than Radar SepMin, possible to reduce S with ATC intervention using Radar: This was the case for B-RNAV (ATC intervention studies) and Advanced RNP in TMA (demonstrated in two RTS run in Budapest)*
2. *If CRM returns S close to Radar SepMin, need to ensure that ATC intervention does not increase the risk if aircraft deviates. Even a small deviation can cause the controller to intervene to avoid the risk of being at fault (violation of separation) while the situation is 'statistically stable'. The nature of ATC intervention (to correct the aircraft deviating) should not increase the risk, so does not challenge S as long as the workload is acceptable. Space is needed for detection, time for the controller to react, correction by the controller, instruction to the pilot and pilot reaction.*
3. *RTS in 2005 (Malmo) RNP 1 RNAV for OR 3 A/B and two RTS in 2008/2010 (Budapest) A-RNP 1NM both demonstrated that controller perception affected by screen resolution (a function of sector size), radar update rate, aircraft symbol & label size. It is not so much the screen resolution but rather the scale combined with the size of the symbols' positions (if ATC must separate the positions at the centre of the symbols). The Malmo simulation also identified a requirement to configure the geometry of the routes (in three dimensions) so as not to invoke nuisance TCAS alerts on crossing tracks. (In this case, TCAS accommodation and controller 'perception' required vertical separation to be increased to 2000'at the crossing point and the angle distended between crossing tracks to be limited). In the initial Budapest simulation, controllers attempted to reduce the en route spacing of parallel routes, but then requested that a spacing of 7NM be retained for ENR to ensure the 5NM Radar SepMin would not be infringed, however 6NM at the TMA boundary was deemed acceptable (see 2). 5NM was demonstrated in the TMA.*

ANNEX 1, PART B – OVERVIEW OF THE EUROCONTROL 2015/16 NAVIGATION PERFORMANCE DATA COLLECTION FOR 2016 ROUTE SPACING CRM

Background

Various route spacing studies have been conducted by EUROCONTROL prior to 2015/16. An overview of the route spacings which resulted from these studies is given in Table 1.

Table 1 : Overview of past Route Spacing Studies and resulting route spacings

Spacing between Parallel Routes	How spacing demonstrated	Airspace Applicable	Extra distance needed on turns	Nav Spec	Additional conditions (DOC ref)
16.5 NM	Comparative Analysis	En route between straight tracks only; same direction	YES	B-RNAV	As per generic safety assessment
18 NM	Comparative Analysis	En Route between straight tracks only; opposite direction	YES	B-RNAV	As per generic safety assessment
10 to 15 NM	ATC Intervention Studies	n/a	YES	B-RNAV	As per generic safety assessment
8-9 NM	CRM	En route between straight tracks only; same direction	YES	P-RNAV	As per generic safety assessment
7 NM (London-Paris)	CRM	En route between straight tracks only; same direction	YES	P-RNAV	As per generic safety assessment
7-8 NM	CRM	Terminal between straight tracks only; same direction	YES	P-RNAV	As per generic safety assessment
7 NM	CRM + 2 RTS	En route	NO	Advanced RNP (1 NM TSE)	As per generic safety assessment and RTS report
7 NM	CRM	Terminal	NO	Advanced RNP (1 NM TSE)	As per generic safety assessment
5 NM	2 x RTS	Terminal	NO	Advanced RNP (1 NM TSE)	As per generic safety assessment and RTS report
6 -7 NM	CRM	Terminal	NO	Advanced RNP (0.5 NM TSE)	As per generic safety assessment

One characteristic of these studies is that they used historical navigation performance data to determine the lateral overlap probabilities. A well-known reference for this historical data is the *EUROCONTROL report 216, "Navigational Accuracy of Aircraft Equipped with Advanced Navigation Systems – Final Report", June 1988*. Until the beginning of 2015, nearly all EUROCONTROL Route Spacing CRM studies were based on data from this report. Some studies, especially the Advanced RNP route spacing studies were complemented by real-time simulations during which the proposed route spacings were operationally evaluated and validated by controllers. Already it was found that besides the results obtained from Collision Risk Modelling, operational constraints such as controller workload and Radar display resolution were important factors to take into account in the determination of route spacings.

Another problem with these past studies is the nature as well as the age of the data used from the EUROCONTROL report 216. This data was collected before 1988 in Karlsruhe and Maastricht upper airspace, excluding any terminal area. Most of the aircraft types and equipment from which the navigation performance was measured are no longer in operation as of 2016 (e.g. Tristar, DC10, Airbus 310) and date from a pre-GNSS era. RNAV systems were exclusively based on automatic DME-DME updating of inertial sensors. An example of the navigation performance documented in the EUROCONTROL report 216 and used in previous CRM route spacing studies, is a lateral Total System Error (TSE) along a straight segment of a route of less than 0.85 NM with 95% probability and a TSE less than 1.4 NM with 99% probability. For the reasons mentioned above, it was decided that for the new collision risk modelling presented in this handbook, new navigation performance data was needed.

New navigation data collection

The new navigation performance data collection was started in 2014 and provided to EUROCONTROL by 3 major European ANSPS: LVNL (Amsterdam Schiphol airport), NATS (London Heathrow airport) and DSNA (Paris Charles de Gaulle airport). Table 2 provides an overview of the procedures at the three airports for which data was collected, as well as the duration over which the data was collected.

Table 2 : Overview of procedures

	SID			STAR	Approach Transitions
DSNA (Jan-Dec 2014)	ATREX_AD	ERIXU_3GK	NURMO_AD	BIBAX_MOPAR2W	VEDUS_LORNI3E
	ATREX_BE	ERIXU_3HL	NURMO_GK	TINIL_OKIPA2W	KEPER (BANOX)
	ATREX_GK	ERIXU_4GK	OKASI_BE		KEPER (NERKI)
	BUBLI_AD	ERIXU_4HL	OKASI_HL		LUKIP_MOPAR
	BUBLI_BE	ERIXU_AD	OPALE_AD		TINIL_OKIPA2E (OKIPA)
	BUBLI_GK	ERIXU_BE	OPALE_BE		TINIL_OKIPA2E (OKIPA)
	BUBLI_HL	LATRA_AD	OPALE_GK		TINIL_OKIPA2N
	LANVI_AD	LATRA_BE	OPALE_HL		MOPIL_LORNI2E
	LANVI_BE	LATRA_GK	PILUL_3AD		
	LANVI_GK	LATRA_HL	PILUL_3BE		
	LANVI_HL	LGL_BE	RANUX_AD		
		LGL_HL	RANUX_GK		
LVNL (April-Sept 2014)	ANDIK 2E/1S			DENUT 1A	ARTIP 2A/2C/3B
	ARNEM 3E/2S/1V/1Z			EELDE 1A	RIVER 2A/3B
	BERGI 2E/1S/1Z/3V			HELEN 1A	SUGOL 2A/3B
	LEKKO 2E/1S/1Z/2V			LAMSO 1A	
	LOPIK 2E/1S/1Z/2V			MOLIX 2A	
	LUNIX 1E/1S/1V/1Z			NORKU 2A	
				REDFA 1A	
				REKKEN 2A	
				TOPPA 2A	
NATS (Jan-March 2014)	DOKEN 1A				
	DOKEN 1B				
	DOKEN 1C				
	DOKEN 1D				

To analyse the data, a tool was developed by EUROCONTROL navigation experts, in which the data can be loaded, visualised and processed. The recorded data is compared with the reference procedure which is coded in the tool. A screenshot of the tool is provided in Figure 1.

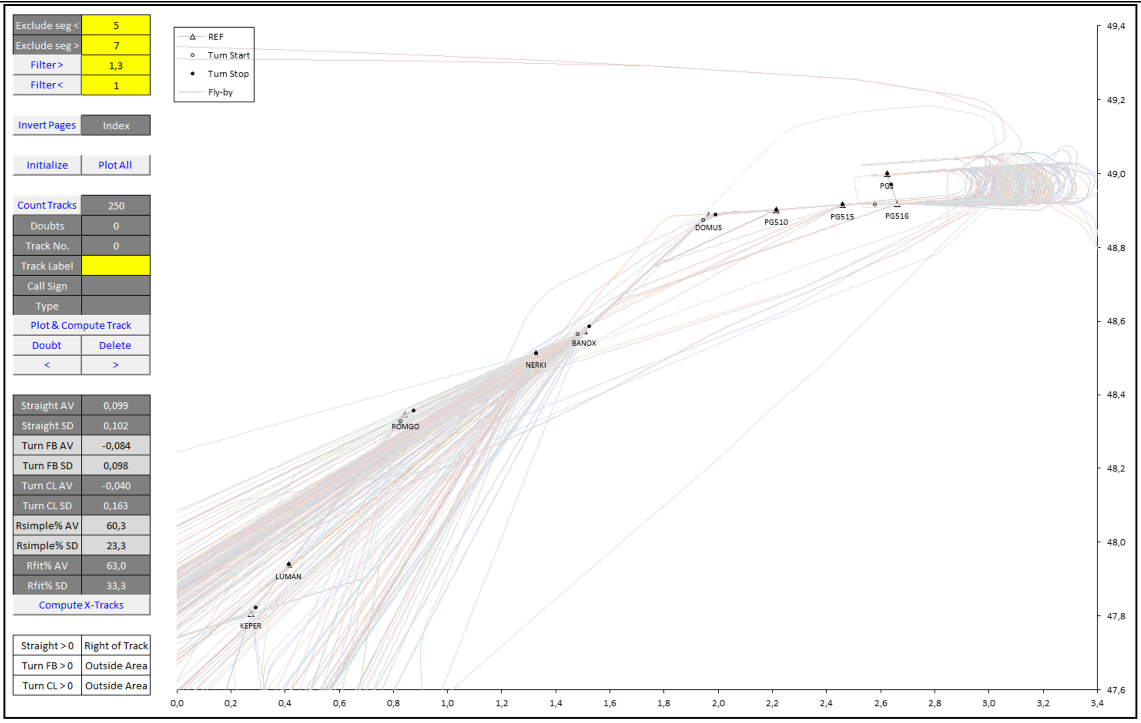


Figure 1 : EUROCONTROL navigation performance data analysis tool

Data Filtering

As the received data contained all the tracks recorded in the specified time period (including the tracks which deviated from the planned route due to ATC intervention), the data had to be filtered. A three-step process was created for the data filtering:

- **Step 1**: selection of the start and end segments of the reference route; this was done by visually determining route segments for which route adherence was generally acceptable. For example in Figure 1, this was the route segment from BANOX to PG510.
- **Step 2**: automatic filtering of all excessive deviations from the reference route between the defined start and end segments. Excessive deviations were defined as deviations for which the cross-track error from the reference route exceeded a certain threshold.
- **Step 3**: Visual inspection of each remaining track, one by one.

Figure 2 provides an example containing the same tracks as those in Figure 1 after they were processed by the automatic filter. The start and end points of the reference route were BANOX and PG510. The threshold for excessive deviations in the automatic filter was set to 1.3NM. Out of 250 tracks in Figure 1, 218 tracks remain in Figure 2. The 32 deleted tracks were all tracks that obviously were radar vectored to one of the waypoints after BANOX or to a right-hand downwind pattern. One remaining track which passed the automatic filtering but which was removed after visual inspection during Step 3, is indicated in red in Figure 2. The reason why it was removed was that although it was close to the route centreline of the reference procedure, the track had a typical shape which suggested radar vectoring.

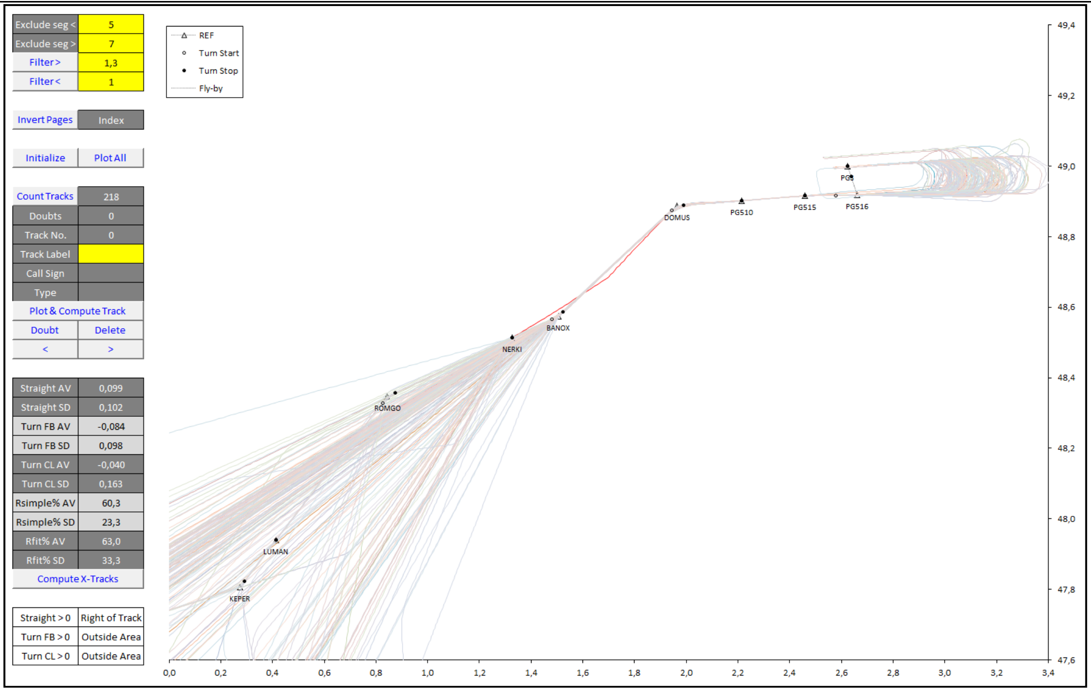


Figure 2 : Remaining tracks in data analysis tool after Step 1 and 2 of the filtering process

Figure 3 provides another example of a procedure (different to the procedure shown in Figure 2) whereby the displayed aircraft tracks obviously deviates from the route centreline. However in this case, the track was not removed from the dataset because the nature of the deviation is not clear. Probably the deviation was not due to radar vectoring.

In summary, due to lack of availability of ATC audio recordings in combination with the huge volume of data, the data was filtered using a process involving automatic filtering and a subjective visual inspection of each track. The quality of this filtering process was assessed and this is explained in the next paragraph.

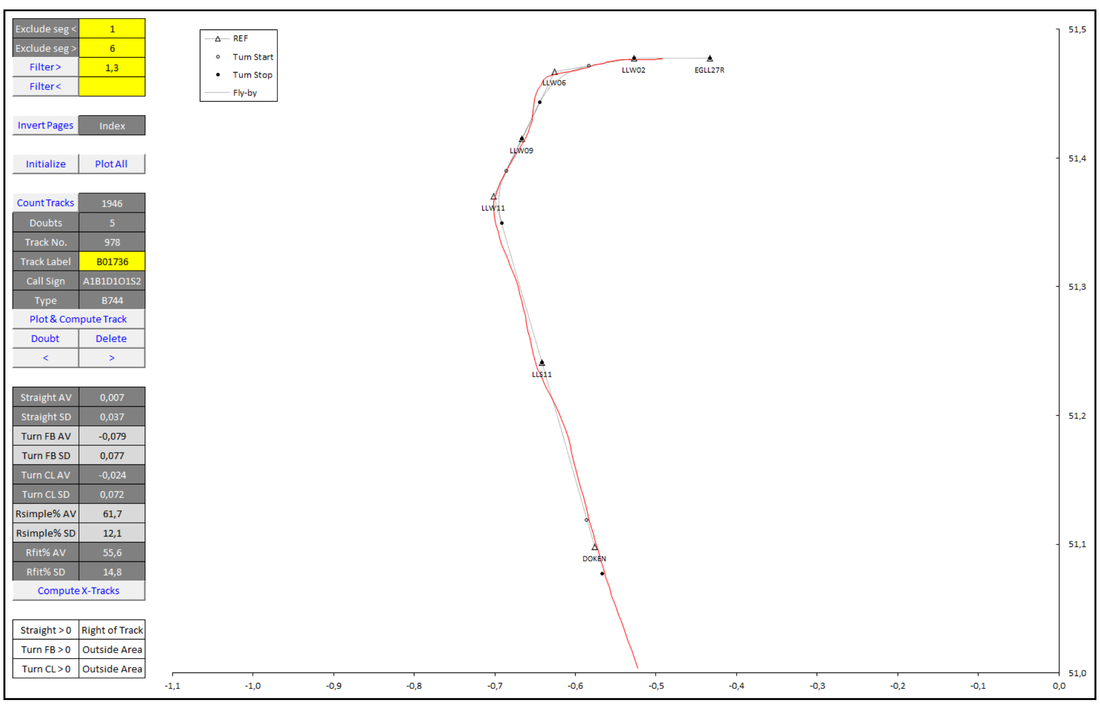


Figure 3 : Example of a track deviating from route centreline

Validation of the data filtering

As explained in the previous paragraph the process of data filtering to remove the tracks with tactical interventions, was based on automatic filtering and intensive visual inspection of the tracks. This is because of the high volume of collected data and the workload and time associated with analysing ATC audio recordings, had they have been made available by the ANSPs. However, for one subset of the collected data, audio recordings were analysed by the data provider. This was the case for the NATS data. For this subset of data, the results of the data filtering using ATC audio recordings was compared with results of the filtering method applied by EUROCONTROL, using different thresholds for the automatic filter and with or without visual inspection as a final step. After each filtering process, the cross-track deviations of the remaining tracks from the reference trajectory were computed. Figure 4 shows the 1-cumulative distribution of these cross-track deviations for each filtering method. Note that the 1-cumulative distribution gives the probability of occurrence of a cross-track deviation greater than a certain value in the dataset. The five distributions in Figure 4 were obtained using the following filtering techniques:

- automatic filter using a 0.5NM threshold without visual inspection of each track
- automatic filter using a 1NM threshold without visual inspection of each track
- automatic filter using a 1.5NM threshold without visual inspection of each track
- filtering based on the NATS ATC audio recordings
- automatic filter using a 1NM threshold and visual inspection of each track

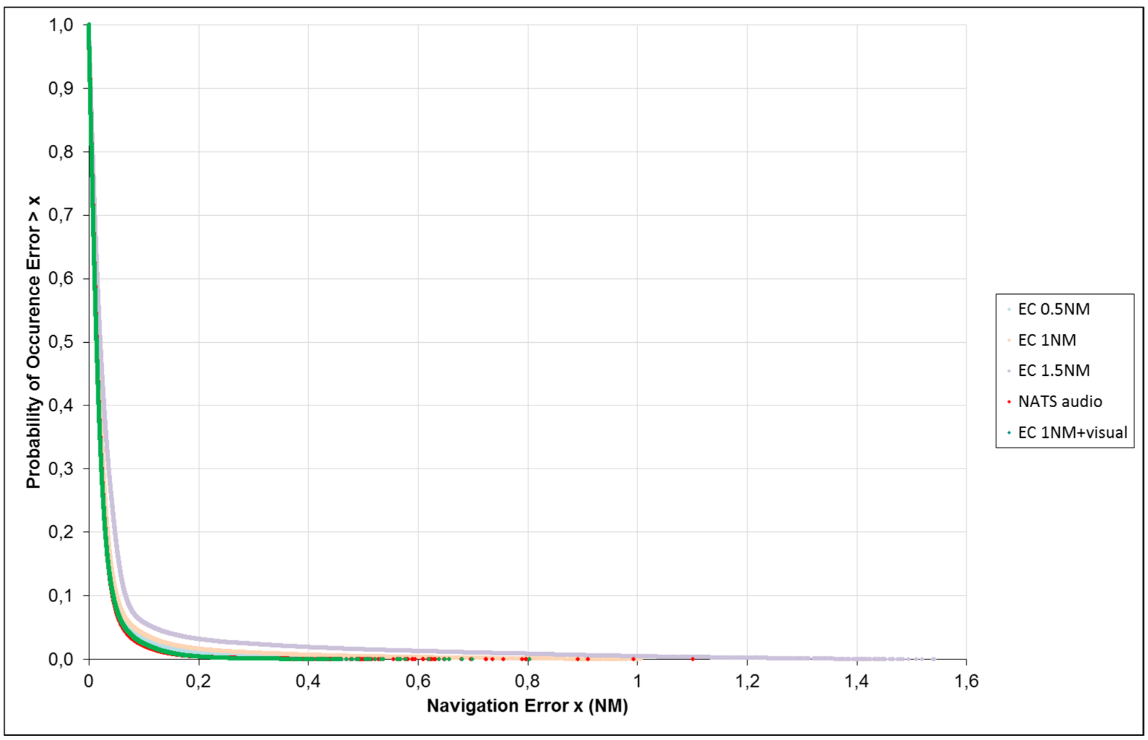


***Figure 4** : 1-cumulative cross-track error distributions of NATS data after different methods of filtering*

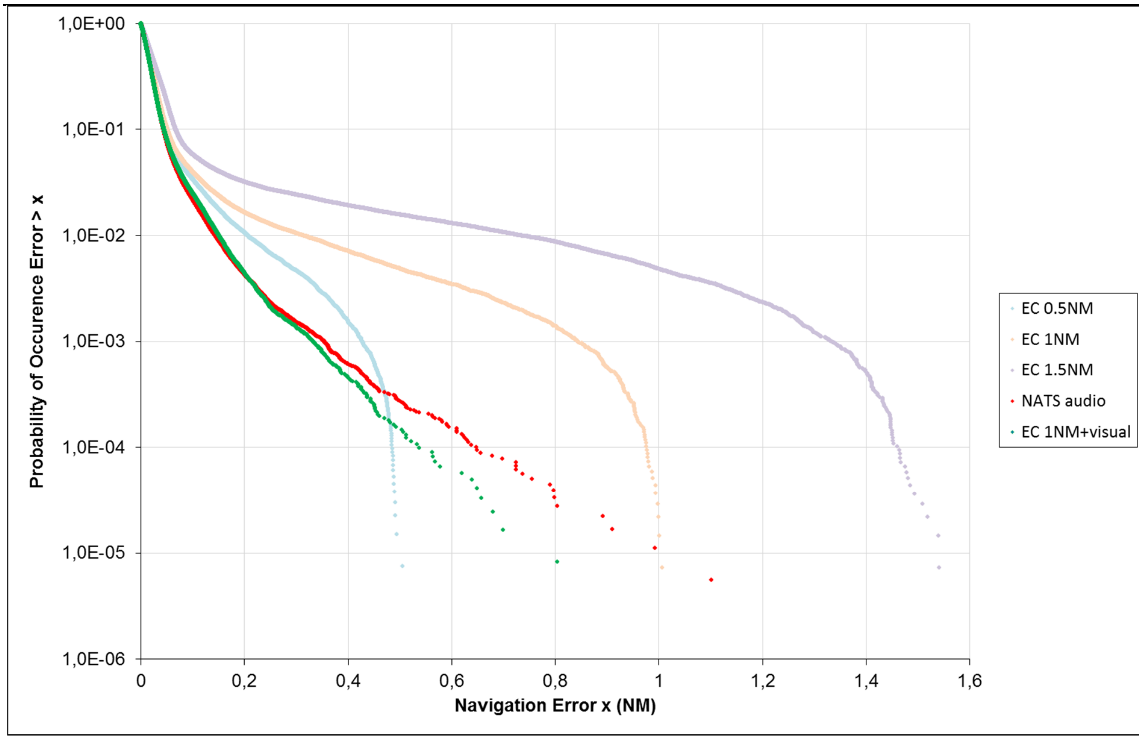


Figure 5 : 1-cumulative cross-track error distributions of NATS data after different methods of filtering (logarithmic scale)

Figure 5 provides the same results as Figure 4 except that a logarithmic scale is used in Figure 5 for the probability of occurrence. The shape of the distributions after solely automatic filtering looks typically different from the shapes of the distributions after filtering based on audio recordings or using the automatic process aided by visual inspection of each track. Therefore it was concluded that using only an automatic filter with fixed threshold is not satisfactory. The combination of automatic filtering + visual inspection however generates a distribution with a shape that looks like the shape of the distribution filtered using the audio recordings, which can be seen by the green and red curves in Figure 5. The difference in probability of occurrence between the green and red curves in Figure 5 for a high cross-track deviation of 0.8NM is as follows: $8.2*10^{-6}$ for the EUROCONTROL filter using 1NM automatic threshold + visual inspection, versus $2.8*10^{-5}$ for the filter based on audio recordings used by NATS. This is a ratio of 2.8/0.82 = 3.4. It was concluded that the filtering method using the automatic filter with visual inspection was the best method in the absence of ATC audio recordings. It can be expected that the filtering method provides distributions that could be slightly on the optimistic side though, which can be explained by the fact that a visual inspection method is likely to delete a few tracks which did not contain ATC interventions. It can also be seen in Figure 5 that a 1NM threshold for the automatic filter yielded a distribution which was missing the highest cross-track deviation of 1.1NM as observed in the distribution filtered using the ATC audio recordings. Therefore it was decided to put the threshold for automatic filtering of the tracks to 1.3NM either side of the reference route centreline. It was expected that this would provide the best compromise between filtering efficiency and accuracy.

Computation of cross-track deviations

For the computation of cross-track deviations and turn radii, the remaining tracks in the datasets after filtering were subdivided in two categories: straight segments and turns segments. The start and end points of each turn segment were set equal to the start and end points of the fly-by transition area defined in *RTCA DO-236C / EUROCAE ED-75D - Minimum Aviation System Performance Standards (MASPS) - Required Navigation Performance for Area Navigation*. The start and end point of the fly-by transition area are defined in this document by the maximum allowed turn radius, as follows:

$$Max\ Radius = \frac{(Groundspeed)^2}{g \cdot \tan(Bank\ Angle)}$$

With g = 9.81 m/s^2 and Groundspeed and Bank Angle depending on altitude.

For low-altitude transitions:

- Groundspeed = 500kts
- Bank Angle = Minimum of half the track change and 23°

For high-altitude transitions:

- Groundspeed = 750kts
- Bank Angle = 5°

In addition, the initiation of a turn should be limited to a 20NM distance from the turn waypoint.

Most aircraft execute the turn using a radius which is smaller than the maximum allowed turn radius. Theoretically this is allowed as long as their trajectory during the fly-by turn remains within the fly-by transition area, bounded by the inbound and outbound tracks and the maximum allowed turn radius as defined in the MASPS. To assess the actual navigation performance during the turn, the actual turn radius was computed for each track at each turn waypoint in the dataset. Two methods were used for the computation of the actual turn radius:

- **Simple method**: this consisted in determining the point in the trajectory where the aircraft track was the inbound track + ¼ of the track change and the point where the aircraft track was the inbound track + ¾ of track change. With L the distance between these two points and θ the track change, the turn radius could then be estimated using the following formula:

$$Radius = \frac{L}{2\sin\left(\frac{\theta}{4}\right)}$$

- **"Kasa" circle fitting method**: a circle fitting method was used as described by *I. Kasa, "A circle fitting procedure and its error analysis", IEEE Transactions on Instrumentation and Measurement, March 1976*. This method also required a conversion of the WGS-84 coordinates to a stereographic projection with the turn waypoint as origin.

Comparison of the two methods described above yielded that the simple method provided results which were satisfactory and accurate enough with less outliers than the "Kasa" method. Therefore, all further analysis was performed using the turn radius obtained by the simple method. After calculating the actual turn radius for all the tracks at a certain waypoint, an average turn radius was calculated for this waypoint and the turn segment was further subdivided into three subcategories:

- **Pre-turn**: the segment between the start point of the fly-by transition boundary and the start point of the arc defined by the average turn radius
- **Mid-turn**: the segment between the start and end points of the arc defined by the average turn radius
- **Post-turn**: the segment between the end point of the arc defined by the average turn radius and the end point of the fly-by transition boundary

Figure 6 illustrates an example of tracks abeam a turn waypoint "KOLIV". The reference route centreline, the fly-by transition boundary with start and end points and the arc defined by the average turn radius including start and end points are indicated. Most of the tracks in Figure 6 are well within the fly-by transition area and so is the arc defined by the average radius. A couple of tracks undershoot or overshoot the fly-by transition area.

For the computation of cross-track deviations in the three turn segment subcategories described above, the distance from the actual track was measured perpendicular to the original route centreline in the pre- and post-turn areas and perpendicular to the arc defined by the average radius in the mid-turn area. This was done for all data points in the turn segment while along straight segments, cross-track deviations were computed for data points separated by at least 1NM and by maximum 2NM.

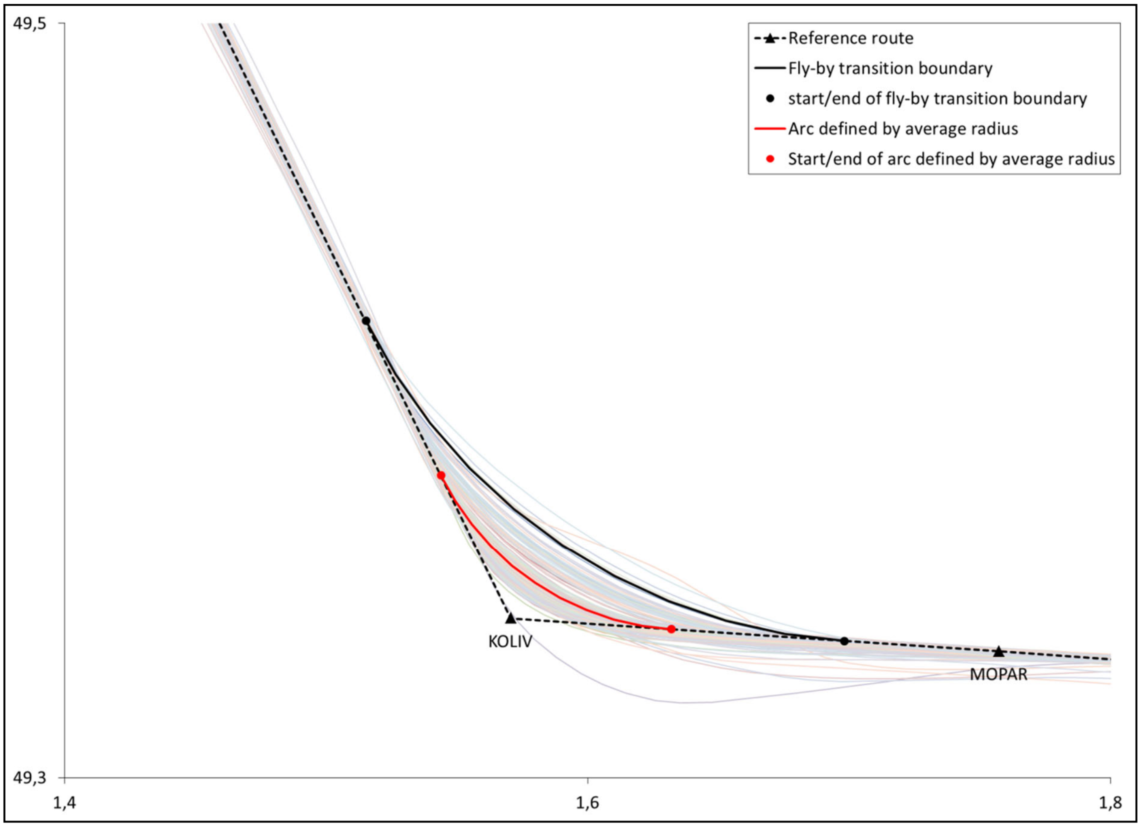


Figure 6 : Example of tracks in a turn with indication of the fly-by transition boundary and the arc defined by the average radius

Database size and fleet composition

Table 3 lists the total number of tracks which were received from each ANSP as well as the number of tracks which were retained after filtering of the data.

Table 3 : Number of tracks before and after filtering

Source	No. of Tracks	No. of Tracks After Filtering	% Retained
NATS	12605	7237	57%
LVNL	131262	15333	12%
DSNA	434829	65529	15%
TOTAL	**578696**	**88099**	**15%**

Table 4 provides an overview of the aircraft types contained in the overall dataset after filtering, with associated number of tracks and data points for each aircraft type. Note that these aircraft types represent the actual fleet anno 2014 which was operating at EHAM, EGLL and LFPG. Note that operations at EHAM require RNAV 1 approval since end 2012. The navigation specification for RNAV 1 requires GNSS or DME-DME sensors as an input to the navigation system.

Table 4 : Fleet composition with number of tracks and number of data points after filtering

AC Type	No. of Tracks	No. of Points
A320	15165	655173
A319	11614	516836
A321	6320	281809
B738	5761	272047
B77W	5243	208151
E190	4767	204262
A318	4521	195749
A332	4069	175083
B772	4139	163832
E170	3036	131478
A388	2253	88048
A343	1923	82767
B744	1818	78346
B763	2322	77861
RJ85	1618	69905
B737	1685	65852
A333	1451	58339
B752	1270	41308
F70	973	38385
B77L	857	35794
B733	689	27814
A346	823	27217
B739	576	24831
B788	605	22416
B735	442	19926
AT72	550	19908
E145	583	17433
A306	344	15687
CRJ9	243	12553
MD11	333	11180
CRJ7	209	9555
B734	189	8265
DH8D	146	6247
F100	117	5992
B748	115	5503
RJ1H	76	5038
SB20	117	5032
AT43	185	4882
B764	196	4877
B736	112	4369
A310	128	4255
B712	71	2577
A342	49	2329
B753	41	2229
B773	40	1882
B463	50	1217

AC Type	No. of Tracks	No. of Points
CRJ2	21	1133
B462	22	959
C56X	20	897
B762	17	850
H25B	16	722
MD83	17	678
A345	17	603
E120	20	473
C25A	10	421
GLF4	9	369
CL30	7	322
F2TH	10	291
MD87	6	265
CRJX	5	241
F900	7	222
E135	4	218
CL60	6	215
FA7X	3	213
C510	4	197
F50	4	183
GLF5	5	152
GLEX	3	142
IL96	3	103
B742	2	102
MD82	2	94
B74S	1	93
E195	1	87
E55P	2	76
C550	3	74
E50P	1	70
D328	2	69
LJ60	1	67
LJ40	1	65
GL5T	1	56
P180	2	54
GALX	1	42
TBM8	1	41
C25C	1	39
LJ35	1	36
CRJ1	1	36
SW4	1	24
B350	1	23
SF34	1	23
G280	1	23
C750	1	22
TOTAL	**88099**	**3725324**

Influence of Navigation Sensors

A mixture of navigation sensors can be expected to be installed on the aircraft in the overall dataset, including inertial systems with GPS and/or DME/DME updating. However, as the LVNL data sample contained call signs, it was possible to make a link with the EUROCONTROL PRISME and Network Management database and determine for which flights in the LVNL dataset, the availability of GNSS was indicated in the flight plan. In Table 5, the aircraft types which operated to EHAM and which did not have a GNSS capability indicated in the flight plan are listed, together with the number of tracks which were flown without GNSS and the total number of tracks (flown with or without GNSS) for each aircraft type. According to this analysis, in total 11% of the tracks in the LVNL dataset were flown with aircraft types which did not have GNSS indicated in the flight plan. The majority of these aircraft types are Fokker 70 and (probably older versions of) Airbus A320. Note that Table 5 is the result of an analysis which was done using filed flight plan information. As is commonly known, this information is not entirely error-free and therefore small errors can be present in the data in Table 5. For example, the appearance of Embraer E190 and E170 aircraft in Table IV can be questioned as it is very unlikely that these aircraft do not have GNSS.

Table 5 : Number of tracks without GNNS in LVNL dataset (according to flight plan data)

AC Type	No. of Tracks without GNSS	Total No. of Tracks	Tracks without GNSS / GRAND TOTAL
F70	967	973	6,3%
A320	396	1310	2,6%
F100	95	96	0,6%
B763	95	357	0,6%
B735	41	135	0,3%
B733	27	116	0,2%
B734	23	24	0,2%
B752	21	87	0,1%
A306	17	42	0,1%
E170	9	36	0,1%
E190	8	1912	0,1%
B772	3	519	0,0%
RJ85	2	43	0,0%
A310	1	13	0,0%
B762	1	1	0,0%
B773	1	24	0,0%
All other types	0	9645	0,0%
GRAND TOTAL	**1707**	**15333**	**11,1%**

Figure 7 provides a histogram of computed cross-track deviations in the LVNL data sample for straight segments (green) and mid turns (orange), for the procedures flown by aircraft equipped with GNSS. The vertical axis displays the frequency of occurrence of a certain cross-track deviation indicated on the horizontal axis. Figure 8 provides the same information but only for those procedures in the LVNL dataset which were flown by aircraft not equipped with GNSS. Obviously the histogram for the procedures flown without GNSS is slightly wider with a lower peak at the center. The standard deviations are 0.056NM (straight segments) and 0.089NM (turns) respectively for the cross-track deviations caused by aircraft with GNSS, while they are 0.074NM (straight segments) and 0.140NM (turns) respectively for the cross-track deviations caused by aircraft without GNSS.

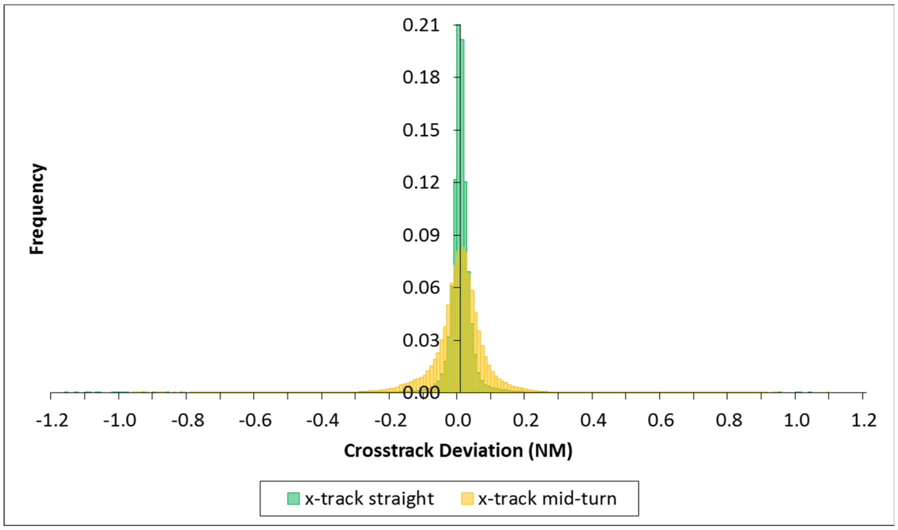


Figure 7 : Histogram of cross-track deviations in LVNL data sample for straight segments (green) and mid turns (orange) for aircraft with GNSS

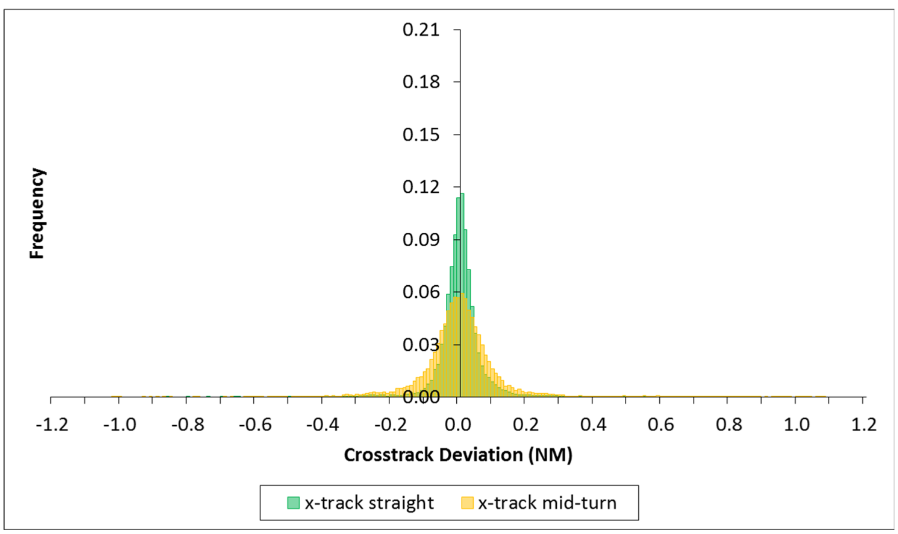


Figure 8 : Histogram of cross-track deviations in LVNL data sample for straight segments (green) and mid turns (orange), for aircraft without GNSS

Navigation performance distributions

For the computation of the of the sample route spacings using the Collision Risk Model as provided in this document, the data was split into the following 5 categories:

- **Combined LVNL-NATS-DSNA distribution, straight segments, high groundspeed (>350kts)**
- **Combined LVNL-NATS-DSNA distribution, straight segments, low groundspeed (<=350kts)**
- **Combined LVNL-NATS-DSNA distribution, turns with 30-60° track change, high groundspeed (>350kts)**

- **Combined LVNL-NATS-DSNA distribution, turns with 30-60° track change, low groundspeed (<=350kts)**
- **Combined LVNL-NATS-DSNA distribution, turns with 90° track change, low groundspeed (<=300kts)**

Figures 9 through 13 illustrate the histograms and the 1-cumulative distributions for the 5 categories of navigation performance distributions listed above. Note that the 1-cumulative distribution gives the probability of occurrence of a cross-track deviation greater than a certain value in the dataset.

Finally, Table 6 provides an overview of the most common statistical parameters of each of the 5 distributions, such as the sample size, average, standard deviation, minimum and maximum values. Note that in Table 6, the absolute value of the minimum or maximum values of the cross-track deviations in the dataset are in some cases slightly higher than 1.3NM, which was the threshold used in the automatic filter when processing the data. The reason for this is that the average value of the original cross-track deviations at each individual measurement point was sometimes not equal to zero, which indicates that there was in some cases a small bias in the data. There could be serval reasons for this bias, one of them being the fact that the data originates from radar measurements. For distributions where there was a bias in the data, the bias was removed so that the average value of the cross-track deviations at each individual measurement point was zero.

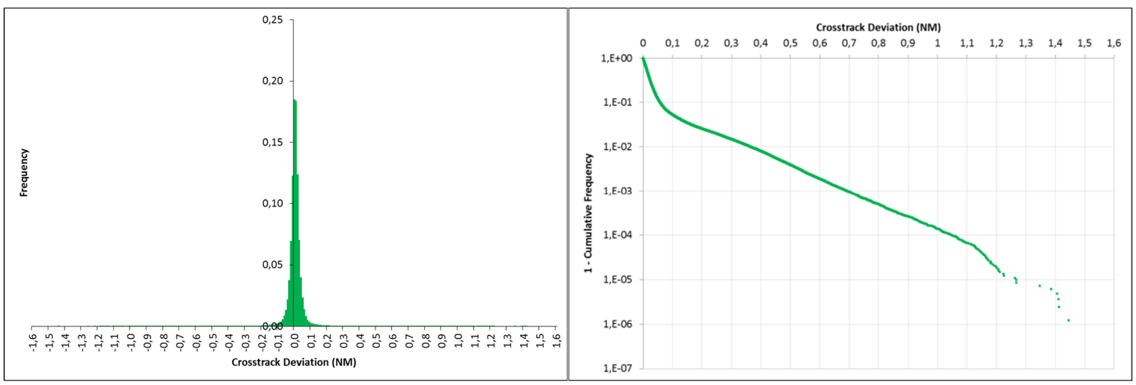


Figure 9 : Combined LVNL NATS DSNA distribution – Straight Segments – High Groundspeed (>350kts)

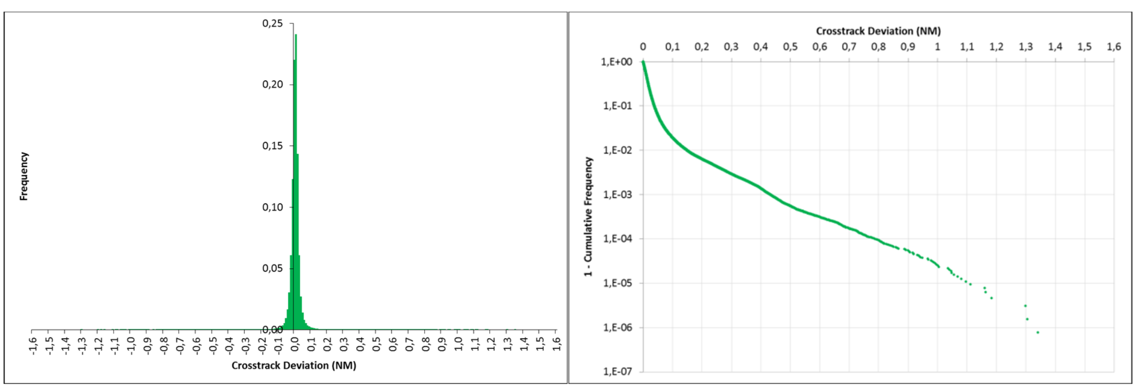


Figure 10 : Combined LVNL NATS DSNA distribution – Straight Segments – Low Groundspeed (<=350kts)

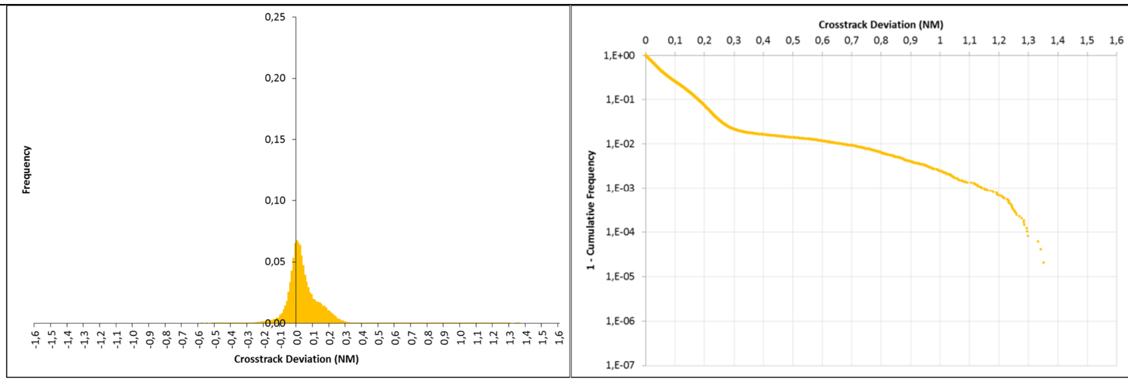


Figure 11 : Combined LVNL NATS DSNA distribution – Mid Turn 30-60° Track Change – High Groundspeed (>350kts)

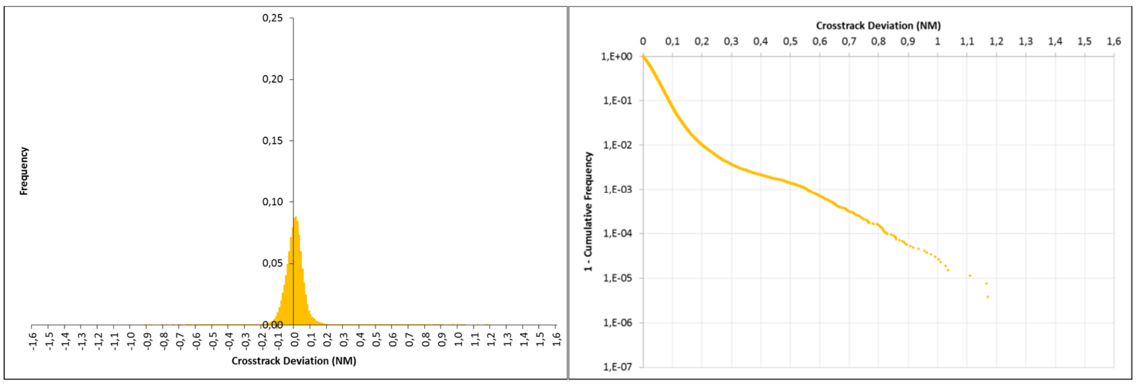


Figure 12 : Combined LVNL NATS DSNA distribution – Mid Turn 30-60° Track Change – Low Groundspeed (<=350kts)

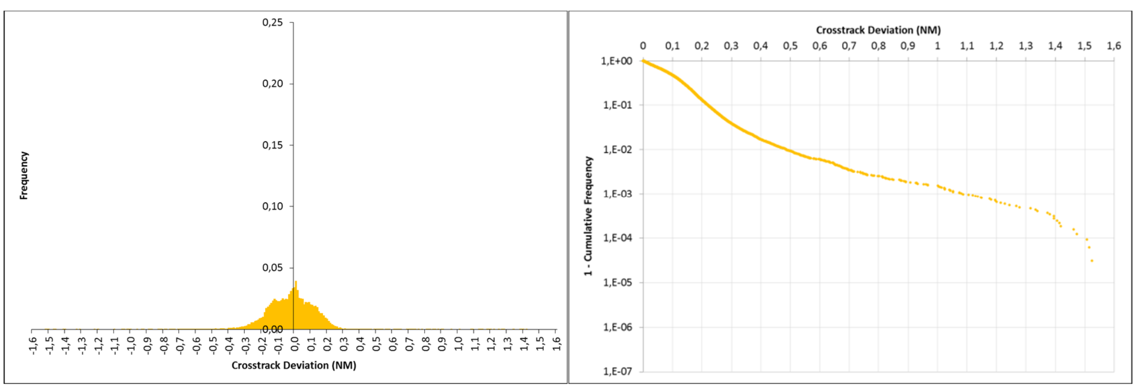


Figure 13 : Combined LVNL NATS DSNA distribution – Mid Turn 90° Track Change – Low Groundspeed (<300kts)

Table 6 : Distribution Parameters

	No. of data points	Cross-track deviations (NM)			
		Average	StdDev	Min	Max
Straight Segments High GS (>350kts)	825264	0,00	0,07	-1,45	1,41
Straight Segments Low GS (<=350kts)	1297549	0,00	0,04	-1,31	1,34
Mid Turn 30-60° High GS (>350kts)	48672	0,04	0,13	-0,59	1,35
Mid Turn 30-60° Low GS (<=350kts)	267099	0,00	0,06	-0,92	1,17
SID Mid Turn 90° Low GS (<300kts)	32579	-0,03	0,15	-1,53	1,42

Collision Risk Modelling

A conventional parallel route Collision Risk Model was used for the computations of route spacings and associated risks for the sample route spacing configurations presented in this document. A detailed report of the Collision Risk Modelling is given by *Dr. G. Moek, "Update to Deliverable D3 – Determination of Horizontal Overlap Probability, Lateral Collision Risk and Identification of Appropriate Spacing Minima", September 2016*. The basic principle is summarised below and the equation used in the Collision Risk Model is as follows:

$$N_{ay} = P_{ATC}(S_y)P_{xz}P_y(S_y)\left[\frac{V_x}{2\lambda_x} + \frac{V_y}{2\lambda_y} + \frac{V_z}{2\lambda_z}\right]$$

The meaning of the various parameters in this equation is explained in Table 7, while the quantities of the parameters used in the sample route spacing configurations are provided in Table 8.

Table 7 : Definition of parameters in Collision Risk Model

Quantity	Description
N_{ay}	Expected number of fatal accidents per flight hour due to the loss of lateral separation on parallel routes in radar airspace
$P_{ATC}(S_y)$	Probability of ATC intervention failure as a function of the spacing S_y between parallel routes in radar airspace
P_{xz}	Probability of joint longitudinal and vertical overlap for aircraft on parallel routes in radar airspace
$P_y(S_y)$	Probability of lateral overlap for aircraft on parallel routes due to loss of lateral separation resulting from lateral navigation performance of PBN aircraft and flight crew
V_x	Average value of the absolute relative longitudinal speed between two aircraft (possibly subdivided into same- and opposite-direction traffic)
V_y	Average value of the absolute relative lateral speed between two aircraft
V_z	Average value of the absolute relative vertical speed between two aircraft
λ_x	Average aircraft length
λ_y	Average aircraft width
λ_z	Average aircraft height

Table 8 : Collision risk model parameter values

Parameter	Value	
	En-route airspace	**Terminal airspace**
$P_y(S_y)$	See Dr G. Moek, *"Update to Deliverable D3 – Determination of Horizontal Overlap Probability, Lateral Collision Risk and Identification of Appropriate Spacing Minima", September 2016*	
$P_{ATC}(S_y)$		
Flow rate (ac per flight level per hour)	15	30
P_x	1.477 x 10^{-3}	3.940 x 10^{-3}
P_z	0.367	0.076
P_{xz}	5.419 x 10^{-4}	2.995 x 10^{-4}
$V_x(opp)$: V_x (opposite direction)	900 kts	440 kts
$V_x(same)$: V_x (same direction)	35 kts	26 kts
V_y	43 kts	32 kts
V_z	1.5 kts	1.5 kts
λ_x	0.022 NM	0.022 NM
λ_y	0.020 NM	0.020 NM
λ_z	0.0063 NM	0.0063 NM

The lateral overlap probability $P_y(S_y)$ was determined for each sample route spacing configuration based on the convolution of two functions which were used to model the 1-cumulative distributions presented in Figures 9 to 13. The mathematical models which were fitted to the 1-cumlative distributions were either a Gaussian-Double Exponential (GDE), or a Double-Double Exponential (DDE) model. Figure 14 provides an example of a Double-Double Exponential (DDE) function used to fit the combined LVNL NATS DSNA distribution – Straight Segments – High Groundspeed (>350kts).

The ATC intervention failure probability $P_{ATC}(S_y)$ is given by *Dr G. Moek, "Update to Deliverable D3 – Determination of Horizontal Overlap Probability, Lateral Collision Risk and Identification of Appropriate Spacing Minima", September 2016*. Note that The ATC intervention failure probability $P_{ATC}(S_y)$ is given as a function of the route spacing S_y for both en-route and terminal airspace.

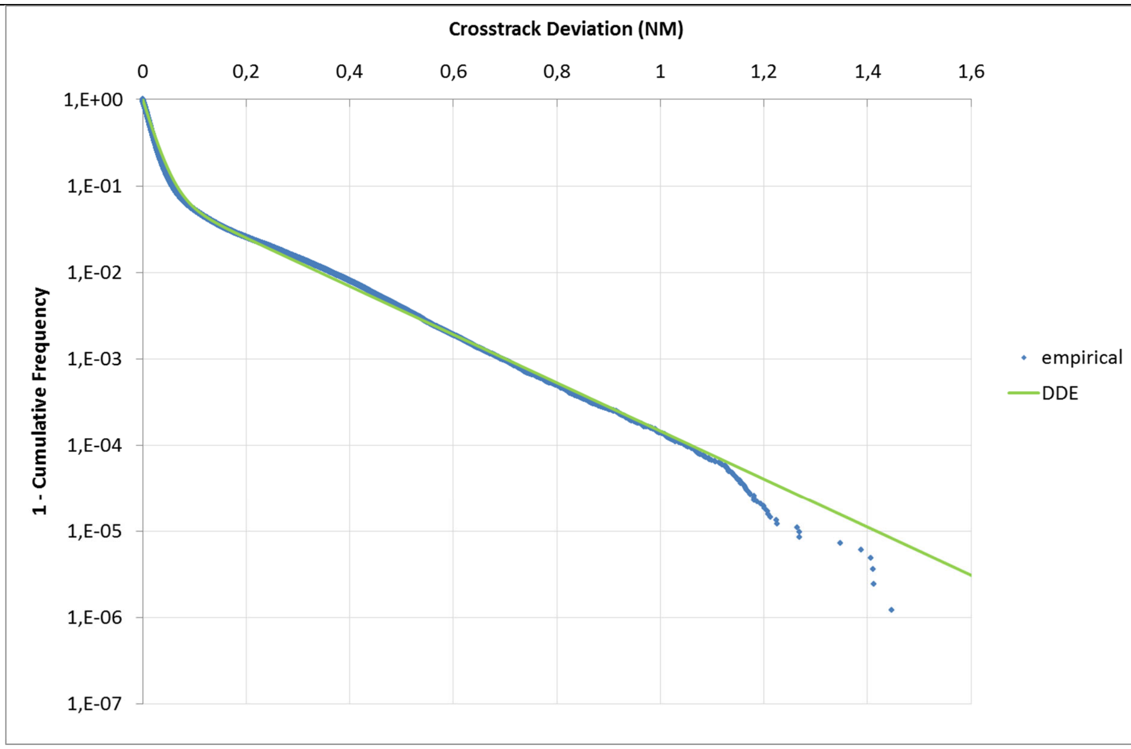


Figure 14 : Example of a Double-Double Exponential (DDE) function used to fit the combined LVNL NATS DSNA distribution – Straight Segments – High Groundspeed (>350kts)

ANNEX 1, PART C – EUROCONTROL ROUTE CONFIGURATIONS & SPACING

The table below provides examples of specific route configurations which were evaluated using the Collision Risk Model (CRM). The Navigation Performance distributions used in the CRM were based on the data collected by 3 major ANSPs: LVNL, NATS and DSNA and analysed by EUROCONTROL. The distributions used, as well as the assumed Target Level of Safety are indicated above each route configuration. The table lists the computed risk (indicated as $N_{ay\text{-}best}$ for the best estimate) for a given route spacing and assumed average groundspeed (indicated as GS) in a specific route configuration. The route spacings used in the CRM were chosen such that they are not below the Radar Separation Minima (assumed to be 3NM in the extended TMA) and such that they provide a risk which is below the Target Level of Safety.

Lateral collision risk for the converging route configurations has been calculated by means of the conventional parallel route CRM. The probability of lateral overlap has been calculated by means of the straight-segment lateral deviation distribution for the aircraft on the straight route and an appropriate distribution for the converging aircraft as follows:

- For a converging aircraft making a fixed radius turn, the straight segment deviation distribution was used. This was based on the assumption that navigation performance during a fixed radius turn will approximate the performance along a straight track, according to studies conducted in the past (by e.g. EUROCONTROL, MITRE, to70).
- For a converging aircraft making a fly-by turn, the mid-turn lateral distribution for the pertinent turn angle was used.

Route configurations 17 and 18 are crossing tracks. In Route configuration 17, the arriving aircraft crosses above the departing aircraft. The parameters d_A and d_D presented in the table are the distances after the crossing point at which respectively the arriving aircraft can continue its descent and the departing aircraft can continue its climb. The risk of collision at the closest location to the crossing point of d_A and d_D is indicated as CR_{max}. Route configuration 18 is similar except that the departing aircraft crosses above the arriving aircraft. In this configuration d_A and d_D are the distances before the crossing point at which respectively the arriving aircraft must be at or below its cleared level and the departing aircraft must be at or above its cleared level. Both configurations 17 and 18 assume 1000ft vertical separation. The results are given for various crossing angles.

Numerous Real-Time Simulations undertaken over ten years for RNAV 1, RNP 1 and Advanced RNP as well as practical implementations following an implementation safety case, have indicated that operationally, achievable route spacings are greater than the Radar Separation Minima and appear to follow the pattern:

Route spacing = applicable Radar Separation Minima + buffer (between 1 and 2 NM).

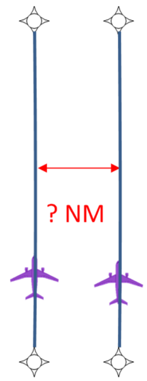
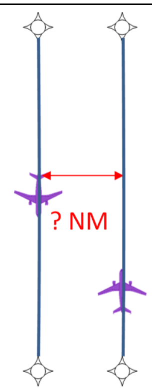
For example, when the Radar Separation Minima is 3 NM, route spacings of 4-5 NM have been achieved. Similarly, when the Radar Separation Minima is 5 NM, route spacings of 6-7 NM have been achieved.

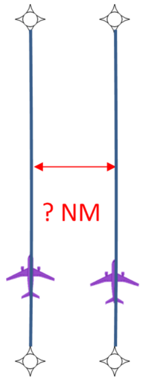
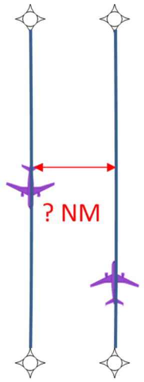
Therefore when reading the table, attention is drawn to the three key points located in the main body of the document, repeated here for emphasis:

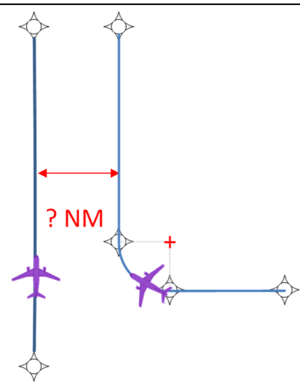
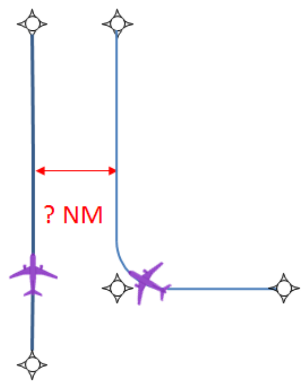
KEY POINT 1: A limitation of using Radar Surveillance as a mitigation of risk is that the spacing between two routes cannot be the same or less than the Radar Separation Minima (thus if the Radar Separation Minima is 3 NM, the spacing between routes cannot be 3NM or less). This is because a lateral deviation could instantly cause a separation infringement. As such, allowing for sufficient time for the controller to detect and correct a deviation and for the pilot to respond correctly has tended to convert into **at least a minimum of 4-5 NM route spacing in an environment using 3NM Radar separation minima.**

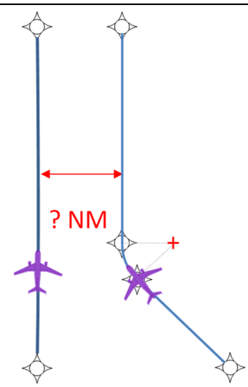
<u>KEY POINT 2</u>: Any published table showing route spacing values determined by particular studies must be seen in this light. No published spacing results for continental application (or study supporting these results) can be considered universal norms. Results are valid only for the assumptions and data used, the particular operating environment and airspace and operational concept envisaged. One key assumption is that aircraft being separated on closely spaced routes are within the same ATC sector. It is also stressed that route spacing values supported by extensive data, statistical analysis, mathematical modelling and airspace design do not ensure that the aircraft will adhere to the route to ensure that the route spacing is maintained. Essential to successful flight operations are proper procedure design, the correct coding of procedures in the aircraft databases and validation of the procedure to check **flyability**.

<u>KEY POINT 3</u>: **the resolution of the Radar display** (a function of ATC sector size) has very clearly become a determining human factor which forms part of the post-CRM implementation safety analysis to determine the acceptable (final) route spacing. To be included in these considerations are items such as label size and algorithm affecting label orientation both of which affect the potential for label overlap, as well as the aircraft 'target' size and so forth.

<table>
<tr><th>Route Configuration</th><th>Description</th><th colspan="2">Sample route spacings and risks based on the Collision Risk Model</th></tr>
<tr><td rowspan="2">1.
Parallel Tracks</td><td rowspan="2">
Same Direction
Both AC in Level Flight</td><td colspan="2">Combined LVNL, NATS, and DSNA straight-segment data
Applicable TLS: 4×10^{-9} fatal accidents per flight hour (f.a.f.h.)</td></tr>
<tr><td><u>GS 450kts</u>
Spacing used in CRM: 3 NM
(see Key Points 1, 2 and 3)
$N_{ay-best} = 3.69 \times 10^{-11}$ (f.a.f.h.)</td><td><u>GS 220kts</u>
Spacing used in CRM: 3 NM
(see Key Points 1, 2 and 3)
$N_{ay-best} = 1.07 \times 10^{-11}$ (f.a.f.h.)</td></tr>
<tr><td rowspan="2">2.
Parallel Tracks</td><td rowspan="2">
Opposite Direction Both AC in Level Flight</td><td colspan="2">Combined LVNL, NATS, and DSNA straight-segment data
Applicable TLS: 4×10^{-9} fatal accidents per flight hour (f.a.f.h.)</td></tr>
<tr><td><u>GS 450kts</u>
Spacing used in CRM: 3 NM
(see Key Points 1, 2 and 3)
$N_{ay-best} = 4.02 \times 10^{-10}$ (f.a.f.h.)</td><td><u>GS 220kts</u>
Spacing used in: 3 NM
(see Key Points 1, 2 and 3)
$N_{ay-best} = 7.76 \times 10^{-11}$ (f.a.f.h.)</td></tr>
</table>

<table>
<tr><td rowspan="2">3.
Parallel Tracks</td><td rowspan="2">
Same Direction
One aircraft climbing or descending</td><td colspan="2">Combined LVNL, NATS, and DSNA straight-segment data
Applicable TLS: 4×10^{-9} fatal accidents per flight hour (f.a.f.h.)</td></tr>
<tr><td><u>GS 450kts</u>
Spacing used in CRM: 3 NM
(see Key Points 1, 2 and 3)
$N_{ay-best} = 7.65 \times 10^{-12}$ (f.a.f.h.)</td><td><u>GS 220kts</u>
Spacing used in CRM: 3 NM
(see Key Points 1, 2 and 3)
$N_{ay-best} = 2.22 \times 10^{-12}$ (f.a.f.h.)</td></tr>
<tr><td rowspan="2">4.
Parallel Tracks</td><td rowspan="2">
Opposite Direction
One aircraft climbing or descending</td><td colspan="2">Combined LVNL, NATS, and DSNA straight-segment data
Applicable TLS: 4×10^{-9} fatal accidents per flight hour (f.a.f.h.)</td></tr>
<tr><td><u>GS 450kts</u>
Spacing used in CRM: 3 NM
(see Key Points 1, 2 and 3)
$N_{ay-best} = 8.33 \times 10^{-11}$ (f.a.f.h.)</td><td><u>GS 220kts</u>
Spacing used in CRM: 3 NM
(see Key Points 1, 2 and 3)
$N_{ay-best} = 1.61 \times 10^{-11}$ (f.a.f.h.)</td></tr>
</table>

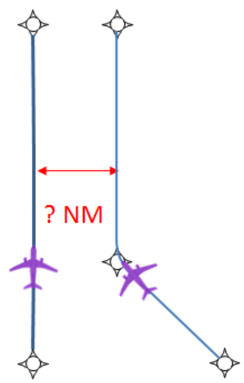
5. Converging Tracks	 Joining a parallel path with a 90° RF/FRT turn. Both AC in Level Flight	Combined LVNL, NATS, and DSNA straight-segment data Applicable TLS: 4×10^{-9} fatal accidents per flight hour (f.a.f.h.) GS 220kts **Spacing used in CRM: 3 NM** **(see Key Points 1, 2 and 3)** $N_{ay-best} = 1.07 \times 10^{-11}$ (f.a.f.h.)
6. Converging Tracks	 Joining a parallel path with a 90° fly-by turn. Both AC in Level Flight	Combined LVNL, NATS, and DSNA straight segment and SID 90 degree turn angle data Applicable TLS: 4×10^{-9} fatal accidents per flight hour (f.a.f.h.) GS 220kts **Spacing used in CRM: 5 NM** **(see Key Points 1, 2 and 3)** $N_{ay-best} = 3.78 \times 10^{-10}$ (f.a.f.h.)

<table>
<tr><td rowspan="2">7.
Converging Tracks</td><td rowspan="2">
Joining a parallel path with a 45° RF/FRT turn.
Both AC in Level Flight</td><td colspan="2">Combined LVNL, NATS, and DSNA straight-segment data
Applicable TLS: 4×10^{-9} fatal accidents per flight hour (f.a.f.h.)</td></tr>
<tr><td>GS 450kts

Spacing used in CRM: 3 NM
(see Key Points 1, 2 and 3)

$N_{ay-best} = 3.69 \times 10^{-11}$ (f.a.f.h.)</td><td>GS 220kts

Spacing used in CRM: 3 NM
(see Key Points 1, 2 and 3)

$N_{ay-best} = 1.07 \times 10^{-11}$ (f.a.f.h.)</td></tr>
<tr><td rowspan="2">8.
Converging Tracks</td><td rowspan="2">
Joining a parallel path with a 45° fly-by turn.
Both AC in Level Flight</td><td colspan="2">Combined LVNL, NATS, and DSNA straight segment and 30 – 60 degree turn data
Applicable TLS: 4×10^{-9} fatal accidents per flight hour (f.a.f.h.)</td></tr>
<tr><td>GS 450kts

Spacing used in CRM: 4 NM
(see Key Points 1, 2 and 3)

$N_{ay-best} = 2.34 \times 10^{-10}$ (f.a.f.h.)</td><td>GS 220kts

Spacing used in CRM: 4 NM
(see Key Points 1, 2 and 3)

$N_{ay-best} = 6.68 \times 10^{-11}$ (f.a.f.h.)</td></tr>
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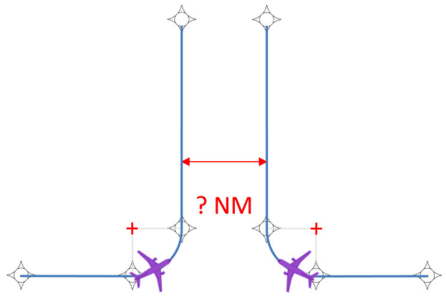
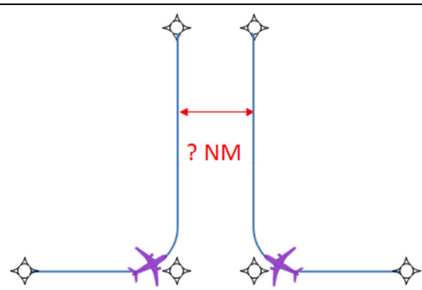
9. Converging Tracks	 Both aircraft at same level and in same direction with 90° RF/FRT turns	Combined LVNL, NATS, and DSNA straight segment data Applicable TLS: 4×10^{-9} fatal accidents per flight hour (f.a.f.h.) <u>GS 220kts</u> **Spacing used in CRM: 3 NM** **(see Key Points 1, 2 and 3)** $N_{ay-best} = 1.07 \times 10^{-11}$ (f.a.f.h.)
10. Converging Tracks	 Both aircraft at same level and in same direction with 90° fly-by turns	Combined LVNL, NATS, and DSNA SID 90 degree turn angle data Applicable TLS: 4×10^{-9} fatal accidents per flight hour (f.a.f.h.) <u>GS 220kts</u> **Spacing used in CRM: 5 NM** **(see Key Points 1, 2 and 3)** $N_{ay-best} = 8.37 \times 10^{-10}$ (f.a.f.h.)

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<tr>
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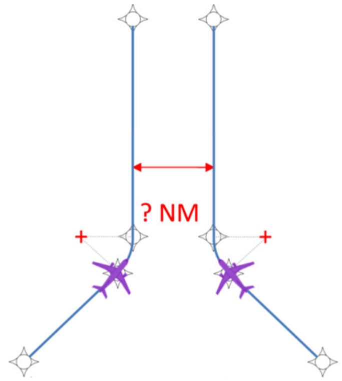
Converging Tracks</td>
<td rowspan="2">

Both aircraft at same level and in same direction with 45° RF/FRT turns</td>
<td colspan="2">Combined LVNL, NATS, and DSNA straight segment data
Applicable TLS: 4×10^{-9} fatal accidents per flight hour (f.a.f.h.)</td>
</tr>
<tr>
<td><u>GS 450kts</u>
Spacing used in CRM: 3 NM
(see Key Points 1, 2 and 3)
$N_{ay-best} = 3.69 \times 10^{-11}$ (f.a.f.h.)</td>
<td><u>GS 220kts</u>
Spacing used in CRM: 3 NM
(see Key Points 1, 2 and 3)
$N_{ay-best} = 1.07 \times 10^{-11}$ (f.a.f.h.)</td>
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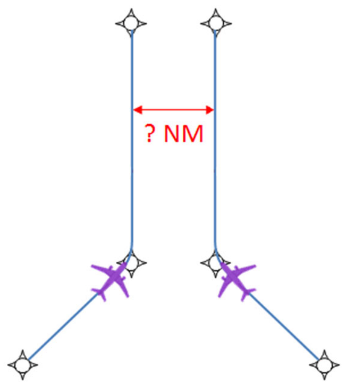
<td rowspan="2">12.
Converging Tracks</td>
<td rowspan="2">

Both aircraft at same level and in same direction with 45° fly-by turns</td>
<td colspan="2">Combined LVNL, NATS, and DSNA 30 – 60 degree turn data
Applicable TLS: 4×10^{-9} fatal accidents per flight hour (f.a.f.h.)</td>
</tr>
<tr>
<td><u>GS 450kts</u>
Spacing used in CRM: 4 NM
(see Key Points 1, 2 and 3)
$N_{ay-best} = 6.61 \times 10^{-10}$ (f.a.f.h.)</td>
<td><u>GS 220kts</u>
Spacing used in CRM: 4 NM
(see Key Points 1, 2 and 3)
$N_{ay-best} = 1.39 \times 10^{-10}$ (f.a.f.h.)</td>
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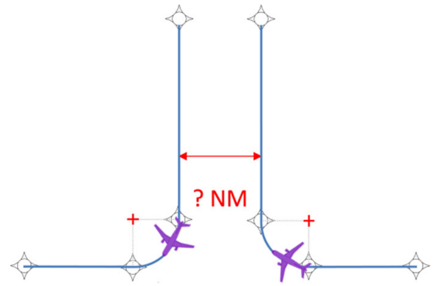
<td rowspan="2">13.
Converging Tracks</td>
<td rowspan="2">

Both aircraft at same level in opposite directions with 90° RF/FRT turns</td>
<td>Combined LVNL, NATS, and DSNA straight segment data
Applicable TLS: 4×10^{-9} fatal accidents per flight hour (f.a.f.h.)</td>
</tr>
<tr>
<td><u>GS 220kts</u>

Spacing used in CRM: 3 NM
(see Key Points 1, 2 and 3)

$N_{ay-best} = 7.76 \times 10^{-11}$ (f.a.f.h.)</td>
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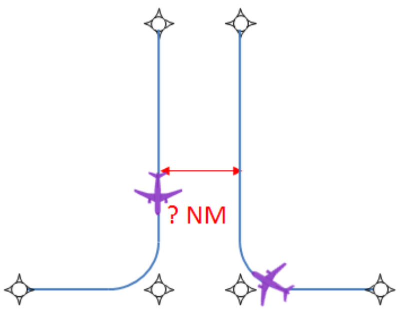
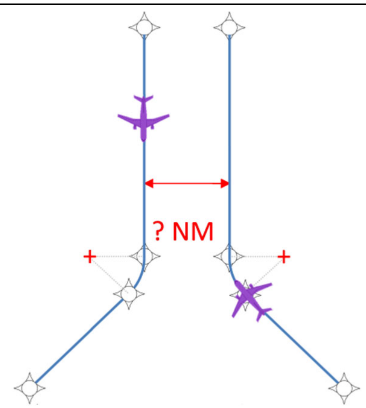
<td rowspan="2">14.
Converging Tracks</td>
<td rowspan="2">

Both aircraft at same level in opposite directions with 90° fly-by turns</td>
<td>Combined LVNL, NATS, and DSNA SID 90 degree turn data
Applicable TLS: 4×10^{-9} fatal accidents per flight hour (f.a.f.h.)</td>
</tr>
<tr>
<td><u>GS 220kts</u>

Spacing used in CRM: 6 NM
(see Key Points 1, 2 and 3)

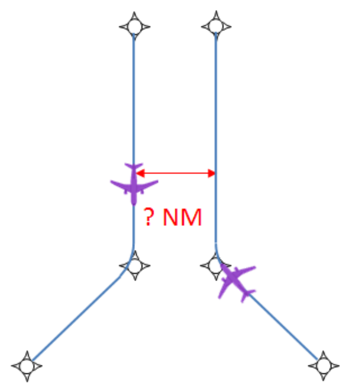
$N_{ay-best} = 2.99 \times 10^{-10}$ (f.a.f.h.)</td>
</tr>
</table>

<table>
<tr><td rowspan="2">15.
Converging Tracks</td><td rowspan="2">
Both aircraft at same level in opposite directions with 45° RF/FRT turns</td><td colspan="2">Combined LVNL, NATS, and DSNA straight segment data
Applicable TLS: 4×10^{-9} fatal accidents per flight hour (f.a.f.h.)</td></tr>
<tr><td><u>GS 450kts</u>

Spacing used in CRM: 3 NM
(see Key Points 1, 2 and 3)

$N_{ay-best} = 4.02 \times 10^{-10}$ (f.a.f.h.)</td><td><u>GS 220kts</u>

Spacing used in CRM: 3 NM
(see Key Points 1, 2 and 3)

$N_{ay-best} = 7.76 \times 10^{-11}$ (f.a.f.h.)</td></tr>
<tr><td rowspan="2">16.
Converging Tracks</td><td rowspan="2">
Both aircraft at same level in opposite directions with 45° fly-by turns</td><td colspan="2">Combined LVNL, NATS, and DSNA 30 – 60 degree turn data
Applicable TLS: 4×10^{-9} fatal accidents per flight hour (f.a.f.h.)</td></tr>
<tr><td><u>GS 450kts</u>

Spacing used in CRM: 5 NM
(see Key Points 1, 2 and 3)

$N_{ay-best} = 1.03 \times 10^{-9}$ (f.a.f.h.)</td><td><u>GS 220kts</u>

Spacing used in CRM: 4 NM
(see Key Points 1, 2 and 3)

$N_{ay-best} = 1.00 \times 10^{-9}$ (f.a.f.h.)</td></tr>
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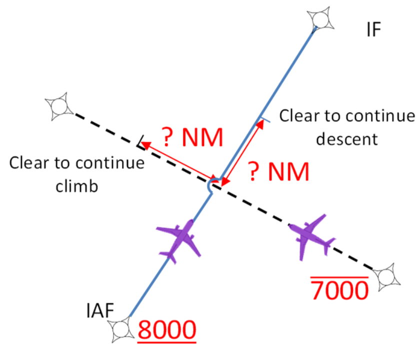
<table>
<tr><td rowspan="2">17.
Crossing Tracks
(OR3A)</td><td rowspan="2">

STAR crossing above SID
Earliest point after crossing at which both aircraft can continue climb/descent to ensure 1000’ separation</td><td colspan="3">Combined LVNL, NATS, and DSNA straight-segment data
TLS: 1×10^{-9} fatal accidents per event (aircraft pair passing the crossing point)
d_A: distance beyond crossing point for arriving aircraft to be clear to continue descent
d_D: distance beyond crossing point for departing aircraft to be clear to continue climb</td></tr>
<tr><td><u>Crossing Angle 90°</u>

$\boldsymbol{d_A} \geq$ **1 NM and** $\boldsymbol{d_D} \geq$ **1 NM**

$CR_{max} = 4.32 \times 10^{-10}$</td><td><u>Crossing Angle 60°</u>

$\boldsymbol{d_A} \geq$ **1 NM and** $\boldsymbol{d_D} \geq$ **1 NM**

$CR_{max} = 4.23 \times 10^{-10}$</td><td><u>Crossing Angle 30°</u>

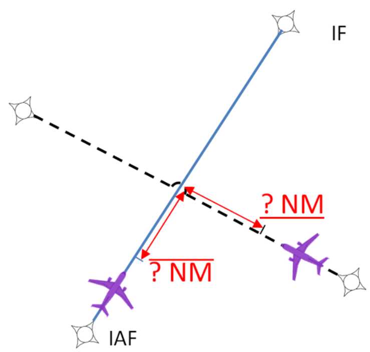
$\boldsymbol{d_A} \geq$ **1 NM and** $\boldsymbol{d_D} \geq$ **2 NM**

$CR_{max} = 4.71 \times 10^{-10}$

OR

$\boldsymbol{d_A} \geq$ **2 NM and** $\boldsymbol{d_D} \geq$ **1 NM**

$CR_{max} = 5.58 \times 10^{-10}$</td></tr>
</table>

<table>
<tr>
<td rowspan="2">18.
Crossing Tracks
(OR3B)</td>
<td rowspan="2">

SID crossing above STAR
Latest point before crossing at which both aircraft must reach their level to ensure 1000’ separation</td>
<td colspan="3">Combined LVNL, NATS, and DSNA straight-segment data
TLS: 1×10^{-9} fatal accidents per event (aircraft pair passing the crossing point)
d_A: distance before crossing by which arriving aircraft must stop its descent
d_D: distance before crossing point by which departing must stop its climb</td>
</tr>
<tr>
<td><u>Crossing Angle 90°</u>

$\boldsymbol{d_A} \geq$ 2 NM and $\boldsymbol{d_D} \geq$ 3 NM

$CR_{max} = 1.11 \times 10^{-10}$

OR

$\boldsymbol{d_A} \geq$ 3 NM and $\boldsymbol{d_D} \geq$ 1 NM

$CR_{max} = 9.29 \times 10^{-11}$</td>
<td><u>Crossing Angle 60°</u>

$\boldsymbol{d_A} \geq$ 2 NM and $\boldsymbol{d_D} \geq$ 3 NM

$CR_{max} = 9.88 \times 10^{-11}$

OR

$\boldsymbol{d_A} \geq$ 3 NM and $\boldsymbol{d_D} \geq$ 1 NM

$CR_{max} = 8.18 \times 10^{-11}$</td>
<td><u>Crossing Angle 30°</u>

$\boldsymbol{d_A} \geq$ 2 NM and $\boldsymbol{d_D} \geq$ 3 NM

$CR_{max} = 1.35 \times 10^{-10}$

OR

$\boldsymbol{d_A} \geq$ 3 NM and $\boldsymbol{d_D} \geq$ 1 NM

$CR_{max} = 1.16 \times 10^{-10}$</td>
</tr>
</table>

1. ANNEX 2 – SAMPLE VALUES OF ROUTE SPACING IMPLEMENTED IN SOME STATES

Spacing	Radar Airspace Applicable	How spacing demonstrated	Origin
3 NM	Spacing between Route and Traffic in Hold	Local implementation safety case by State for given circumstances.	NATS
8 NM	Spacing between Route and Nominal holding track	Local implementation safety case by State for given circumstances.	NATS
3 – 5 NM	Spacing between route and holding track	Local implementation safety case by State for given circumstances.	DSNA
2 NM	Spacing between nominal holding track and boundary of alternative holding protection area	Note 1, which explains how spacing was determined between an ATS Route and a holding area.	Study commissioned by LVNL (2010)
5 NM			
1 NM beyond primary area	Separation between Route and holding area	Local implementation safety case by State for given circumstances.	ENAV
Min Radar Separation	Between Holding traffic and route.	Local implementation safety case by State for given circumstances.	ENAV
Non-overlapping primarily protected areas	En Route – between ATS Routes	Local implementation safety case by State for given circumstances.	ENAV
Non-overlapping secondary protected areas	Terminal – between arrivals/departures (SIDs/STARs)	Local implementation safety case by State for given circumstances.	ENAV
0 NM Route can be on lateral/vertical limit	Spacing between route and TRA (with buffer inside)	Local implementation safety case by State for given circumstances.	ENAV
2.5 NM	TRA Dog Fight activity – buffer inside; separation between route or Radar vectoring track and outer boundary	Local implementation safety case by State for given circumstances.	DFS
2.5 NM	Spacing of Route or Radar Vector from Special TSA having military airborne activity	Local implementation safety case by State for given circumstances. Additional: (Special case study required)	DSNA
5 NM	Spacing of Route or Radar Vector from Special TSA having military airborne activity.	No special case study required	DSNA
2.5 or less	Radar vectoring track can be on external limit of TRA in which case military create buffer inside TRA	No special case study required. Requirements on technical infrastructure and procedures – see Note 2.	LVNL

Note 1. - For separation purposes, an alternative holding protection area was defined by taking the nominal holding track at the highest altitude the holding could be flown at and adding 2 NM to the front and sides, and adding 5 NM to the tail. By taking the normal distance (based on separation standard and buffer) from the boundary of this area to an adjacent ATS Route, traffic flying the holding and traffic at the adjacent ATS Route could be considered 'strategically deconflicted'. This means that in a radar environment the monitoring workload for ATC would be sufficiently low as the chance of ATC needed to interfere in order to separate the aircraft would be very small.

Note 2. – In context, the applied radar separation standard is still 5 NM – hence no safety case required – but obviously requirements are placed on the technical infrastructure – e.g. radar data for civil and mil ATC coming from the same source – and procedures in order to apply the 'shaded area' principle.

Attachment A & B

Attachment A – Area Navigation

Area navigation on board the aircraft

To be able to effectively navigate, an aircraft must know its current location (position) and its destination to know where to go to so that guidance (path steering) can be provided. An on-board navigation computer enables the aircraft to do this and is key to PBN. This navigation system, sometimes called an area navigation system, or RNAV system (or if included in a Flight Management System) can be referred to as a Flight Management Computer (FMC) or more generically an FMS. In general terms, this computer is capable of receiving position information from various sources, provided the sensors are fitted to the aircraft and integrated with the RNAV system, so that an aircraft is able to estimate its position in space in four dimensions and then provide effective steering guidance along a desired path.

Given that the performance-based part of navigation relates to accuracy, integrity and continuity of service, the following needs to be understood. These performance-based notions are discussed again at the close of this chapter to complement understanding.

Accuracy – Position and path steering

Position

Position information can be received by the RNAV system from a variety of navigation aids (NAVAIDS) including VOR, DME, GNSS, IRU or a combination of these. Although VOR and DME have been used independently of area navigation, when they are used as navigation positioning sensors these sensors are *automatically tuned by* the navigation computer such that the flight crew are not required to manually select individual DMEs or VORs.

Not all positioning sensors used by the RNAV system provide the same level of accuracy. In the hierarchy of NAVAID positioning accuracy, a fully functioning GPS constellation provides the greatest accuracy – and VOR, the least accuracy. Often the positioning is enhanced by the integration of an Inertial Reference Unit (IRU), e.g. GPS/IRU or DME-DME/IRU. An Inertial Reference Unit is also capable of determining the aircraft's position on its own. In this case, when the IRU is not updated, the positioning accuracy degrades over time.

The accuracy provided by positioning sensors can vary over *time* and due to others factors such as *geometry* (for DME/DME or GPS satellite positions), *height* (for DME/DME or VOR/DME) or range (for VOR/DME or DME/DME positions). So it cannot be assumed that the illustrative hierarchical positioning 'precision' (below) is *always* true. PBN is one discipline where questions often elicit a response prefaced with 'it depends'.

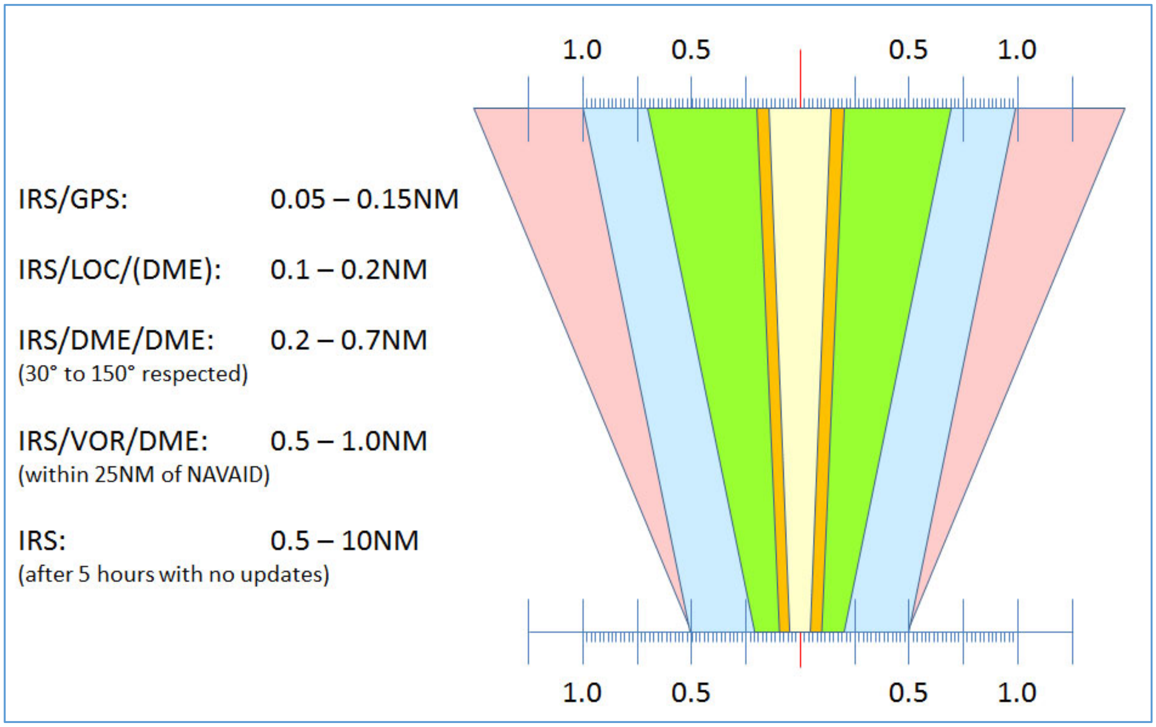


Figure 1 : Illustrative Hierarchy of positioning sensors

Path Steering

Flight Management Computer

The FMC (Flight Management Computer) is a computer system that uses a database to allow routes to be pre-programmed. The system is constantly updated with aircraft position by reference to available navigation aids. The integrated system is known as the FMS (Flight Management System) of which the FMC is just one component. A high-end FMS is capable of four dimensional area navigation (latitude, longitude, altitude & time) while optimising performance to achieve the most economical flight possible. It allows the pilots to input the whole flight plan and to modify it in flight.

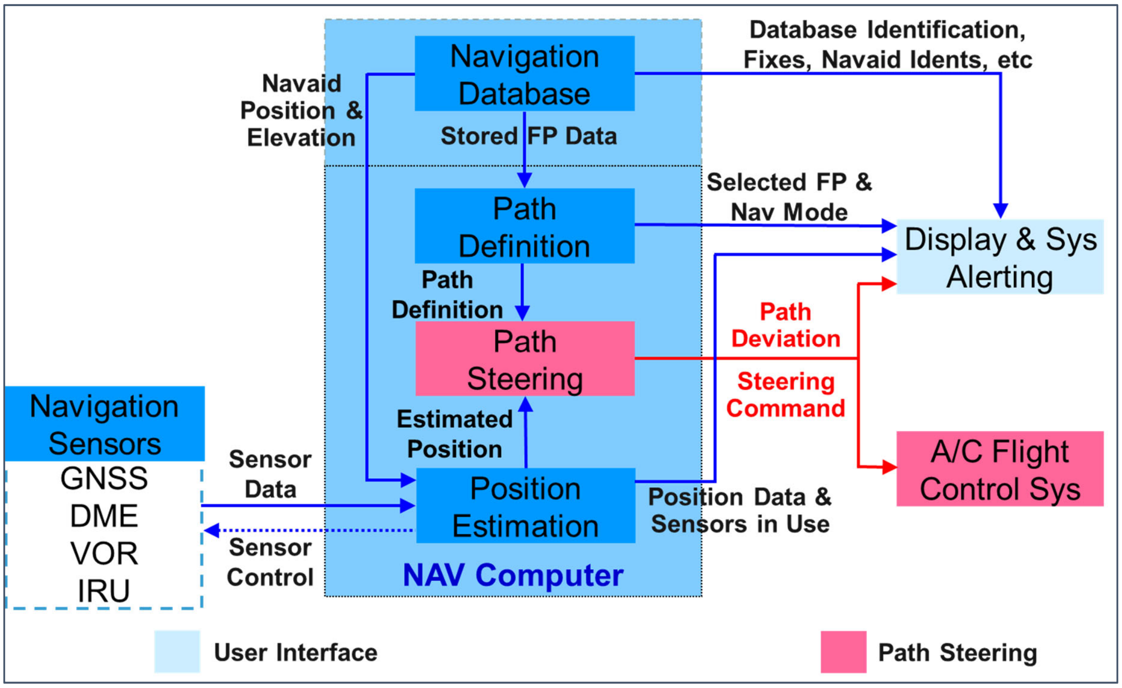


Figure 2: Positioning and Path Steering

Navigation sensors

The estimation of the aircraft position is performed by the FMS and is based on different navigation sensors: GNSS, DME and VOR (radio navigation sensors) and, if installed, an IRU (Inertial Reference Unit). Depending on the aircraft's design and sometimes operator preferences, all or a selection of these sensors are fitted to the aircraft. The FMS computes the best aircraft position estimate generally based on the following hierarchy of navigation modes (however, in some systems the position can be an aggregated position from various inputs):

1. GNSS/IRU
2. DME/DME/IRU
3. VOR/DME/IRU
4. IRU only

Generally, if one positioning source fails, the next best one will be selected. If no usable navigation sensor information is available and if the aircraft is equipped with IRU, the FMS will estimate the aircraft's position based on IRU data only, until the aircraft is in a location where sensor information is once again available. The FMC automatically determines which DME/DME combinations will yield the best result given their position relative to the aircraft. The FMS will also compute and provide true and/or magnetic track information, cross-track deviation from the route centreline and other variables such as True Airspeed and Groundspeed.

Navigation Database

The navigation database (containing navigation aids data, waypoints, airports, airways, runways, SIDS, STARS, company route information) provides the elements from which the flight plan is constructed. These are defined via the ARINC 424 standard. In accordance with the ICAO Standards and Recommended Practices (SARPS) for aeronautical data as published in Annex 15 to the Chicago

Convention addressing Aeronautical Information Services, the navigation database is updated every 28 days, in order to ensure that its content is current. Waypoints can also be defined by the pilot(s) either by manual insertion of coordinates or by reference to other waypoints, for example by specifying a bearing and distance from another waypoint. The navigation database is used to store route information which the autopilot will fly when an appropriate lateral guidance mode (for example "LNAV") is activated.

Navigation Display

The (ND) Navigation Display provides the pilot with a plan overview of the flight (essentially navigational, sometimes enhanced with weather and terrain information) allowing him/her to see the aircraft's lateral position relative to the defined track. The ND will also display a range of other navigation data such as waypoints, airports and the route ahead.

Aircraft Flight Control Systems

Dependent upon how the aircraft is flown, whether it is under automatic or manual control, has an impact on the accuracy. The selections made by the pilot(s) will either automatically move and control the aircraft flight control surfaces or display FD (flight director) commands for the pilot to follow. The FD computes and displays the proper pitch and bank angles required for the aircraft to follow a selected path.

Within the PBN navigation specifications the Flight Director (FD) and Autopilot (AP) functions are generally listed together. Both the FD and AP command the attitude necessary to follow a trajectory.

The Flight Director (FD) displays guidance commands from the Flight Management and Guidance Computer (FMGC) on the Primary Flight Display (PFD). The pilot may manually fly the aircraft, following FMGC commands, or crosscheck the FMGC orders when the autopilot is engaged.

With AP engaged, the avionics will automatically command the position of the flight control surfaces for pitch, roll and yaw, stabilize the aircraft around its centre of gravity and acquire and track a flight path.

FD is not considered to be as accurate as AP due to the reaction time by the pilot to follow the input; this is commonly referred to as 'lag time'.

However, due to the level of AFCS serviceability and to enable as many aircraft as possible to meet the majority of the navigation specifications, most PBN specifications also allow for manual flight with the navigation computer providing path deviation information on a Course Deviation Indicator (CDI) or Horizontal Situation Indicator (HSI). This flight operation is considered the least accurate.

Path steering and guidance

Most navigation systems are initialized with data. The flight crew must fix the system to the present position as part of the initialization process (departure position). The flight plan is generally determined on the ground, before departure. It is entered into the FMS either by typing it in or selecting it from a saved library of common routes (company routes). For aircraft that do not have GNSS, the initial position must be inserted into the navigation computer.

Given the flight plan and the aircraft's position, the FMS calculates the course to follow. Once in flight, a principal task of the FMS is to determine the aircraft's position and the accuracy of that position. The system compares the current calculated position using data received from the navigation sensors, to the calculated trajectory position and corrects for discrepancies. The pilot can follow this course manually or the autopilot can be set to follow the course. The FMS mode is generally called LNAV (or Lateral Navigation) for the lateral flight plan and VNAV (or vertical navigation) for the vertical flight plan if the aircraft is equipped with a VNAV capability. VNAV provides speed and pitch or altitude targets and LNAV provides roll steering command to the autopilot in order to keep the aircraft navigating correctly along the calculated flight trajectory.

Deviations from the centre of the desired flight track are corrected using intercept procedures and flight track adjustments. The FMS will compute and monitor cross track error, which is defined as the lateral distance separating the aircraft from its defined path of flight.

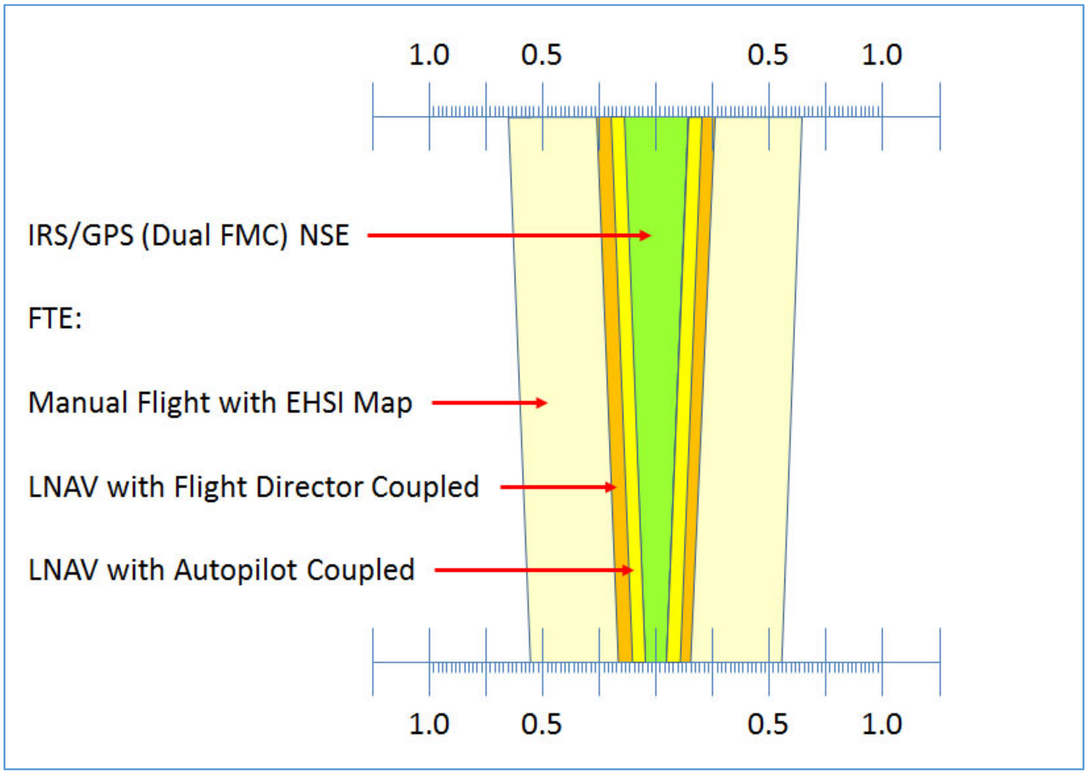


Figure 3: Positioning and Path Steering

Total System Error

To fly safely on the designated flight path, the aircraft manufacturer must demonstrate that the aircraft is capable of maintaining within the specified performance tolerance for the ATS route 95% of the flight time. For RNP capable aircraft, in normal operations, an alert should be given if the required performance along that ATS route is not met. Three potentially significant sources of error are considered in the analysis of the aircraft navigation system: path definition error, navigation system error and flight technical error.

- Path Definition Error (PDE) is a measure of how closely the airspace definition of the flight path matches that used by the FMC. This error is not significant when both the FMC and the route designers use the same coordinate reference to define the path end points. When the route designers and the FMC use the same geodetic reference, the contribution of path computation error to total system error is considered small enough that it is of little concern.
- Navigation System Error (NSE) indicates how well the aircraft position, as determined by navigation sensors, matches the true aircraft position. Because the aircraft's navigation sensors are not perfect, a difference (or error) may exist between the estimated (or calculated) aircraft position and the actual aircraft position.
- Flight Technical Error (FTE) is a measure of how well the aircraft is tracking the lateral and vertical paths calculated by the navigation system. The flight crew observes FTE by means of pointers on a lateral

deviation indicator or numerical cross-track indications on the Navigation Display. FTE is the one component of the error budget that can be controlled by the flight crew.

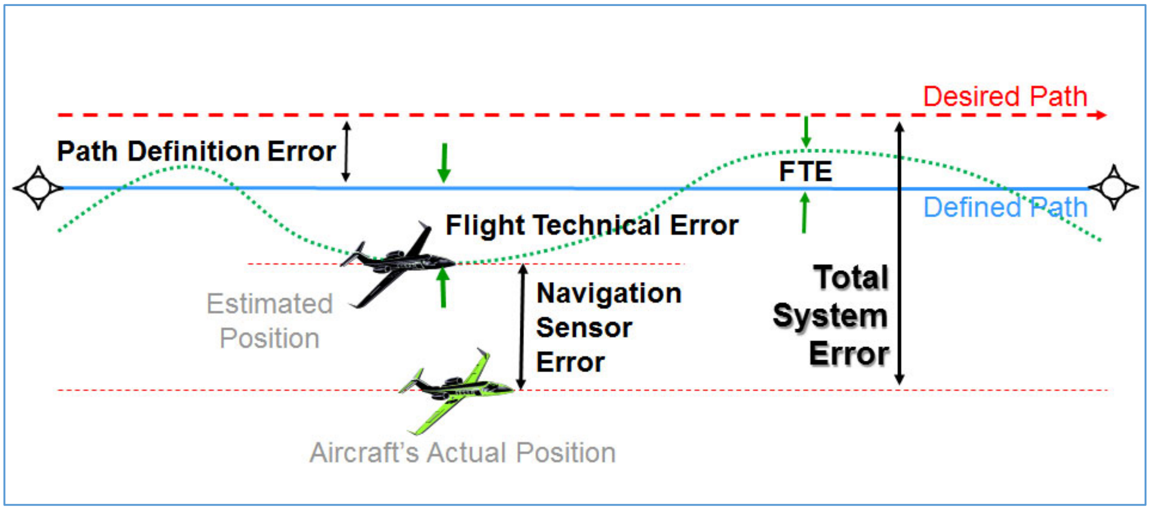


Figure 4: Total System Error contributions

Note: that when an aircraft is certified, it is for the Total System Error (TSE) which of course comprises all errors.

To ensure that the aircraft remains on the desired path, the flight crew limits the errors in total navigation performance over which they have control and monitors the errors that they cannot influence. FTE can be controlled by the flight crew and should be minimized through the use of an AP/FD or by manually maintaining the deviation within half of full scale deflection on an appropriately scaled Course Deviation Indicator (CDI). Navigation system error cannot be controlled by the flight crew but should be monitored to ensure that it remains within acceptable limits. Path definition error cannot be monitored (or controlled) but generally is considered sufficiently small that it can be ignored.

Integrity

Integrity is the level, or measure, of trust that can be placed in the correctness of the position solution. Integrity includes the ability of the system to provide timely and valid warnings (alerts) when it is unsafe to use the system. The integrity risk is the probability that the position estimation is greater than the required performance and no alert is issued.

On-board performance monitoring and alerting

An on-board performance monitoring and alerting function (OPMA) is required in all RNP specifications. It is an on-board functionality of the FMS and provides an alert to the flight crew when a required confidence in the position information is no longer met. If the navigation system is working correctly and using GNSS, then the probability of the aircraft position information exceeding the required performance without generating an alert is set at 10^{-7} per flight hour. However, if the navigation sensor was degraded PBN requires that an alert be given when the uncertainty in aircraft position exceeds double the performance requirement set for the route. The probability that this would not occur is lower than 10^{-5} per flight hour. In this scenario it is perfectly possible that the aircraft is still within the lateral performance requirement of the route but the aircraft does not know. The principle of on-board performance monitoring and alerting is illustrated in Figure 5.

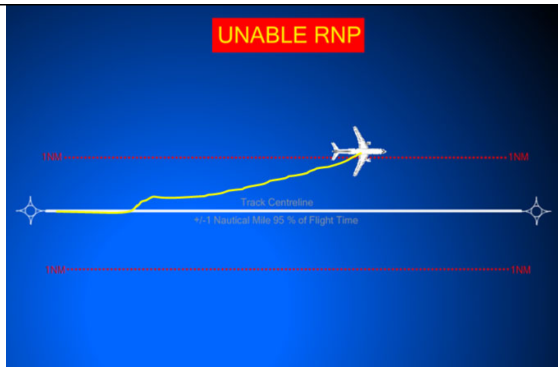
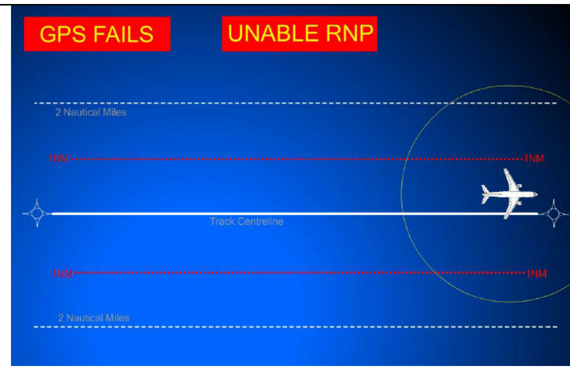
	
(a) RNP1 – System operating correctly. Alert given at 1NM. Probability of no alert is 10^{-7} per flight hour.	(b) RNP1 – GPS fails and navigation reverts to IRS. When uncertainty in position is double the required performance (e.g. 1NM for RNP1), an alert is issued. Probability of no alert is less than 10^{-5} per flight hour. Aircraft may still be meeting performance requirements but aircrew does not know.

Figure 5: Performance Monitoring (Integrity)

Continuity

Continuity is defined as the probability that the user is able to determine his/her position within the specified accuracy and is able to monitor the integrity of the determined position over the time required for that operation.

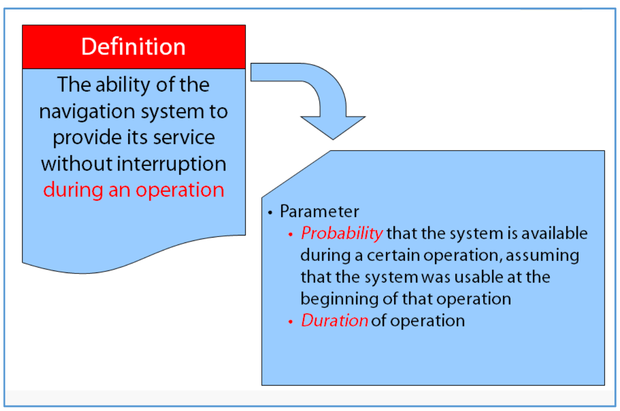


Figure 6: Continuity

Availability

Historically, availability was a further requirement set on the navigation system and was defined as the probability that a user will be able to define his/her position with a specified accuracy and is able to monitor the integrity of the determined position at the initiation of the operation. However, PBN only sets an availability requirement on the GNSS signal-in-space (SIS), over which the user has no control.

Attachment B: References relevant to Route Spacing

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