EUROCONTROL

European Airspace Concept Handbook for PBN Implementation

Edition 3.0

This handbook has been developed by EUROCONTROL in support of the ICAO EUR/EUROCONTROL Airspace Concept Workshops for PBN Implementation. The material contained herein is based on existing EUROCONTROL material - see *Sources*.

FOREWORD

The continued growth of traffic and the need to provide greater flight efficiency makes it necessary to optimise available airspace. This is being achieved world-wide by enhanced Air Traffic Management and by exploiting technological advancements in the fields of Communication, Navigation and Surveillance. More specifically, the application of Area Navigation techniques in all flight phases contributes directly to improved airspace optimisation.

On board Area Navigation system capabilities are increasingly being exploited with a view to maximizing airspace resources. To this end, both flight crew and ATC need to understand Area Navigation system capabilities and ensure that these match airspace requirements. The use of Area Navigation systems lies at the core of PBN, which introduces approval requirements for use of Area Navigation systems in airspace implementations.

Purpose of this Handbook

The first two Editions of this Handbook were published as supporting material to the ICAO PBN Airspace Workshops being rolled out in various world regions. The basis for the handbook's contents were the Terminal Airspace Design Guidelines published by EUROCONTROL in 2005 (now the European Route Network Improvement Plan, Part I) which became the major contributions to the ICAO Implementation Processes in the PBN Manual. This European version (Edition 3) of the handbook expands the original material and provides additional explanatory information for European PBN Implementation. The handbook relies on the premise that readers have a clear understanding of PBN and the ATM/CNS environment.

This handbook is intentionally short, its activities intended as a prompt. It provides generic guidance on how to develop the airspace elements of an Airspace Concept in the context of PBN. As such, it is primarily intended for airspace planners involved in PBN implementation in continental airspace – the anticipated arena of wide-spread PBN uptake in Europe.

Given the specific PBN context and principal audience, the Handbook:

- amplifies the airspace design elements of the Airspace Concept by focusing on ATS routes as well as arrival and departure routes from a PBN perspective (as enabled by RNP or RNAV specifications – see Figure on Page 8); and
- plays down non-PBN elements of the airspace concept such as the design of airspace volumes (CTAs or airspace reservations); flexible use of airspace; special techniques (e.g. continuous descent operations); airspace classification or inter-centre letters of agreement which govern operations between centres.

Since its first publication in 2010, the usefulness of this handbook has also been expressed by other PBN stakeholders who are not airspace designers. As such, procedure designers, avionics specialists and Navaid Infrastructure experts may also find this handbook useful with its ATM operational contextualisation.

This handbook does not deal with the final approach phase of flight. Methodology associated with the implementation of RNP procedures on final approach are published in: EUR RNP APCH Guidance Material (EUR Doc 025), First edition, 2012.

Airspace Design

Although airspace design is often associated with the construction of instrument flight procedures in accordance with obstacle clearance criteria prescribed in PANS-OPS (ICAO Doc. 8168), this document does not use the term design in that sense and obstacle clearance criteria are not included in this document.

In a PBN context, *design* has a broader meaning: it refers to the *planning, placement and design* of **ATS routes**/instrument flight procedures (including SIDs/STARs[1]), the **structures** needed to protect those routes and the ATC **sectorisation** required for management of the air traffic. The planning, placement and design of routes is where airspace design and PBN meet, with PBN making it possible to strategically deconflict RNAV and/or RNP routes by allowing airspace planners to take credit for the aircraft's navigation performance.

Airspace design is one of several components of the Airspace concept which is based on clearly defined operational requirements (e.g. ATM).

[1] *In Context, use of the expression 'routes' or ATS Routes incl SIDS/STRARS which have been designated as per ICAO Annex 11 Appendix 1 or 3. 'FREE ROUTE'-S' based on DCTS are not included.*

The PBN concept is clear that the placement of RNAV and RNP routes is driven by operational and regulatory requirements and not exclusively by technical requirements or procedure design necessity. (Thus the placement of RNAV and RNP routes aims first to support the objectives of ATM and then designed in accordance with PANS-OPS criteria to ensure the protection of IFR flight paths against obstacles). This said, the PBN concept is equally clear that one of its main objectives is to limit the creation of new navigation specifications so as to reduce certification costs for aircraft operators. As such, *operationally driven* airspace design is limited by certain cost realities.

Document Status

This is a living document whose prime purpose is education and support to PBN Implementation. As such, this handbook will be updated on a needs basis.

Source documentation

Given the guidance material already available on airspace design and planning (listed in the next column), existing material is not replicated in this handbook. Instead, this handbook has selected guidance from the cited Source Documents and added to it the lessons learned from PBN implementation. In order to allow airspace planners to orientate themselves with the Implementation Guidance published in Volume I of the PBN Manual, specific 'activities' of Airspace Concept development (listed in this handbook) are mapped against the 'steps' of the Implementation Guidance Processes (published in the PBN Manual) and provided as an Attachment to this handbook. The non-linear, iterative nature of Airspace Concept development becomes immediately evident.

Source documents and web material used in the compilation of this handbook include:

- ICAO: ATS Planning Manual, Doc. 9426; http://www.icao.int/icaonet/.
- ICAO: Performance Based Navigation Manual (Doc 9613, 2013 Edition 4; http://www.icao.int/icaonet/.
- EUROCONTROL: Terminal Airspace Design Guidelines (Ed. 2.0, 2005); 'Guidance Material' at http://www.ecacnav.com/content.asp?CatID=10).
- EUROCONTROL: En Route Airspace Design Guidelines.
- EUROCONTROL Navigation Domain – P-RNAV Implementation Methodology.
- EUROCONTROL: Introduction to Performance Based Navigation and Advanced RNP (brochure).
- European Route Network Improvement Plan Part I

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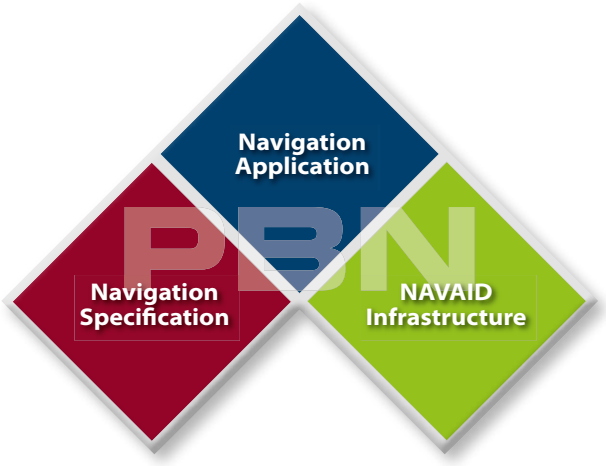
1. BACKGROUND INFORMATION

The use of Area Navigation systems lies at the core of Performance Based Navigation, which introduces approval requirements for the use of RNAV Systems.

PBN enables the systemisation of air traffic organisation and the strategic deconfliction of published ATS routes (including SIDs/STARs and Instrument Approach Procedures) so as to reduce the need for tactical ATC intervention. Put differently: PBN allows aircraft-to-aircraft separation and route spacing to be 'built-into' the airspace design.



The Performance-Based Navigation Concept

ICAO's Performance-based Navigation (PBN) Concept has replaced the RNP Concept; it was introduced through publication of the ICAO PBN Manual (Doc 9613) in 2008. The PBN Concept is geared to respond to airspace requirements.

To these ends, ICAO's PBN concept identifies three components: the **NAVAID Infrastructure**, **Navigation Specification** and the **Navigation Application**

- The **NAVAID Infrastructure** refers to ground- and space-based navigation aids.
- The **Navigation Specification** is a technical and operational specification that identifies the required functionality of the area navigation equipment and associated aircraft avionics. It also identifies the navigation sensors required to operate using the NAVAID Infrastructure to meet the operational needs identified in the Airspace Concept. The Navigation Specification provides material which States can use as a basis for developing their certification and operational approval documentation.
- The **Navigation Application** is the use of the **NAVAID Infrastructure** and **Navigation Specification** for the design of ATS routes (incl. SIDS/STARS) as well as Instrument Approach Procedures.

What's new about PBN?

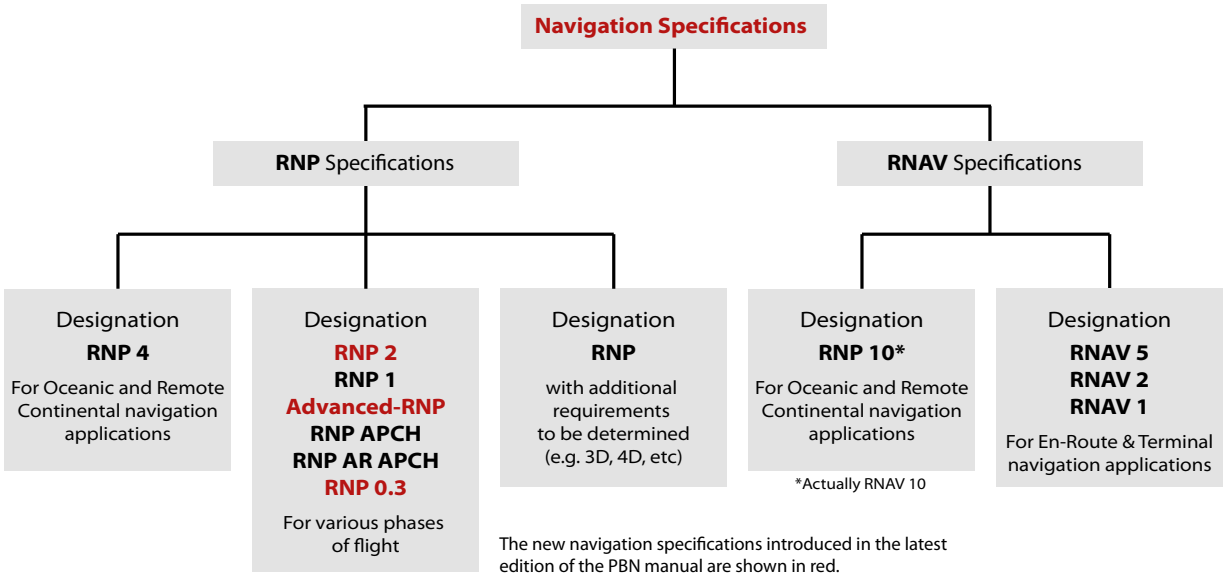
Three fundamental points must be understood about PBN:

- PBN requires the aircraft to be capable of area navigation which is enabled through the use of an on-board navigation computer referred to as an RNAV or RNP system;
- PBN creates requirements for airworthiness certification and operational approval to use RNAV or RNP systems in airspace implementations;
- The RNAV or RNP system's functionality as well as its navigation accuracy, enabled by the NAVAID environment of the subject airspace, must conform to the requirements stipulated in the relevant ICAO navigation specification.

Simply put, for PBN both the aircraft and air crew have to be qualified against the particular Navigation Specifications required for operation in the airspace.

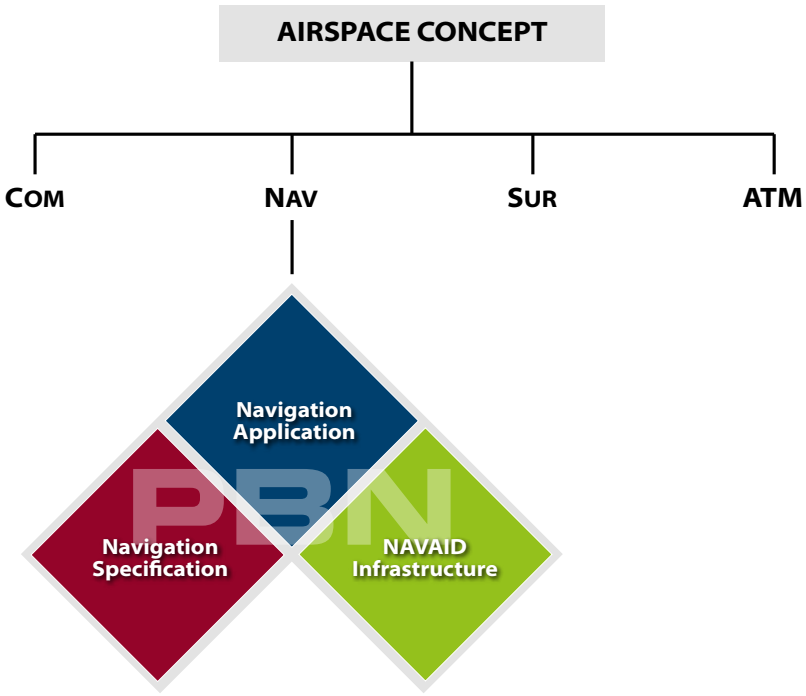
The updated 2013 edition of the PBN Manual contains eleven navigation specifications: four of these are RNAV specifications (see below, right) and seven of these are RNP specifications (see below, left).

Documented in Volume II of the PBN Manual, each of these navigation specifications is roughly 20 pages in length and contains core and contextual material. Core material relating to the navigation specification per se includes descriptions as to the performance (accuracy, integrity and continuity) required from the area navigation system, the functionalities required to meet the requirements of the Navigation Application, the approval process, aircraft eligibility and operational approval, etc. The more contextual type of material relates primarily to Air Navigation Service Providers (ANSP) considerations and includes requirements related to the Navaid, Communication and Surveillance Infrastructures, air traffic controller training, ATS system monitoring and aeronautical publication etc.

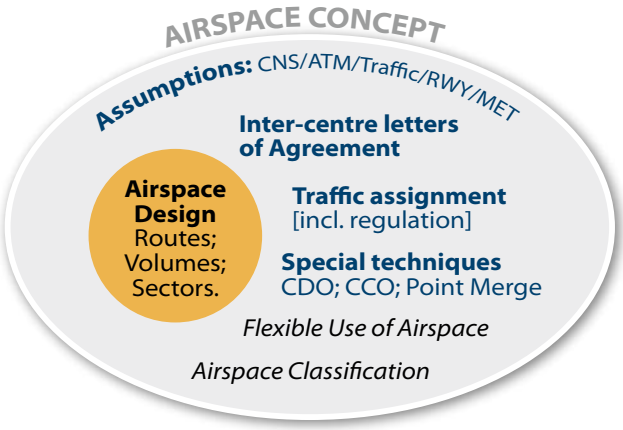


The new navigation specifications introduced in the latest edition of the PBN manual are shown in red.

Airspace Concept



The PBN Manual introduces the Airspace Concept as a formal way to set out and respond to airspace requirements. As such, the development of the Airspace Concept is a key step in PBN implementation. From an ANSP's perspective, PBN is one of several enablers of the Airspace Concept. From an aircraft and air crew perspective, PBN clarifies and provides a uniform structure to requirements for airworthiness certification and operational approval for use of **area navigation systems** in airspace implementations.



An Airspace Concept describes the intended operations within an airspace. Airspace Concepts are developed to satisfy strategic objectives such as safety, capacity or flight efficiency. Airspace Concepts include details of the practical organisation of the airspace and its operations as well as the CNS/ATM assumptions on which it is based. Practical organisation of the airspace includes the ATS route structure, separation minima, route spacing and obstacle clearance. Thus the Airspace Concept hinges on the airspace design.

Once fully developed, an Airspace Concept provides a detailed description of the target airspace organisation and operations within that airspace and can, when complete, be anything from five pages in length (for extremely simple airspace changes) to a document of several hundred pages.

Note: *More information on the Airspace Concept is published at the EUROCONTROL Training Zone.*

Global PBN

The ICAO Resolution at the 36th Assembly and the publication of ICAO's PBN Concept in 2008 effectively triggered the launch of PBN. The ICAO Resolution was updated at the 37th Assembly and marks a significant step in that it reflects international concordance as to high-level goals and ambitions for global uptake of PBN. Text from Resolution 37-11 is replicated in the box below.

ICAO's Global Air Navigation Plan (GANP) as complemented by the Aviation System Block Upgrades (ASBU) has identified PBN as the highest priority for the international organisation.

The Assembly:

1. **Urges** all States to implement RNAV and RNP air traffic services (ATS) routes and approach procedures in accordance with the ICAO PBN concept laid down in the *Performance-Based Navigation (PBN) Manual* (Doc 9613);

2. **Resolves** that:

   a) States complete a PBN implementation plan as a matter of urgency to achieve:

      1) implementation of RNAV and RNP operations (where required) for en route and terminal areas according to established timelines and intermediate milestones; and
      2) implementation of approach procedures with vertical guidance (APV) (Baro-VNAV and/or augmented GNSS), including LNAV only minima for all instrument runway ends, either as the primary approach or as a back-up for precision approaches by 2016 with intermediate milestones as follows: 30 per cent by 2010, 70 per cent by 2014; and
      3) implementation of straight-in LNAV only procedures, as an exception to 2) above, for instrument runways at aerodromes where there is no local altimeter setting available and where there are no aircraft suitably equipped for APV operations with a maximum certificated take-off mass of 5 700 kg or more;

   b) ICAO develop a coordinated action plan to assist States in the implementation of PBN and to ensure development and/or maintenance of globally harmonized SARPs, Procedures for Air Navigation Services (PANS) and guidance material including a global harmonized safety assessment methodology to keep pace with operational demands;

3. **Urges** that States include in their PBN implementation plan provisions for implementation of approach procedures with vertical guidance (APV) to all runway end serving aircraft with a maximum certificated take-off mass of 5 700 kg or more, according to established timelines and intermediate milestones;

4. **Instructs** the Council to provide a progress report on PBN implementation to the next ordinary session of the Assembly, as necessary;

5. **Requests** the Planning and Implementation Regional Groups (PIRGs) to include in their work programme the review of status of implementation of PBN by States according to the defined implementation plans and report annually to ICAO any deficiencies that may occur; and

6. **Declares** that this resolution supersedes Resolution A36-23.

Benefits

The development and implementation of a PBN-based Airspace Concept makes significant contributions in terms of safety, environment, capacity and flight efficiency. For example:

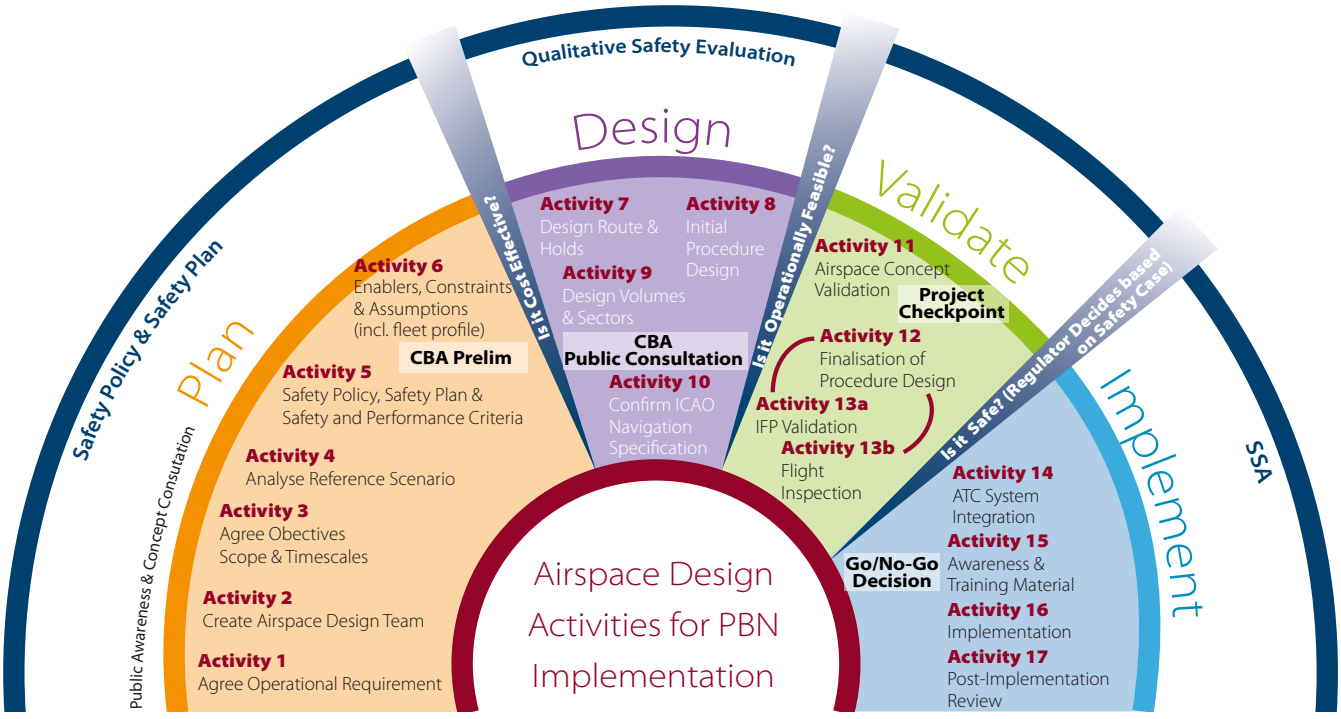
- PBN's partnership approach to developing the Airspace Concept ensures that conflicting requirements are tackled in an integrated manner and that diverse interests are addressed without compromising safety, environmental mitigation, flight efficiency and capacity requirements;
- Safety is enhanced by ensuring that the placement of ATS routes and Instrument Flight Procedures service both Air Traffic Management and Obstacle Clearance requirements;
- Environmental mitigation can be improved by granting environmental needs the same level of importance as capacity enhancement when defining the operations in an airspace and affecting the airspace design.
- Capacity and Flight Efficiency are enhanced by placing ATS routes and Instrument Flight Procedures in the most optimum location in both lateral and vertical dimensions.
- Access to airports is improved particularly in terrain rich environments.

2. AIRSPACE CONCEPT DEVELOPMENT

This section of the handbook provides phased guidance in the form of Activities for Airspace Concept development. There are 17 such activities, clustered under the broad headings of Planning, Design, Validation and Implementation.

Given that Airspace Concept development is driven by strategic objectives, it follows that the first Activity is triggered by operational requirements. These triggers are usually formalised in a Strategic Objective such as Safety, Capacity, Flight Efficiency, Environmental Mitigation and Access. While some strategic objectives may be explicitly identified, others will remain implicit. Trade-offs and prioritisation of strategic objectives may be needed where there are conflicts between these objectives. Nevertheless, the maintenance of safety remains paramount and cannot be diluted by compromise.

Airspace Concept development relies on sound planning and iterative processes. **Planning** begins before starting the Airspace Design, Validation and Implementation. Planning needs to be an in-depth (and therefore, quite a lengthy) process because sound preparation is one of the pre-requisites to successful Airspace Concept development. Careful consideration is needed in terms of *what* needs to be done and the organising of the necessary *time and resources* to do it. **Iteration** is the other key to any Airspace Concept development: development of an Airspace Concept is **not** a linear process but relies on several iterations and refinement moving backwards and forwards between some of the 17 activities.



Airspace Concept development for PBN Implementation can develop in a number of managerial 'frameworks' which affects the planning for PBN Implementation. By way of illustration, three sample 'projects' are shown with their PBN aspects highlighted and remarks indicated

Example of Projects	
Example	**Effect on Planning**
A new runway is to be added to an airport; this triggers a need for new RNAV or RNP SIDs/STARs.	The PBN Airspace Concept development team would be one of various projects running simultaneously under an overall project steering committee. Implementation date is likely to be decided by the overall steering group. Such projects often span several years and may require close monitoring of the fleet's PBN capability as it develops over time.
Environmental mitigation measures are ordered by a court or government ministry which results in a requirement to re-design certain arrival and/or departure routes requiring RNAV or RNP. Typically, such projects are politically loaded.	These projects can often be 'high speed' and 'high pressure' due to the political charge. Usually there is a high level of scrutiny regarding placement of routes. Such projects can be accomplished within several months, particularly when political pressure is high but qualification of air crew and/or aircraft to the required navigation specification affected may take longer.
An airspace change is launched as a direct consequence of an operational requirement which has been identified and triggered either by air traffic management or airspace users. Typically operational requirements are safety, capacity, flight efficiency etc, and may involve, for example improvement to flight profiles using Continuous Climb and Continuous Descent Operations (CCO and CDO – both of which can be PBN based applications) or re-alignment of route placement enabled by RNAV or RNP routes.	Usually simple managerial structure and implementation date chosen by the team responsible for PBN implementation. More complex projects tend to prefer phasing sometimes, for example, starting with RNAV SIDs/STARs with the intention to migrate to RNP SIDs/STARs over time. Phases can stretch over several years.

Public Awareness and Public Consultation

Many European governments have requirements for ANSPs to extensively consult with the general public when making airspace changes, particularly around airports. To this end, some ANSPs have become specialised in public awareness and consultation so as to ensure that government requirements are fulfilled. These consultation processes can be extensive and time consuming, and can affect the duration of projects and, in some cases, even limit the ability to change how an airspace is designed and the operations within it. Some requirements demand repetitive/phased consultation throughout the life-cycle of the project in an attempt to enhance the probability of a project's success.

As there is no single European blue-print for these processes, this handbook includes a few reminders to undertake the public consultation or airspace user consultation during the project life-cycle (though these may be different from State to State). In practical terms, those implementing PBN need to be aware that project planning must allow for time for consultation.

Activity 1

Agree on Operational Requirement(s)

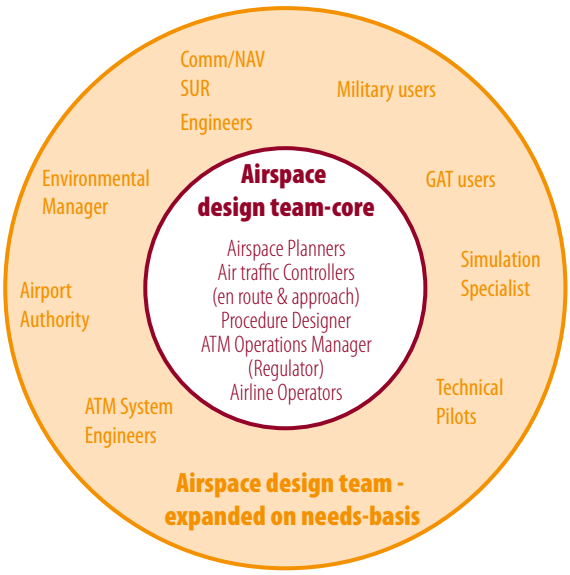
Airspace changes are triggered by **operational requirements**. Examples of operational requirements include: the addition of a new runway in a terminal area (here the corresponding strategic objective may be to increase capacity at an airport); pressure to reduce aircraft noise over a residential area (this strategic objective is to reduce environmental impact over a particular area) or need to allow operations at an airport during low visibility conditions (i.e. improved access). Operational requirements tend to be reasonably high level and are often decided at a high managerial level. These requirements drive the project objectives, scope and timelines.

Strategic Objective	Sample Operational Requirement	Sample PBN Project Objectives
Increase **capacity**	Addition of new runway	Design new RNP SIDs/STARs for new runway and adapt existing ATS Route network to PBN
Reduce **environmental impact**	Avoid noise sensitive areas at night	Design of RNP SIDs/STARs with CCO and CDO
Increase **flight efficiency**	Use airspace users on-board capability	Develop ATS Route network based on Advanced RNP
Increase **safety** on Approach	Improve vertical profile enabling stabilised approaches	Introduce RNP APCH
Increase **flight efficiency**	Improve vertical interaction between flights to avoid unnecessary levelling off	Redesign RNP SID/STAR interactions and move SIDs clear of holding areas
Increase **access**	Provide alternative to conventional NPA	Develop RNP APCH Procedures

Activity 2

Create the Airspace Design Team

In order to tackle the operational requirements, an Airspace Concept will need to be developed, validated and implemented. Such an Airspace Concept, addressing all of the requirements, cannot be developed by a single individual working in isolation. Airspace Concepts, from inception to implementation, are the product of an integrated team of people working together: the **Airspace Design Team** (non-exclusive example shown below). Commonly, this team is led by an ATM specialist with an in-depth operational knowledge of the specific airspace under review and a sound knowledge of PBN. This specialist needs to be supported by Air Traffic Controllers familiar with the airspace in question, ATM and CNS System specialists and Technical pilots from lead carriers operating in the airspace. Instrument flight procedure designers play an integral role in this team as do the data houses, airspace users, regulatory authorities, safety and environmental managers. Whilst PBN is relatively new, it is possible that people on the team will not be familiar with PBN. In such cases, adequate training is needed. Roles and responsibilities of team members need to be clearly understood across the team and the speed, timing and content of individual contributions need steering by the team leader.



Activity 3

Agree project objectives, scope... and timescales

One of the first tasks of the airspace design team is to decide what the objectives of the airspace project are. **Project objectives** are easily derived from the operational requirements which have triggered the project. For example, if the project is triggered by need to reduce noise impact over a residential area, the (airspace) project objectives would be linked to noise reduction (reduce the noise footprint over Village X, by designing new RNP SIDs/STARs, for example).

Deciding **project scope** can be much more challenging. Experience has shown that the definition of a project's scope and remaining within the limits of that scope can be extremely difficult. As such, scope 'creep' is a project risk in almost every project implementation and it often causes the failure of projects. Once the scope of the project has been decided, it is important to avoid extending the project objectives (if at all possible) as this invariably results in a need to increase the scope which causes cost overruns and delays. For this reason it is critical to decide what needs to be done to achieve the project objectives and to agree – and stick to – a specific body of work to reach those objectives. The project's scope is very much a function of how much **time** and **resources** are available to complete the project.

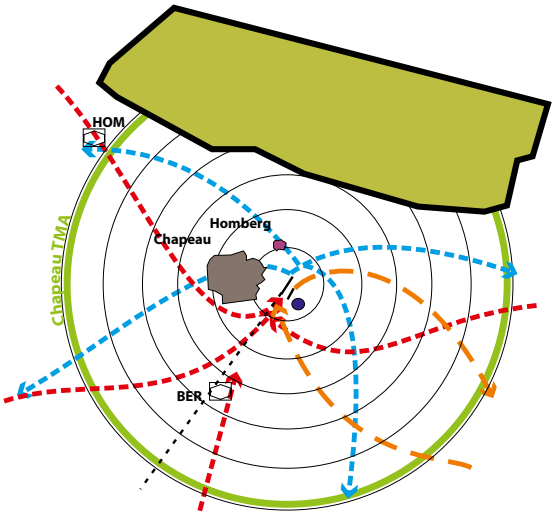
Two possibilities exist as regards available time: either the team decides its implementation date based on all the work that needs to be completed or the implementation date is fixed beforehand and the team's challenge is to fit the work into the available time. Resources, Time and Scope are the three sides of the project planning 'triangle'. .

Whilst in their daily lives controllers are accustomed to having a very short interval between planning and execution, the timing element on airspace projects can be the trickiest to manage. Take, for example, a case where an airspace concept has unexpectedly identified the need for a new DME to provide coverage throughout a terminal airspace. The installation and commissioning for use of an additional DME could take up to two years to achieve, if one considers the need to find an available frequency and that it may be necessary to find a location (and perhaps build an access road and provide a power supply). Procurement processes for the equipment can be lengthy, as can the delivery time, civil works needed to build the site, installation, calibration both ground and flight check until final commissioning for use by the CAA. Similarly, the time needed in some cases for public consultation can be extensive e.g. the placement of SIDs/STARs may be a sensitive issue for a particular community and necessitate comprehensive environmental impact analysis; ATS routes over a nature reserve below a specific altitude can become an issue of visual 'intrusion' and result in the need for complex negotiations. Mindful of the unpredictability of some of these timescales, a Sample Project Task list with time estimations is provided at Attachment 1 by way of showing how time estimations for a project can be made.

Activity 4

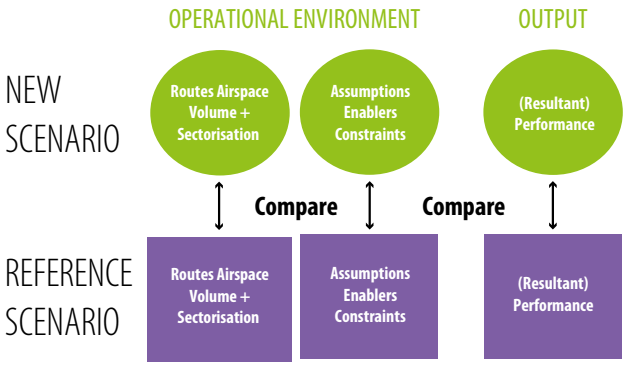
Analyse the Reference Scenario – Collect Data

Before starting the design of the new Airspace Concept, it is important to understand and analyse existing operations in the airspace. These existing operations may be called the



Reference Scenario. The Reference Scenario includes all existing ATS Routes, SIDs/STARs, airspace volumes (e.g. TMA), ATC sectorisation, the air traffic data and as well as all the inter-centre and inter-unit coordination agreements.

Description and analysis of the Reference Scenario is a crucial exercise – a step not to be missed.



This is because analysis of the Reference Scenario in terms of the project's performance indicators, (1) makes it possible to gauge how the airspace is performing today; (2) allows the airspace design team to know with certainty what works well in an airspace, and hence should be kept, and what does not work well and could be improved; (3) by fixing the performance of the Reference Scenario, a benchmark is created against which the new Airspace Concept can be compared. Use of this benchmark makes it possible to measure the performance of the proposed Airspace Concept. It also becomes possible to establish whether the Safety and Performance criteria of the new Airspace Concept have been achieved.

In some (rare) instances, the targeted Airspace Concept may be so different from the Reference Scenario that a comparison is not possible. This would be the case, for example, if a new airport is to be built with a new terminal airspace surrounding it. If, in such a case this new airport were intended to replace or complement existing operations at another terminal area, it could prove useful to compare the performance of the existing versus the new terminal area.

Activity 5

Safety Policy, Safety Plan and Selection of Safety and Performance Criteria

A regulator's Safety Policy drives a service provider's Safety Plan and enables Safety Criteria to be identified. For the Airspace Design team, the crucial question speaks to the criteria to be used to determine the adequate safety of the PBN-based Airspace Concept. As such, the Airspace Design team must decide upon the safety criteria to be used, as determined by the Safety Policy. This Safety Policy will normally be set externally to the project but if it does have to be established by the project team it is vital that it is agreed at highest level early in the development. Safety criteria may be qualitative or quantitative (often a mix of both is used). The Safety Policy has to be known at the outset of the project. Safety Policy concerns itself with questions like:

- Which Safety Management System?
- Which Safety Assessment Methodology?
- What evidence is needed to prove that the design is safe?

Support and guidance from the regulatory authorities at this stage is extremely beneficial and therefore this stakeholder is recommended to be involved as a member of the Implementation team. The in-depth analysis of the Reference Scenario in Activity 4 provides direct input to the new Airspace Concept of the project being undertaken. In deciding the project's objectives and scope, it is necessary to know how a project's success can be measured in terms of performance. For example, the project may be considered to be a success when its strategic objectives is satisfied. So – if the strategic objectives are to double the throughput on runway X, if this is demonstrated in a real-time simulation of the (new) Airspace Concept, this is a strong indication that the project will satisfy this performance criterion.

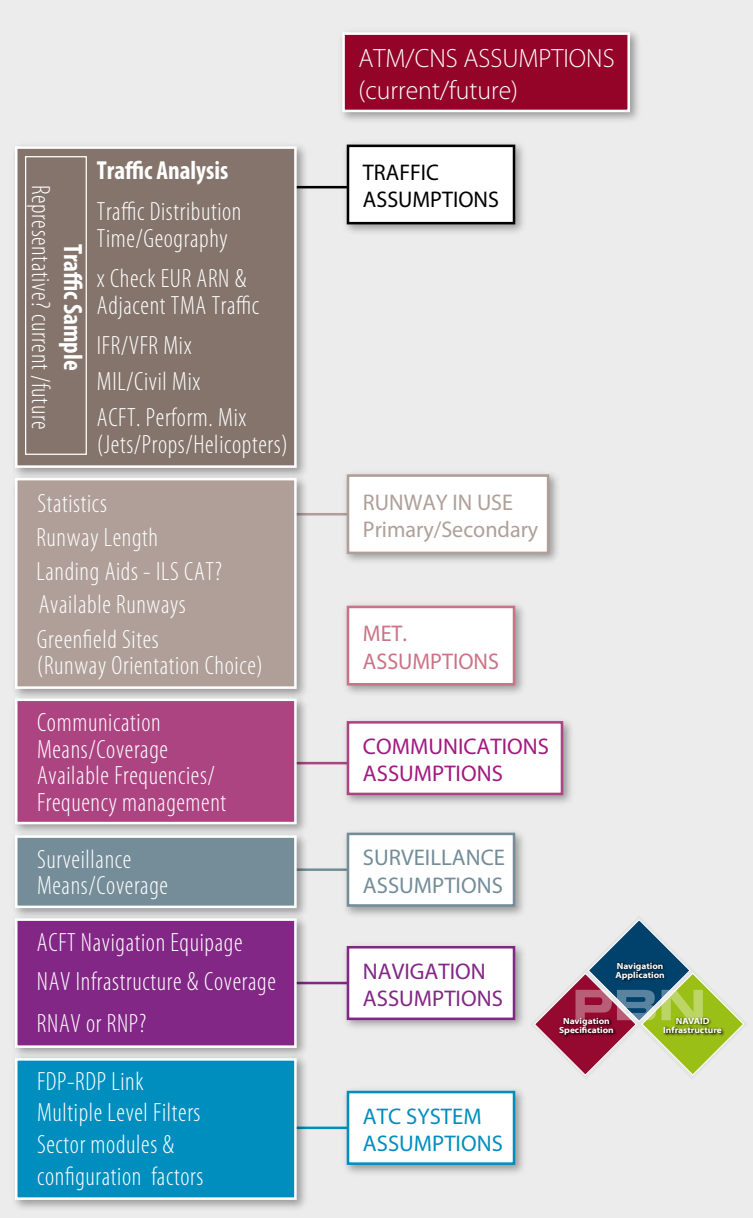
Activity 6

Enablers, Constraints and ATM CNS Assumptions

For the Airspace Concept to be realised, the technical operating environment needs to be agreed. This requires knowledge, as regards the ground infrastructure and airborne capability, as to which CNS/ATM **enablers** are already 'available', the limitations or **constraints** which exist and what the future environment will be when the when the Airspace

Concept is implemented: the **assumptions**. Whilst enablers and constraints are usually not difficult to establish, agreeing assumptions can be challenging. Their 'realism' is important because the airspace concept which is designed and the PBN specification(s) used as a basis for that design relies on these assumptions being correct.

ATM/CNS assumptions cover a wide field and need to take account of the expected environment applicable for the time when the new airspace operation is intended to be implemented (e.g. in 20XX). General assumptions include, for example: the predominant runway in use within a particular TMA; the percentage of the operations which take place during LVP; the location of the main traffic flows (in 20XX, are these likely to be the same as today? If not how will they change?); the ATS Surveillance and Communication to be used in 20XX. Should any specific ATC System aspects be considered e.g. a maximum of four sectors are possible for the en route airspace because of software limitations in the ATM system).

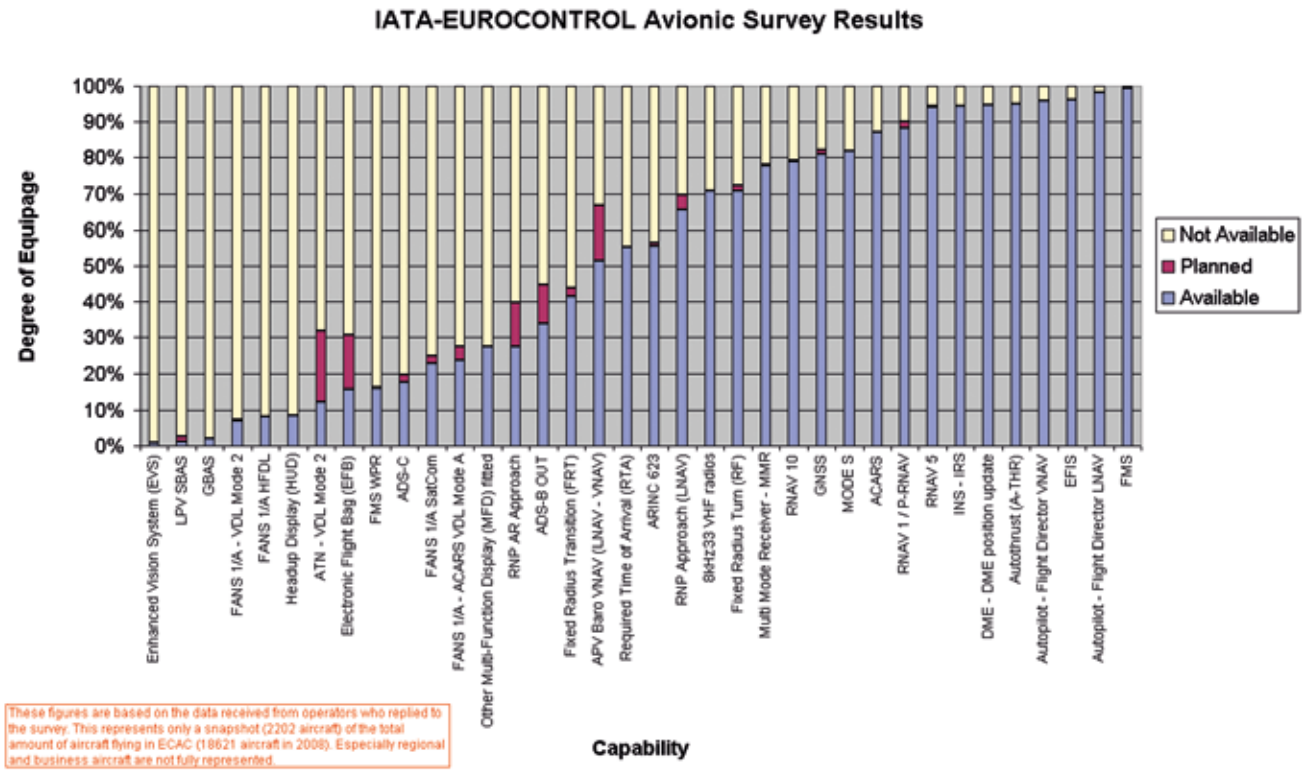


Several key assumptions (related to future enablers) of importance to PBN are singled out for additional explanation. These relate to the airborne navigation capability and Navaid Infrastructure availability.

PBN Assumptions & Enablers 1/2: Fleet Mix and airborne Navigation Capability

Traffic assumptions are of crucial importance to the new Airspace. First, the traffic mix must be known: what proportion is there of jets, twin turboprops, VFR single-engined trainers etc., and what are their overall range of speed, climb and descent performances. Understanding the fleet mix and aircraft performance is important to any airspace concept development, but in a PBN Implementation context, traffic assumptions related to **fleet navigation capability are the most significant**. This is because the predominant navigation capability in the fleet provides the main indicator as to which ICAO navigation specifications can be used as the basis for designing the airspace concept to make the PBN Implementation cost effective.

A **Cost Benefit Analysis (CBA)** is an efficient way of determining whether the design of PBN ATS routes (incl. SIDs/STARs and Instrument Approach Procedures) will be cost effective. (The Navaid Infrastructure costs are also integral to a CBA and is discussed below). Particularly when an airspace mandate is envisaged, the higher the number of aircraft already qualified for the intended navigation specification, the lower the retrofit costs and benefits can be realised more quickly. But high fleet equipage with a particular functionality is only helpful if ALL the functionalities associated with the targeted navigation specification are also widely available in the fleet. This means that for PBN implementation to be cost effective, the majority of the fleet should have all the capability required in the navigation specification intended for implementation. Partial qualification for a navigation specification is not possible. A sample CBA process used by one State is provided at Attachment 2a.



An equipage questionnaire culminating in a graph such as the one above (a 2010 European Avionics Survey) is a useful tool for analysing fleet capability

In undertaking such an analysis, it is equally important to determine what area navigation system upgrades are expected in the period up to implementation; these may affect the implementation date and significantly impact the CBA. The certification of a specific RNAV capability and maintaining pilot currency in the operation of that capability is costly for the operator. As a result, especially with regional operations, operators will only seek approval sufficient to meet the existing navigation requirements for the airspace. The (future Airspace Concept may require functionality present in the software but not specified in the existing certification. While it will cost operators to gain approval and undertake the pilot training for this new functionality, the cost is likely to be significantly less than if the aircraft requires retrofitting with new equipment or software as well as having an adverse effect on implementation timescales.

Focusing the fleet analysis for selection of a potential Navigation Specification

The PBN Manual makes it clear that the ICAO navigation specifications cover certain flight phases. For Terminal operations, for example, there are essentially three available navigation specifications i.e. RNAV 1, RNP 1 and Advanced RNP. The PBN Manual also explains that certain RNP specifications can be 'augmented' by additional functionalities such as Radius to Fix (RF). So if the airspace concept is for a complex, high-density airspace where routes are to be placed in close proximity, an RNP specification with some extra functionalities is more likely to provide that extra design flexibility. In such a case, the fleet analysis could, from the outset, be probing for fleet equipage related to functionalities associated with either/both the Advanced RNP or/and RNP 1 functionalities thereby focusing the fleet analysis. The Table on page 19 shows the ICAO navigation specifications (with equivalent European operational approvals) and permitted additional functionalities.

Navigation Specification	Flight phase								Additional Functionalities (Required or Optional)			
				Approach								
	En route oceanic/ remote	En route continental	Arrival	Initial	Intermediate	Final	Missed[1]	DEP	RF	FRT	TOAC	Baro VNAV
RNAV 10	10											
RNAV 5[2] *AMC 20-4*		5	5									
RNAV 2		2	2					2				
RNAV 1 *Rev 1* *JAA TGL 10*		1	1	1	1		1	1				O
RNP 4	4									O		
RNP 2	2	2								O		
RNP 1[3]			1	1	1		1	1	O[8]			O
Advanced RNP[4]	2[5]	2 or 1	1	1	1	0.3	1	1	R[8]	O	O	O
RNP APCH[6] *AMC 20-27* *AMC 20-28*				1	1	0.3	1		O[8]			O
RNP AR APCH *AMC 20-26*				1-0.1	1-0.1	0.3-0.1	1-0.1		*Specific requirements for RF & VNAV*			
RNP 0.3[7]		0.3	0.3	0.3	0.3		0.3	0.3	O[8]			O

Note:

1. *Only applies once 50m (40m Cat H) obstacle clearance has been achieved after the start of climb.*
2. *RNAV 5 is an en route navigation specification which may be used for the initial part of a STAR outside 30 NM and above MSA.*
3. *The RNP 1 specification is limited to use on STARs, SIDs, the initial and intermediate segments of Instrument Approach Procedures and the missed approach after the initial climb phase; beyond 30 NM from the airport reference point (ARP), the accuracy value for alerting becomes 2 NM.*
4. *Advanced RNP also permits a range of scalable RNP lateral navigation accuracies – refer to the A-RNP Nav Spec in the PBN manual.*
5. *Optional – requires higher continuity.*
6. *There are two sections to the RNP APCH specification; Part A is enabled by GNSS and Baro VNAV, Part B is enabled by SBAS.*
7. *The RNP 0.3 specification is primarily intended for helicopter operations.*
8. *Refer to the RF Appendix in Volume II Part C of the PBN manual for conditions of user.*

PBN Assumptions & Enablers 2/2: NAVAID Infrastructure availability

The Navaid Infrastructure is comprised of all navigation aids permitted by PBN, be they ground or space based. Navaids transmit *positioning* information which is received by the appropriate on-board sensor providing input to the navigation computer. The air crew in combination with the RNAV or RNP system enables ***path steering*** to be maintained along a route within a required level of accuracy.

Ground-Based (or terrestrial NAVAIDS) permitted for use with navigation specifications include DME, and to a more limited extent VOR. NDB is not a PBN positioning source.

Space-Based NAVAIDS are synonymous with GNSS (including augmentation systems). Existing operational GNSS constellations include GPS (USA), GLONASS (Russia) with the following under development: Galileo (EU), Beidou (BDS) and QZSS (Japan). Augmentation systems include wide-area and local area augmentations (termed Satellite Based Augmentation System or Ground Based Augmentation System, SBAS and GBAS, respectively). Wide-area augmentations are included in PBN; operational GNSS augmentations in use today include EGNOS (Europe) and WAAS (US). GAGAN (India), SDCM (Russia) and MSAS (Japan) are under development.

One of the original aims of PBN is to permit aircraft to use any available sensor (e.g., navigation aid and/or aircraft integration with inertial reference unit, IRU). In practice however, this freedom of choice is increasingly limited by the performance requirements for a particular navigation specification, e.g., only a specified set of sensor combinations has been determined suitable to achieve the performance requirements of a specific navigation specification. On the NAVAID infrastructure side, this means that for each aircraft sensor choice offered, suitable navigation facilities must be available and authorised for use in the desired coverage volume.

Each navigation specification stipulates which positioning sensor may be used for a particular navigation application, as can be seen from the table on the next page. The table shows that the only navigation specification with full sensor flexibility is RNAV5. The flexibility reduces the more demanding the navigation specification becomes. The table also shows that only GNSS is able to meet the requirements of any navigation specification. Because GNSS is available globally, it is essential to make GNSS available for aviation use. The steps required to do this are described in detail in the ICAO GNSS Manual (ICAO Doc 9849). However, as is shown in the figure on page 18 listing avionics capabilities, not all airspace users are currently equipped with GNSS.

Consequently, matching up the local fleet avionics capability with a particular navigation specification requires that infrastructure is available to support all potential airspace users. Specifically, Air Navigation Service Providers should provide VOR/DME infrastructure for RNAV5, and DME/DME infrastructure for RNAV5, RNAV1 and potentially also RNP specifications. However, if it would be cost prohibitive or impractical (terrain limitations etc.) to provide a specific type of infrastructure coverage, then this limitation of sensor choice will need to be declared in the AIP, with the consequence that airspace users who do not have the required sensor combination could not use those routes or procedures. Aligning airspace requirements with aircraft PBN equipage and available NAVAID infrastructure is the interactive process implied by the PBN triangle. Normally it is the NAVAID engineering department which performs the assessment of available infrastructure, in cooperation with procedure designers and flight inspection services. If facility changes are required to enable a certain application, such as the installation of a new DME or the relocation of an existing facility, sufficient lead time is required (see page 15). Consequently, this interaction should take place as early as possible to determine the initial feasibility of the infrastructure to meet airspace requirements. A short description of the infrastructure assessment process is given in Attachment 6. The input that is needed for this activity from airspace planners is which type of coverage is needed in which geographic area (horizontal and vertical dimensions). In setting those requirements, it should be remembered that providing terrestrial navaids coverage is increasingly difficult at lower altitudes.

NAV SPEC	NAVAID				
	GNSS	IRU	DME/ DME	DME/ DME/ IRU	VOR/ DME
RNAV 10	✓	✓			
RNAV 5	✓	✓	✓		✓
RNAV 2 & 1	✓		✓	✓	
RNP 4	✓				
RNP 2	✓		✓	✓	
RNP 1	✓		✓	✓	
Advanced RNP	✓		✓	✓	
RNP APCH APV Baro	✓				
RNP APCH APV SBAS	✓ + SBAS				
RNP AR APCH	✓				
RNP 0.3	✓				

Note:

The above table has been formulated from the ICAO Navigation Specifications in the PBN Manual (though naturally a local implementation would specify acceptable sensors).

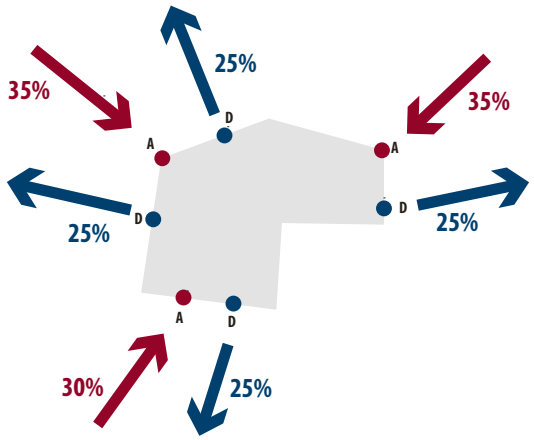
- ***Tick (Pink Background)**, sensor mandatory;*
- ***Tick (Green Background)**, Sensor use subject to ANSP requirement & aircraft capability);*
- ***Tick (grey background)**, Sensor optional.*

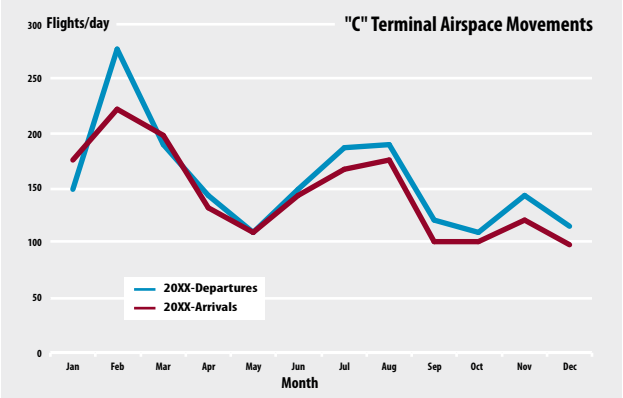
Traffic Assumptions: The Traffic Sample

The traffic sample for the new Airspace Concept is as important as the knowledge of the fleet and its navigation performance composition. This is because RNP and RNAV route placement (be they ATS Routes, SIDs/STARs or Instrument Approach Procedures) is decided to ensure maximum flight efficiency, maximum capacity and minimum environmental impact. In a terminal area, for example, RNP or RNAV SIDs and STARs/Approaches provide the link between the major en route ATS routes with the active runway (hence the importance of knowing the primary and secondary runway in use).

A traffic sample for a new Airspace Concept is usually a future traffic sample i.e. one where certain assumptions are made about the fleet mix, the timing of flights, and the evolution of demand with respect to both volume and traffic pattern. Various models are used to determine air traffic forecasts, e.g. the econometric model, and it is not surprising to note that the success of an airspace design can stand or fall on its traffic assumptions. Despite ATC's intimate knowledge of existing air traffic movements, the future traffic sample for 20XX must be thoroughly analysed (in very futuristic cases, it may even be necessary to create a traffic sample). Invariably, certain characteristics will be identified in the traffic sample e.g. seasonal, weekly or daily variations in demand (see diagram below); changes to peak hours and relationship between arrival and departure flows (see diagram below).

'Once the Implementation team has agreed the anticipated future environment then these assumptions and agreed future enablers should continue to be the stable basis for the project. That said, continuous revision of validation of these assumptions and enablers should be ensured particularly where projects continue over several years.





For both en route and terminal airspace, the design of airspace is an iterative process which places significant reliance on qualitative assessment and operational judgement of controllers and airspace and procedure designers involved from the start of in the design.

Once Activity 6 is complete, it is time to design the airspace which, in ECAC, has extensive surveillance and communication coverage. The availability of independent surveillance (i.e. Radar as opposed to ADS-B only) across most of the European continent means that the airspace design benefits more from PBN than would be the case in an airspace without radar surveillance. PBN allows, particularly in the terminal areas, repeatedly used radar vectoring paths to be replicated with RNAV or RNP SIDs/STARs thereby reducing the need for controller intervention.

The reliance on navigation performance through a navigation specification as the basis of ATS route placement is significant for the route planning in en route and terminal airspace. Whilst airspace planners know that connectivity between en route and terminal routes must be assured, if a different navigation specification is required in en route airspace to the one used for SIDs/STARs, the route spacing possibilities in en route and terminal can be different requiring a transition area where the route spacing is adjusted. Consequently, PBN-based ATS routes whether in the en route or terminal need to be fully integrated and an understanding of plans/strategies in the connecting airspace is required.

For terminal airspace changes it is important that the procedure designer participates in the conceptual design led by the operational controllers. Whilst the operational controllers seek the best route placement from an efficient traffic management perspective, procedure designers provide critical input as regards obstacles and aircraft performance.

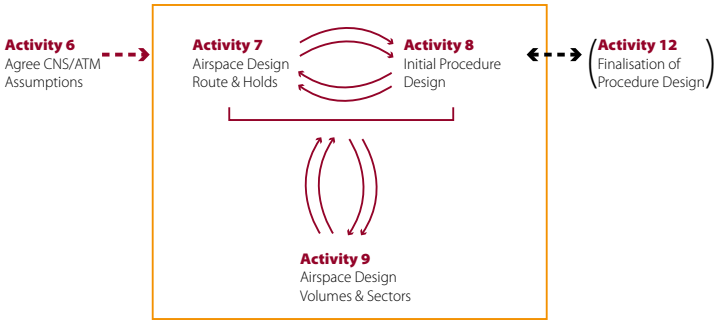
Airspace design usually follows this order:

(i) First the SIDs/STARs and ATS Routes are designed conceptually; (**Activity 7**)

(ii) Second, an initial procedure design is made of the proposed traffic flows (**Activity 8**) [this paves the way for finalising the Procedure design in Activity 12].

(iii) Third, an overall airspace volume is defined to protect the IFR flight paths (e.g. a CTA or TMA) and then this airspace volume is sectorised (**Activity 9**);

As suggested by the diagram below, Activities 7 to 9 do **not** follow a linear progression. **Iteration** is the key to the success of these three activities; the moving forwards and backwards between the activities until finally the airspace design is sufficiently mature to make it possible to move to Activity 10 and onward.



Activity 7

Airspace Design - Routes & Holds

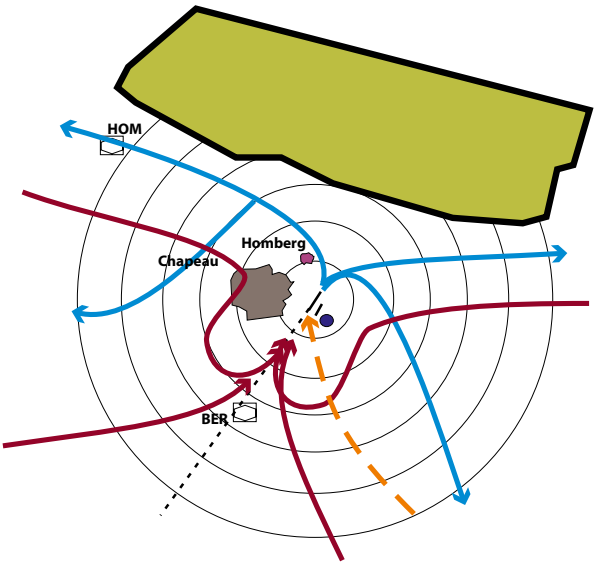
The design of traffic flows (which ultimately become the future SIDs/STARs and ATS Routes) is the starting point of this exercise. This is an analytical & iterative process (which 'at its simplest level could be achieved by using pencil and paper). Route placement is usually determined by the traffic demand, runways in use and strategic objectives – and, to a greater or lesser extent, the airspace reservations and their flexibility. Route spacing is determined by the operational requirements and the navigation approvals of the aircraft fleet determined in Activity 6 (see Note 1). For example: if a 10-15 NM route spacing is intended in an en route airspace where Radar surveillance is provided, this has been found to be viable in European airspace if the fleet is approved to RNAV 5 as determined during Activity 6. As such, the intended route spacing and CNS infrastructure indicate that PBN (in this case an RNAV 5 specification) is needed. If, on the other hand, Advanced RNP equipage is needed but the fleet does not have this capability, then it becomes necessary to decide whether to mandate Advanced RNP carriage or whether to widen the route spacing associated with a less demanding navigation specification.

Note 1: *Airspace Concepts and their generic route spacings (determined by ICAO's Separation and Airspace Safety Panel (SASP) and other organisations such as EUROCONTROL) are published in an Appendix to Volume II of the PBN Manual. Route Spacing information pertinent to European airspace planners is also provided in Attachment 5 to this Handbook.*

Note 2: *The role of the procedure designer in the terminal airspace route description and placement is of crucial importance. This specialist advises the team whether the intended routes match the navigation assumptions (Activity 6) and can be designed in accordance with obstacle clearance criteria.*

Note 3: *In some oceanic airspace concepts, principles of route placement may differ. A 'shadow' route network may exist with the tactical separation between aircraft being provided as a function of the aircraft's level of equipage. This sort of system traditionally relies on ADS-C reporting in relatively low density traffic areas.*

One of the greatest advantages of PBN is that ATS Routes, SID/STARs and Instrument Approach Procedures do not have to pass directly over ground-based NAVAIDs. PBN makes it possible to place routes in the most optimum locations subject to the necessary coverage being provided by the ground- and/or space-based NAVAIDS. This 'placement' benefit provides huge advantages. It means that routes can be placed where they give flight efficiency benefits by, for example, avoiding conflicts between flows of traffic. Similarly, routes can be designed to provide shorter track miles or vertical windows at crossing points supporting continuous descent or climb operations enabling more fuel efficient profiles with reduced environmental impact (noise, CO2 etc). It also means that parallel routes can be designed to avoid having bi-directional traffic on the same route and to provide various route options between the same origin and destination airports. Most significantly, perhaps, this placement benefit provided by PBN makes it possible to ensure the efficient connectivity between en route and terminal routes so as to provide a seamless (vertical) continuum of routes.



Key to obtaining these advantages (particularly in a terminal airspace) is the need for arrival and departure routes (STARs/IAPs and SIDs) to be designed as a function of the interaction between them as well as servicing the traffic's desired track and ensuring obstacle clearance. Route placement for PBN does not negate best practices in route design developed over decades. Some of these are provided below.

Note: *For convenience, in the text which follows, ATS routes refer to those routes usually designated as per Annex 11 Appendix 1 (e.g. UL611), whilst the undefined expression 'terminal routes' generally refers to Instrument Approach Procedures (IAPs) and arrival and departure routes (SIDs/STARs) designated in accordance with Annex 11 Appendix 3 (e.g. KODAP 2A).*

Free Routes

Increasing use is being made of Free Routeing in some part of the European upper airspace. A difference between ATS Routes and Free Routes is that fixed ATS Routes which are published in the AIP are designated using conventions prescribed in ICAO Annex 11, Appendix 1 e.g. UL611. This is not the case for European free routes which may or may not be published in the AIP. In the European continental application of free routes, some of these routes are published as DCTs (directs) between two waypoints.

This difference in designation may have some impact on the RNAV or RNP system. Current ARINC 424 coding norms allows the specification of performance and functionality

attributes to designated ATS routes, called 'airway records' in the navigation database. Particular navigation performance and functionality attributes are associated to these 'airway records' such as the navigation accuracy required along a flight segment e.g. RNP 1, or a particular way of executing a turn at a waypoint along the route (e.g. using Fixed Radius Transition). The extent to which such navigation performance attributes can be ascribed to a DCT 'route' (which have not been designated as per ICAO Annex 11 Appendix 1) is still unclear. To date, indications are that navigation performance and functionality can be ascribed to DCTs in some instances and not in others, but these conclusions are not yet definitive. For example, indications are that performance and functionality attributes assigned to the end fixes of designated ATS routes can be applied along a single DCT connecting these end fixes. For a series of subsequent DCTs for which no airway record is available in the navigation database, the system may default to a standard lateral navigation performance accuracy, e.g. 2 NM in en route. (Attachment 4 of this handbook shows examples of free route and connectivity models used in continental Europe today).

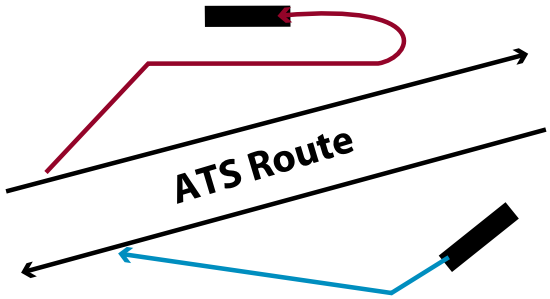
Continental ATS Routes

Published ATS Route networks are planned at continental, regional or FAB (Functional Airspace Block) level, as appropriate. The introduction of PBN means that the more widespread the planning for the use of a common navigation specification as a basis of the network's design, the more seamless the interface between different areas can be because the route spacing would not be altered. PBN does not change general good practice that uni-directional routes are better than bi-directional routes, from an ATM perspective. A parallel system of PBN ATS routes across a continent can provide great benefits in that it is possible to segregate traffic or balance traffic loads on different routes. When creating a parallel route system, care must be taken where the ATC sector lines are drawn when it comes to balancing the ATC workload. In generic European RNAV and RNP route spacing studies, the assumption is made that the parallel routes are contained in the sector of a single controller i.e. the ATC sector line is not drawn between the two routes. This means that if it became necessary to draw a sector line between the parallel routes in order to control ATC workload, the implementation safety assessment would have to address this reality and it may prove necessary to increase the spacing between the two routes. More detailed information on PBN Route Spacing between published ATS Routes is provided in Attachment 5 to this Handbook.

Terminal routes leaving/joining Free Routes or ATS Routes

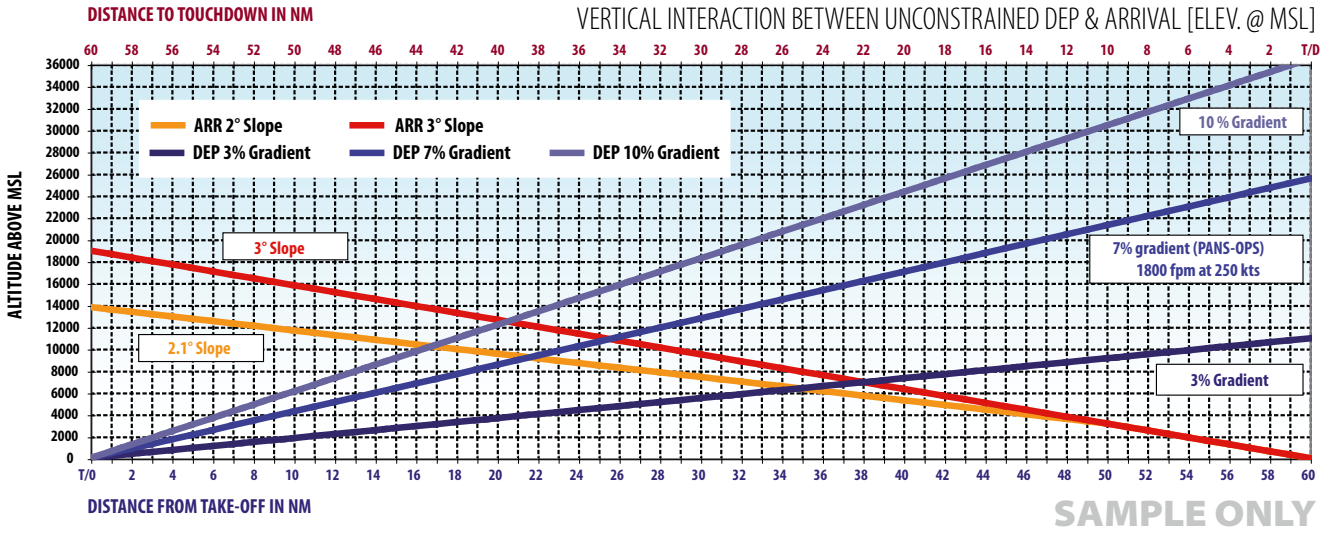
Continental traffic flows (black, in diagram) which service multiple origin and destination airports are best segregated where possible from the terminal routes to/from airports (red/blue routes in diagram). This is to avoid mixing overflying traffic with climbing and descending traffic or fixed en route ATS routes and/or free route trajectories.

Terminal routes leaving/joining the ATS Routes



Climb and Descent profiles of Terminal Routes

Whilst operators, environmental managers and procedure designers consider the placement of each SID/STAR and IAP in terms of flight efficiency, environmental mitigation and safety (obstacle clearance/flyability), ATC has to manage all traffic along the routes as a package. As such, the airspace design from an ATC perspective, needs to address the interaction between arrival and departure flows of STARs/IAPs and SIDs. Different objectives such as flight efficiency, environmental mitigation, safety and air traffic management are not mutually exclusive. It is possible to design terminal routes and achieve most of the (apparently conflicting) objectives. However, care must be taken in choosing the crossing points between departure and arrival routes. The crossing point of SIDs and STARs should not constrain the vertical path of arriving or departing aircraft (hence, knowledge of aircraft performance is essential). The sample graph on the next page (and at Attachment 3) shows that for particular (**blue**) climb gradients – 3%; 7% and 10% – and particular (**red**) arrival profiles – with specific speed assumptions – unconstrained arrival and departure profiles would seek to occupy the same level at various distances from the runway.



For example: if a departure on a 7% climb gradient (marked on graph) had travelled 25 track miles from the departure end of the runway (read on lower X axis) when it crossed the arrival on a 3° slope which was at 35 track miles from the runway (read on upper X axis), both aircraft would be in the region of 11,000 feet AMSL. So choosing this crossing point would not be efficient because it would restrict the departure's continuous climb and the arrival's continuous descent.

The procedure designer along with operational pilots provide most of the aircraft performance data to the airspace design team. With PBN, some navigation specifications provide extra confidence in the vertical as well as the lateral planes and the use of these additional requirements can be of benefit in the airspace design.

Pressure cooker (with holds) vs. extended routeings (without holds)

There tend to be two predominant 'models' used in the design of busy terminal airspaces with ATS surveillance.

The first can be compared to a pressure cooker where a number of holding patterns are spread geographically at a similar distance from the landing runway (nominally, at four 'entry points' to the terminal area). These holding patterns keep the pressure on the terminal airspace by feeding a continuous stream of arriving traffic from the holding stacks to the arrival/approach system with departures threaded through the arriving traffic.

The second model is more 'elastic' in that, in order to avoid holding aircraft, sometimes longer terminal arrival routes are designed to the landing runway. PMS (Point Merge System) is an example of the latter.

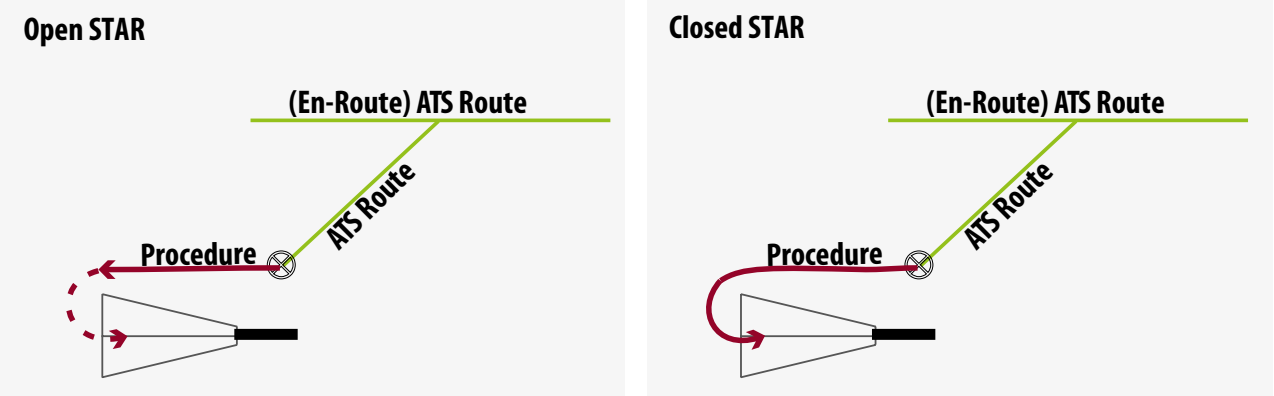
Sometimes a third model is used which is a hybrid of these two.

The advantages and disadvantages of each system can be extensively debated. Some contend that in the end the track miles flown by arriving aircraft are more or less the same irrespective of the model used, which may be true in given circumstances. However, when aiming to facilitate continuous descent, linear extensions on extended routing may provide the pilot with greater ability to plan the descent profile and hence provide benefits over holding, especially at lower altitudes.

Open vs. Closed procedures

PBN makes it possible to design closed or open procedures. Although 'Open' or "Closed' procedures are not ICAO expressions, they are increasingly in common use. The choice of an open or closed procedure needs to take account of the actual operating environment and must take into account ATC procedures.

Open procedures provide track guidance (usually) to a downwind track position from which the aircraft is tactically guided by ATC to intercept the final approach track. An Open



procedure will require tactical routeing instructions to align the aircraft with the final approach track. This results in the RNAV system only being able to calculate the descent up to the final waypoint on the procedure. This means that a continuous descent operation after this point may not be possible, due to the uncertainty of path stretching which ATC may use.

Closed procedures provide track guidance on to the final approach track whereupon the aircraft usually intercepts the ILS. The Closed procedure provides the pilot with a defined distance to touch down thus supporting the area navigation's systems execution of the vertical profile. Where multiple arrival routes are operated onto a single runway, the closed procedure can result in a safety hazard should ATC not be able to intervene to prevent the automatic turn onto final approach towards and towards other traffic. Significantly, however, Closed procedures can be designed and published in a manner that anticipates alternative routeing to be given by ATC on a tactical basis. These tactical changes may be facilitated by the provision of additional waypoints allowing ATC to provide path stretching or reduction by the use of instructions 'direct to a way-point'. However, these tactical changes, needed to maximise runway capacity, do impact on the vertical profile planned by the area navigation system.

Specific Techniques

Continuous Descent and Climb Operations are techniques currently used to respectively mitigate environmental impact and increase flight efficiency. Both of these can be directly enabled by PBN and make it possible to place routes in the most optimum place.

Activity 8

Initial Procedure Design

During the conceptual design of the arrival and departure traffic flows, the procedure designer begins the initial procedure design based on PANS-OPS criteria. This preliminary design considers various perspectives:

- It is necessary to determine whether the placement of the proposed routes are feasible in terms of turns and obstacle clearance, for example. For this analysis, local Instrument Flight Procedure design expertise is crucial because only he or she has the local knowledge of terrain and obstacles as well as the training to determine whether the intended procedures can be coded using ARINC 424 path terminators (applicable to RNAV and RNP SIDs and STARs). If these routes are not feasible from a procedure design perspective, they will need to be modified (this is an iteration between Activity 8 and Activity 7 – as per the diagram on page 22);

- Part of this analysis involves seeing whether the fleet capability and navigation specification identified in Activity 6 can meet the requirements of the intended design of routes and holds completed in Activity 7. Here again, great reliance is placed on the procedure designer and technical pilots included in the team, because if there is no match, the routes and holds will have to be modified with aircraft capability in mind.

- Consideration must also be given to the NAVAID Infrastructure: if the navigation specification identified in Activity 6 requires GNSS and/or DME/DME and the identified fleet capability identified suggests that most aircraft have DME/DME without GNSS, the intended design may generate a requirement for an additional DME. In such a case, the need for an additional DME could cause a delay to the project implementation date (because procurement of the necessary land and installation/calibration of a DME can take time). Alternatively, the conceptual routes and holds may have to be re-designed so as to exclude the need for an additional DME; this could mean a significant change to the airspace concept.

As regards feasibility referred to in the first bullet, it is clear by looking at the diagram of proposed SIDs/STARs (see example at Page 23) that RNAV or RNP would be needed for this design. The procedure designer in the airspace design team would make this clear early on. Certain ARINC 424 path terminators might be needed, as would an on board navigation database. In analysing the aircraft fleet in terms of navigation performance, the analysis would thus focus on the navigation functionalities (e.g. path terminators/data base etc) needed onboard the aircraft to fly these procedures.

Stakeholder Consultation

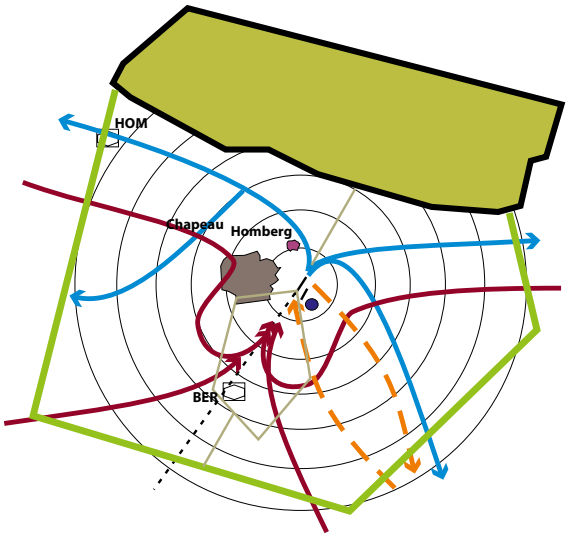
Although public consultation may be an on-going process throughout the life-cycle of the PBN implementation project, it becomes necessary to consult with specific stakeholders at various parts of the project. After Activity 8 is such a time, now that a conceptual design of routes exists. At this point of the design process, before designing the airspace volumes and sectors, it is an opportune – and very necessary – moment to undertake a formal consultation with a wider audience of airspace users. Such consultations can either take place bilterally between the team and different users, but it is often more beneficial to organise an event where several users are present and the route design is discussed with them as well as the work done on the CBA (Activity 6), the fleet analysis and the actual placement of the route from Activity 7 and 8.

Such consultations are integral to the partnership approach advocated by PBN. Every stakeholder needs to be included and to be on-board in order to ensure buy-in and the success of the implementation.

Activity 9

Airspace Design – Structures & Sectors

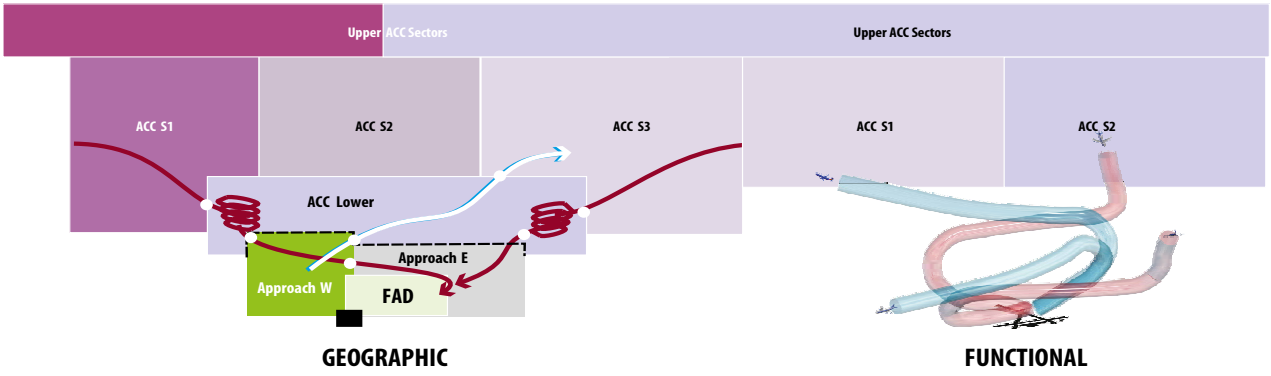
For completeness, mention is made of the non-PBN aspects of airspace design which occur after the routes have been designed and the initial procedure design is complete: first, the design of the airspace volumes followed by the sectorisation of the airspace volume.



Note: *it is highly undesirable to design the routes so as to fit them in a predetermined airspace volume or sector shape. Traffic demand and the operational requirements determine route placement, then the airspace volumes are built to protect the IFR flight paths and finally the airspace volume is sectorised in order to manage ATC workload.*

The airspace volume is created to protect IFR flight paths – both vertically and horizontally. As such it can be of any shape or size. In developing the airspace volume it may be necessary to go back and adjust the routes to ensure that they fit within the airspace volume.

Once the airspace volume is completed, then the airspace is sectorised for purposes of air traffic management. Sectorisation is done as a function of the traffic sample and traffic assignment (see Activity 6) and may be functional or geographical (or a mixture of both). Whilst en route airspace tends to be geographical, terminal airspaces tend to use either one or the other or a mix.



- Geographical Sectorisation is where the airspace volume is divided into 'blocks' and a single controller is responsible for all the traffic in a single block i.e. sector; or

- Functional Sectorisation is characterised by dividing the workload in the Terminal Airspace volume as a function of the aircraft's phase of flight. The most common type of Functional Sectorisation is where one controller is responsible for arriving flights in the Terminal Airspace whilst another is responsible for departing flights in the same Terminal Airspace volume.

Once the sectors are designed, it may be necessary to go back and revisit the route placement as determined by the controller workload generated by a given ATC sector design. The design of ATS routes, terminal routes, airspace volumes and ATC sectorisation is an iterative process.

From a purely airspace design point-of-view, neither the airspace volume nor sectors need to follow national borders. It is possible, and even desirable for reasons of flight efficiency and capacity, to design cross-border airspace volumes or sectors. In such cases, the delegation of ATS will need to be considered.

Note: *Consideration must be given to the availability of communication frequencies when determining ATC sectorisation. Given the density of ATC sectorisation in Europe, frequency management is centralised at European level through the ICAO regional Office In Paris. Additionally, States are required to cooperate on freauency maagement through the NM radio frequency function.*

Activity 10

Confirming the selected Navigation Specification

Once the airspace design activity is complete, it is important to step back and verify that the design can indeed be supported by the navigation specification identified in Activity 6.

This activity is a relatively simple step if Activities 6 – 9 have been done in an integrated manner and if Activity 6 has definitively identified one particular specification as the basis for the design. In such cases, this step can be used to refine the choice between two navigation specifications and to decide on one of the two. Alternatively, it may be viable to have provided for two sets of design each based on different navigation specifications. Both could then be subjected to an in-depth feasibility assessment to establish the final choice.

In rare instances, despite full integration of activities 6 to 9, confirming the chosen Navigation Specification can be quite complex - even once the airspace concept has been completed and the validation phase looms. A specific example of this can be seen in the en route airspace of the ECAC area of Europe where the initial intent of implementing RNAV 1 foreseen for the 1990s had to be scaled back to an RNAV 5 implementation when it became clear nearly three years before the 1998 implementation date that the expected natural replacement of the older equipment meeting RNAV 5 with systems compatible with RNAV 1 was much slower than expected. This example serves to emphasise, again, the importance of fixing realistic assumptions in Activity 6.

VALIDATION

By the time the airspace design is complete, the Airspace Concept has become a comprehensive body of work that needs to be validated and checked. Validation takes place in various phases: the airspace design is usually validated first; once this has been done the Instrument Flight Procedures are designed and validated. In fact, during the design phase, many of the iterations can be considered as part of the validation process.

This section of the brochure first discusses the **airspace design and ATM validation** and then the **validation of instrument flight procedures**.

Activity 11

Airspace Concept Validation

The main objectives of airspace design and ATM validation are:

- To prove that the airspace design has successfully enabled efficient ATM operations in the airspace;
- To assess if the project objectives can be achieved by implementation of the airspace design and the Airspace Concept in general;
- To identify potential weak points in the concept and develop mitigation measures;
- To provide evidence and proof that the design is safe i.e. to support the Safety Assessment.

Two kinds of assessment/validation can be distinguished: Quantitative and Qualitative. Both are needed and they are undertaken at the same time as each needs information produced by the other method. Consequently it is essential that the results are viewed as a single entity even if they are significantly different approaches.

In general terms, **Quantitative Assessment** refers to validation methods that are numerical and rely on the quantification of data. Validation by Quantitative Assessment often relies on tools which are primarily – but not exclusively - computer-based simulators. **Qualitative Assessment** is different in that it is not reliant on data but more on reasoning, argument and justification. These three pointers indicate why Quantitative and Qualitative assessment cannot be separated. Data from a quantitative assessment cannot be accepted as such: it needs to be analysed, reasoned through and checked for validity: these are the very tools of Qualitative Assessment.

	Input	Assessment Bench Mark used	Output	Validation method
Qualitative Assessment	Published & Proposed Airspace Design (Routes/ Holds, Structures and Sectors)	Non-numerical Performance and Safety Criteria based upon ICAO SARPs, Procedures and Guidance material and National/Local regulations.	Mainly textual/ diagrammatic reasoning, argument, justification.	■ Expert ATM/CNS judgement; ■ Airspace Modelling; ■ FTS/RTS; ■ Live ATC Trials.
	Input	**Assessment**	**Output**	**Validation method**
Quantitative Assessment	■ Published and Proposed Airspace Design (Routes/ Holds, Structures and Sectors) usually in computer data format representing Airspace Organisation and Traffic Samples. ■ Surveys - radar data recordings, flight plan recordings, flight recordings, questionnaires. ■ Statistics & forecasts - airports operations statistics, meteorological data collections, traffic demand, traffic distribution.	Absolute Numerical Performance and Safety criteria based upon Performance and Safety Criteria based upon ICAO SARPs, Procedures and Guidance material and National/Local regulations.	Numerical data (primarily).	■ Airspace Modelling; ■ FTS/RTS; ■ Live ATC Trials; ■ Flight Simulator; ■ Data Analytical Tools; ■ Statistical Analysis; ■ Collision risk modelling.

There are several tools or methods available to undertake validation of the airspace concept, or the validation of specific procedures or to validate certain elements of the concept. These are:

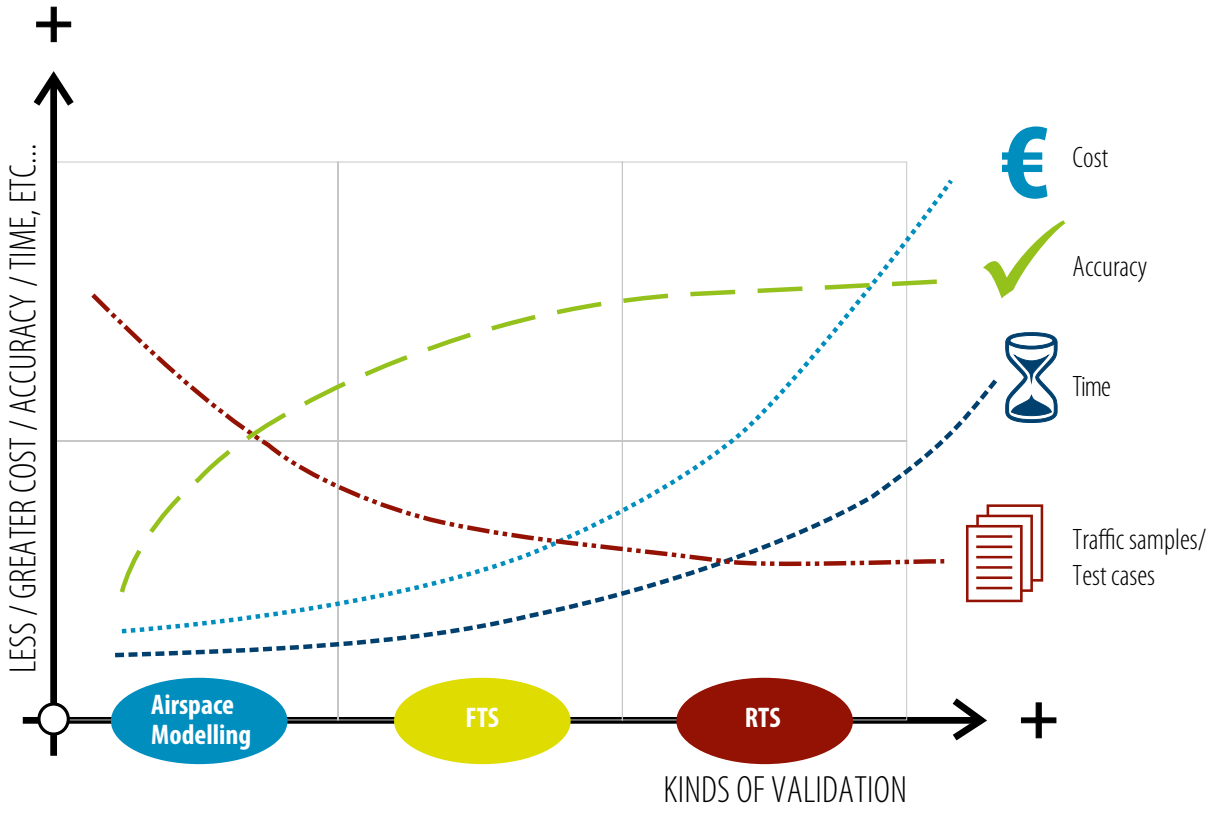
- Airspace Modelling;
- Fast and Real-time Simulation (FTS/RTS);
- Live ATC Trials;
- Flight Simulator;
- Data Analytical Tools;
- Statistical Analysis;
- Collision Risk and Modelling (CRM).

Each of these differ in terms of Cost, Realism (and complexity), Time and the number of Traffic Samples and Test Cases used – see the figure below. Generally, the more complex the simulation method used, the greater the cost, preparation/run time required and the closer to reality the results become. In contrast, and normally for reasons related to cost/time – the number of traffic samples/test cases tend to decrease as the complexity of the simulation method used increases.

General Considerations

One of the most important things to remember about most ATM-related computer- based validation tools is that the navigation performance of the aircraft is usually unrealistically excellent. This may be perceived as a drawback but in reality it does not impact the main aim of the validation exercise which is to check the ATM workability and safety of the proposed Airspace Concept. If specific investigation of the impact of navigation failure modes (e.g. track deviations) is desired this will require scripting into the simulation scenarios. However, the route spacing criteria already take account of navigation failure modes and consequently there may not be a requirement to simulate specific failure scenarios.

The number and extent of validation methods used and their duration is directly linked to the complexity of the airspace design and the complexity of the Traffic Sample. As more changes are envisaged and the greater their safety and operational impact, the greater the requirement becomes for accurate and detailed investigation to prove their operational benefits and fulfilment of safety criteria.



For these reasons, the design team should allocate enough time in the project plan for the appropriate level of assessment (modelling, fast time and real time simulation, and/or live trials). The planning should be made as flexible as possible because the results of one Validation method could heavily impact upon the next Validation step in the sequence or could lead to the suspension of the validation process and a return to the design phase. Of particular importance is the need to book time slots during the project planning phase for the validation of the Airspace Concept. Fast- and Real-time simulators are usually limited resources. Many countries do not own such simulators and it is therefore important that during the project planning phase, a period of time for validation simulations is provided for and the availability of the simulator is assured. Many projects have been delayed because of the non-availability of simulators at the crucial time.

If weaknesses are found during the validation exercise to the extent that it is necessary to return to the design phase of the project, there is merit in doing this. For a variety of reasons, not the least being cost, it is better to return to the drawing board sooner rather than later.

Airspace Modelling

The Airspace modelling is seldom used in isolation to validate an airspace design, but tends to be the first of several validation methods used. Like most validation tools, the airspace modeller is computer based. Most frequently, the airspace modeller is used during the airspace design phase because it enables the airspace design team to visualise, in three dimensions, the placement and profile of routes, the airspace volumes and the sectorisation. This ability to see in three dimensions is extremely useful.

Airspace modelling tools can be considered as "scaled down" version of Fast Time Simulators. Their main usage is to create a non-refined representation of the routes and airspace volumes (sectors) together and their interaction with a selected traffic sample. The tool generates simplified 4D trajectories (position + time) for the aircraft according to the flight plans described in the Traffic Sample (with its Rules) in a particular Airspace Organisation (with its Rules). This process is called traffic assignment. These trajectories are used together with the airspace blocks to calculate a series of statistical data such as: sector loading, route segment loading, conflicts, etc. Some more advanced airspace modelling tools can derive more precise data with regard to the workload and sector capacity.

Fast-Time Simulation (FTS)

As a validation methodology, Fast-Time Simulation is a valuable and frequently used way of validating a proposed design and it may also be used as a way of demonstrating that the safety objectives have been met.

Advantages and Disadvantages of Airspace Modelling

Advantages	Disadvantages
■ great flexibility; ■ simple to assess various alternatives; ■ easy Scenario adaptation and generation of Test Cases; ■ easy to create and assess «what if» Test Cases; ■ easy to test large number of traffic samples; ■ can use data derived from real traffic and ATC environment.	■ crude representation of real environment; ■ can provide only high level statistical data; ■ cannot replicate tactical controller interventions; ■ basic aircraft performance; ■ simplified trajectories; ■ no representation of meteorological conditions; ■ results accuracy depends heavily on the assessor ability and experience; ■ high degree of subjectivity; ■ difficult to involve users.

Advantages and Disadvantages of Fast-Time Simulation	
Advantages	**Disadvantages**
■ one of the most frequently used methods for sector capacity assessments; ■ gives opportunity to collect quality data; ■ relatively unlimited scope and great flexibility; ■ relatively simple to assess various alternatives; ■ relatively easy Test Case adaptation; ■ relatively easy to test large number of traffic samples; ■ can use real traffic and environment data; ■ good acceptance of the results; ■ can evaluate the achievement of the TLS (Target Level of Safety); ■ can inform safety case development.	■ simplified model of "real" operation; ■ can provide only statistical data; ■ cannot replicate tactical controller interventions; ■ quality of results depends heavily on the accuracy of the model; ■ limited aircraft performance and simplified aircraft behaviour; ■ low representation of meteorological conditions; ■ difficult to involve users.

In some cases, the use of an airspace modeller is not made and then the airspace design team use fast-time simulation as the first step in the validation process once the airspace design is complete. Usually used prior to real-time simulation, FTS might also be the only step used to validate the concept. Because fast-time simulation is less demanding than real-time simulation in terms of human resources, this is often a preferred method for improving the proposed design, identifying flaws in the design concept, and/or preparing the path to real-time simulation or direct implementation.

Fast Time simulators need the airspace organisation and Traffic Sample to be defined for the simulated environment using specific computer language and the parameters that are needed include Routes, a traffic sample which is assigned on the routes, Airspace volumes and Sectors and Rules for aircraft behaviour.

The simulator engine generates 4D trajectories (position + time) for each aircraft based upon flight plan information and rules stated in the Test Cases. The system checks each trajectory for certain predefined events. Examples of such predefined events may include conflicts (remembering that defining the parameters of what constitutes a conflict might need to be written into the rules), level changes, routes changes, sector entry or exit. When such an event is detected, the system increments the defined counters and trigger tasks parameters linked to the event. For example, if the system detects that an aircraft has crossed a sector boundary, it will increase by one the number of aircraft counted in that specific sector and will trigger as active the tasks assigned to the controllers (such as hand-over, transfer of communication, identification, etc).

In the simulator model, controller actions are described by task. These tasks are basic ATC actions, which are triggered by specific events and have a time value associated with them. This value is the time required in real life for the controller to fulfil the specific action.

The simulator adds the values of the task parameter for a given Test Case and the result value gives an indication of controller workload. Usually, a controller is considered not to be overloaded if this figure does not exceed 70% of the total time of the Test Case.

The precision of workload indication is higher when the ATC modus operandi is better known and formalised, e.g. it could be described by basic task with clearly identified trigger events and well determined time parameters.

Real-Time Simulation (RTS)

Real-Time Simulation is used in the later stages of the validation of a proposed design and it may also be used as a way of demonstrating that both the safety objectives and operational objectives have been met.

Often, the real-time simulation is used as a final check of the design and as the preparatory step for the implementation. This method is used mainly because it provides live feedback from the operational air traffic controller and for its potential high degree of realism.

A Real Time Simulator tries to replicate as accurately as possible the real working environment of involved air traffic controllers. The main components of a RTS platform are:

- simulator engine;
- active controller positions;
- pseudo pilots and feeder sectors;
- data recording system.

The simulator engine processes the flight plans and the inputs from the pseudo pilots and controllers and provides all positions with replicated data as obtained from operational Radar Data Processing Systems (RDPS) and Flight Data Processing Systems (FDPS).

Advantages and Disadvantages of Real-Time Simulation

Advantages	Disadvantages
■ closest simulation method to the live ATC trials which can be used to assess and validate simulation objectives; ■ gives opportunity to collect high quality quantitative and qualitative data; ■ feed-back from controllers, based on operational experience (further qualitative assessment); ■ feed-back from pseudo-pilots (depending on their expertise and simulation conditions); ■ can indicate and assess human factor related issues (further qualitative and quantitative assessment); ■ automatic data collection (for quantitative assessment); ■ unlimited scope and greater flexibility compared to the live trials (further qualitative assessment); ■ no risk to the live operation; ■ allow testing of contingency procedures and hazard analysis (qualitative and quantitative assessment); ■ simple to assess various alternatives; ■ on-line feed-back and scenario adaptation (qualitative assessment); ■ can use real traffic and environment data (quantitative input); ■ good acceptance of the results by the controllers (wide scope qualitative assessment); ■ can be part of a safety case.	■ sterile environment: limited HMI (Human Machine Interface) capabilities, artificial RT, limited radar performance; ■ limited aircraft performance and simplified aircraft behaviour; ■ not realistic aircraft behaviour due to pseudo-pilots without, or with limited, aviation experience; ■ pseudo-pilots cannot replicate real crews performance; ■ low representation of meteorological conditions; ■ human factor related drawbacks: ❍ controller mind-set; ❍ exercise/scenario learning curve; ❍ subjectivity of assessment (mainly with regard to workload); ❍ macho attitude; ❍ controllers feed-back clouded by historic experience; ❍ cost and time demanding. ■ potentially resource intensive; ■ difficulties related to the operational controllers availability for simulation; ■ difficult to involve users directly. Note: Also see 'lessons learned'

Advantages and Disadvantages of Live ATC Trials	
Advantages	**Disadvantages**
■ it is the most accurate validation method; ■ real data is collected; ■ gather feed-back from all users; ■ good acceptance of the results by the users.	■ safety implication; ■ great detail required which makes preparation time consuming; ■ limited scope in that they tend to look at one specific aspect of an operation, without a big picture overview; ■ limited flexibility.

Live ATC Trials

Live ATC Trials are probably the least used validation method. Generally, this is because it is perceived as carrying the highest risks despite providing what is probably the most realism. When used, Live Trials tend to be aimed at assessing a very specific element of the airspace change such as a new SID or STAR or a new Sector design with very limited traffic.

Flight Simulation

Full flight simulators are renowned for their superior realism and accuracy in reproducing all of the operational characteristics of a specific aircraft type. Normal and abnormal situations, including all of the ambient conditions encountered in actual flight, can be precisely simulated. The use of simulators has increased due to advances in technology and the significant cost savings provided by flight simulation training, compared with real flight time. Today's commercial flight simulators are so sophisticated that pilots proficient on one aircraft type can be completely trained on the simulator for a new type before ever flying the aircraft itself.

In addition to pilot training, flight simulation has an invaluable role to play in other aeronautical areas, such as research, accident investigation, aircraft design and development, operational analysis, and other activities such as space flight. Research areas include new concepts, new systems, flying qualities, and human factors. Most aircraft manufacturers use research simulators as an integral part of aircraft design, development and clearance. Major aeronautical projects would now be impractical without the extensive use of flight simulation, on both cost and safety grounds.

Specific airspace project use

A significant amount of the planning task for (particularly) Terminal Airspace Design can be achieved by the other assessment methods shown in this section with the use of flight simulators.

There are several areas in which the use of a flight simulator can assist in the successful completion of Terminal Airspace projects. One example is in the achievement of credibility. In addition to the well known noise and emission effects on operations on and around runways, environmental issues are now influencing the positioning of routes (and their associated altitude) within the whole of Terminal Airspace at an increasing number of locations due to strong environmental lobby groups. It has become clear that it can be very difficult to convince these groups that their environmental concerns have been addressed fully by the use of mathematical models and/or fast-time simulations – and this is where flight simulators come into their own.

Using representative aircraft (simulators), the various options for airspace can be extensively flown and data recorded, such as airframe configuration (which affects the noise produced by the aircraft), fuel burn, track miles flown, altitude and so on. Depending on the requirements of a project and the sophistication of the data which is gathered, the results can be fed into analysis software for such parameters as aircraft noise and emissions.

Apart from intensive, expensive live flight trials which are difficult to integrate with on-going operations, the use of the flight simulator is the closest to reality. The credibility factor

is further enhanced if operational line pilots are used to fly the flight simulator. Once the data has been analysed, it can then be presented in the most appropriate way for the target audience.

Noise Modelling

The increasing sensitivity to the environmental impact of transport is a reality to which aviation is no stranger. Increasingly, environmental impact assessments need to be made when changes are to be made to terminal routes, within a terminal area. The changed placement of any SID STAR/IAP or the introduction of any new procedure requires an environmental impact assessment in many countries and very often, the biggest political issue with local councils is aircraft noise.

Noise Modellers use an advanced form of fast-time simulator which is capable of calculating noise contours over a pre-defined area. These 'noise-modelling' functionalities are added to typical functionalities (such as a flight trajectory calculation) included in 'standard' fast-time simulators.

In order to generate the noise contours for each simulated aircraft in addition to the flight trajectories, the noise modeller determines (according to the aircraft model) the estimated speed and engine power setting/thrust. Based on this data and taking into account the terrain contours and other environmental conditions (time of the day, meteorological condition, etc), the simulator calculates the noise distribution and noise level at predetermined check points.

The accuracy of the results very much depends upon the realism of the aircraft models used by the simulator and on the model used for calculating noise distribution. Aircraft trajectories can be directly derived from recorded radar data from real-live operations. Even so, modelling individual aircraft is difficult even when using advanced computational technologies. Movements are allocated to different aircraft 'types' and aircraft that are noise 'significant' (by virtue of their numbers or noise level) are represented individually by aircraft type, e.g. B747-400. Some 'types' are grouped together with those having similar noise characteristics. For each 'type', average profiles of height and speed against track distance are calculated from an analysis of radar data. These average profiles are subdivided into appropriate linear segments.

Average ground tracks for each route are calculated based on radar data. Accurate noise exposure estimation requires a realistic simulation of the lateral scatter of flight tracks actually observed in practice. This is done by creating additional tracks which are a number of standard deviations either side of the central average track. The standard deviations and the proportions of traffic allocated to each route are determined by analysis of the radar data.

PROJECT CHECKPOINT

The following paragraph and information blocks have been copied from the PBN Manual. They discuss various aspects of the decision making process at the project checkpoint. This decision point is usually, but not always, internal to the project team. As far as the team is concerned, this is when the design team declares itself satisfied with the airspace concept's suitability for implementation or decides to re-develop the airspace concept or, at worst, decides to abandon the project.

Deciding Factors

During the validation process, it becomes evident whether the proposed PBN implementation is possible, and this is the most likely place to make the decision as to whether to go ahead with implementation. This decision is based on certain deciding factors i.e. not the least of which are whether Safety and Performance Criteria have been satisfied. Other factors can prevent a 'go' decision, e.g.–

a) A change to the ATM system (see below), needed to support the implementation, may prove impossible to realise despite careful identification of this enabler and a go-ahead being given by ATM systems engineers; or, for example

b) Dramatic political events which have nothing to do with the airspace design and which could not have been foreseen when the Traffic Assumptions were chosen, could nullify the entire airspace concept. This could occur, for example, if the entire design concept rested on the (traffic) assumption that 80% of the traffic would enter the Airspace from the west and unforeseen political events change the geographic distribution of the traffic completely;

c) Unforeseen change by the lead operator concerning aircraft equipment upgrades causes the collapse of the Business Case or, for example, Navigation assumptions, or airline insolvency.

An aware and fully integrated PBN Implementation team should not be caught out by last minute surprises described in bullets a) and c), above. One thing is certain, however, the possibility of unexpected events is one of the reasons why it is necessary to fix a go/no-go date for implementation.

Regional and State Considerations

A PBN implementation for oceanic, remote continental and continental en route operations, generally requires regional or multi-regional agreement in order that connectivity and continuity with operations in adjoining airspace can ensure maximum benefits. For terminal and approach operations, the PBN implementation is more likely to occur on a single-State basis although TMAs adjacent to national borders are likely to require multinational coordination.

Note: *For instance, in the European Union the obligation to implement PBN in defined volumes of airspace could be established in the framework of the Single European Sky.*

Where compliance with an ICAO navigation specification is prescribed for operation in an airspace or on ATS routes, these requirements shall be indicated in the State's Aeronautical Information Publication.

Implementation Options: Is there a need to mandate a navigation specification?

One of the toughest decisions to be made by the PBN Implementation team is whether or not to propose a mandatory requirement for a particular navigation specification for operation within an airspace. There are usually three implementation options which can be considered:

No mandate but phased implementation leading to mixed mode navigation capability

Generally, phased implementation of a navigation specification is more popular with airspace users (no costs are involved to retrofit). That said, without a mandate, there may be little incentive for aircraft to obtain operational approval and the fleet's navigation performance remains mixed. Consequently NAVAID infrastructure evolution may also be slowed as all the permitted navigation specifications (or even conventional navigation) must be supported. Information on Mixed Mode Operations is provided at Attachment 7.

Mandate navigation enabler

This option is usually popular with ANSPs because the homogenous nature of the traffic reduces the need for ATM system changes compared to the mixed environment. ATC prefer this option because all aircraft are treated the same way. The airspace design and operations within the airspace are simpler for reasons of uniformity. From the users' perspective, this decision is often not popular, however, because it usually involves retrofits which can be costly. For this reason, a favourable business case is essential to supporting a mandate. It is not possible to persuade airspace users without a positive benefits case.

Two mandate scenarios can be envisaged: an equipment mandate (where all aircraft above a certain mass are required to be approved against a particular navigation specification) or an airspace mandate (requiring all aircraft operating within an airspace volume to be approved against a particular navigation specification). Whilst equipment mandates seem more palatable, their net effect is that a mixed navigation environment can in fact exist if, for example, high-end business jets were to be below the cut off mass. Mandate considerations include:

- **a)** Business case; and
- **b)** The lead-time to be given to airspace users and, depending on the nature of the mandate, various service providers such as ANSPs; and
- **c)** The extent of the mandate (local, regional or multi-regional) ; and
- **d)** Safety cases; and
- **e)** Implementation Plans. This option involves an investment for the airspace user (including a 7 year lead time) with less costs being incurred by the ANSPs. This option will ensure that capacity is maintained or increased. However, this option may result in slowing the pace of change (to more advanced navigation capability) if the lowest common denominator is selected as a mandate for the airborne navigation enabler.

Mixed Mandate.

A "mixed-mandate" can be used within an airspace volume where, for example, it is mandatory to be approved to an RNAV 1 specification for operation along one set of routes, and RNAV 5 along another set of routes within the same airspace. The issues raised under the mixed environment also pertain to such a variant.

In remote continental/oceanic airspace, it is not uncommon to have a mixture with approval against a navigation specification being mandatory along certain routes whilst no such requirements exist on other routes. In such cases, sophisticated ATM systems can determine the required spacing between random tracks or separation minima can be established between aircraft using specific approved conflict probes. This is a truly user-orientated service but difficult to achieve in high density/complex airspace.

Activity 12

Finalisation of Procedure Design

Only once the airspace design and ATM validation is complete does the Instrument Flight Procedures specialist set about finalising the design of the IFPs (SIDs, STARs/IAPs) using the criteria in ICAO Doc 8168 – Aircraft Operations. Being an integral member of the airspace design team from the outset, the IFP designer is familiar with the procedures to be designed and the Airspace Concept into which they will fit. This activity occurs iteratively with Activity 13.

For PBN, procedure designers need to ensure that the procedures can be coded in ARINC 424 format. Currently, this is one of the major challenges facing procedure designers. Many are not familiar with either the path terminators used to code RNAV systems or the functional capabilities of different RNAV systems. Many of the difficulties can be overcome, however, if close cooperation exists between procedure designers and the data houses that compile the coded data for the navigation database.

Once these procedures have been validated and flight inspected (see below), they are published in the national AIP along with any changes to routes, holding areas, or airspace volumes.

Activity 13a

Instrument Flight Procedure Validation

This activity occurs iteratively with Activity 12.

The purpose of this validation is to obtain a qualitative assessment of procedure design including obstacle, terrain and navigation data, and provides an assessment of flyability of the procedure.

The validation is one of the final quality assurance steps in the procedure design process for instrument flight procedures (IFP) and is essential before the procedure is published.

The full validation process includes Ground validation and Flight validation.

Ground Validation must always be undertaken. It encompasses a systematic review of the steps and calculations involved in the procedure design as well as the impact on flight operations by the procedure. It must be performed by a person trained in Flight Procedure Design and with appropriate knowledge of Flight Validation issues.

Ground validation consists of an independent IFP design review and a pre-flight validation. Flight validation consists of a flight simulator evaluation and an evaluation flown in an aircraft (though both evaluations are not always necessary). The validation process of IFP(s) must be carried out as part of the initial IFP design as well as an amendment to an existing IFP. (One of the particular challenges at this point is making a pre-production database available to the flight validation aircraft).

For detailed guidance on validation see ICAO doc. 9906 "Quality Assurance Manual for Flight Procedure Design" vol. 5 "Validation of Instrument Flight Procedures".

Activity 13b

Flight Inspection

Flight inspection of NAVAIDs involves the use of test aircraft, which are specially equipped to measure compliance of the navigation aid signals-in-space with ICAO standards. Due to the flexibility of PBN to create routes or procedures in areas where a particular ground facility has normally not been flight inspected, it may be necessary to perform dedicated flights. Of primary interest is the actual coverage of the NAVAID infrastructure required to support the flight procedures designed by the flight procedure designer. Depending on the avionics capabilities of the test aircraft, flight inspection and flight validation activities may be combined. The amount of flight inspection required is determined by the infrastructure assessment conducted as part of Activity 6, and is part of the validation process.

The Manual on Testing of Radio NAVAIDs (ICAO Doc. 8071) provides general guidance on the extent of testing and inspection normally carried out to ensure that radio navigation systems meet the SARPs in Annex 10 – Aeronautical Telecommunications, Volume I. To what extent a Flight Inspection needs to be carried out is normally determined in the validation process.

Go : No-Go Decision

It is usually during the various validation processes described previously that it becomes evident whether the proposed Airspace Concept can be implemented. The decision whether or not to go ahead with implementation needs to be made at a pre-determined point in the life-cycle of a project. This decision will be based on certain deciding factors, starting with achievement of the goals set for implementation. Other factors could include -

a) whether the ATS route/procedure design meets air traffic and flight operations needs;

b) whether safety and navigation performance requirements have been satisfied;

c) pilot and controller training requirements; and

d) whether changes to ATC systems such as flight plan processing, automation, as well as AIP publications are needed to support the implementation

If all implementation criteria are satisfied, the project team needs to plan for implementation, not only as regards their 'own' airspace and ANSP, but in co-operation with any affected parties which may include ANSPs in an adjacent State.

Pre-Implementation Review

At the go/no-go date, a Pre-Implementation Review is undertaken, the result of which decides whether implementation goes ahead. During the Pre-Implementation Review, the Airspace design project's progress is measured against the implementation criteria selected during the planning stage.

Examples of Criteria which an Airspace Design Team may have selected to determine whether to abandon the' implementation include:

- Collapse of the main assumptions;
- Critical Enablers become void;
- Emergence of a project-critical constraint;
- Performance/Safety Criteria are not satisfied during or by the Validation or Safety Assessment process;
- No regulatory approval;
- 'NO-GO' decision.

Although it can be very discouraging to be confronted with a 'no-go' decision, it is essential that attempts should not be made to 'produce' a quick-fix' or 'work-around' so that implementation takes place at any cost. However difficult it might be not to proceed with implementation, a 'no-go' decision should be respected.

The route to be followed after a 'no-go' decision depends upon the reason for which the 'no-go' decision was reached. In extreme cases, it may be necessary to scrap an entire project and return to the planning stage. In others, it might be appropriate to return to the selection of Assumptions, Constraints and Enablers. Furthermore it is also possible, that new Validation exercises will have to be developed, or a new Safety Assessment completed. Whatever the route, the work needs to be re-organised and re-planned.

'Go' Decision – Plan Implementation

If, on the other hand, all the implementation criteria are satisfied the Airspace design team needs to plan for implementation – not only as regards their 'own' airspace and ANSP but in co-operation with any affected parties which may include ANSPs in an adjacent State. Amongst items to be covered are ATC system integration and Awareness and Training material.

Activity 14

ATC System Integration Considerations

The new Airspace Concept may require changes to the ATC system interfaces and displays to ensure controllers have the necessary information on aircraft capabilities. Such changes could include, for example:

a) Modifying the air traffic automation's Flight Data Processor (FDP);

b) Making changes, if necessary, to the Radar Data Processor (RDP);

c) Required changes to the ATC situation display;

d) Required changes to ATC support tools;

e) There may be a requirement for changes to ANSP methods for issuing NOTAMS.

Activity 15

Awareness and Training Material

The introduction of PBN can involve considerable investment in terms of training, education and awareness material for flight crew, controllers, AIS staff, engineering etc. In many States, training packages and computer based training have been effectively used for some aspects of education and training. ICAO and EUROCONTROL provides additional training material and seminars. Each Navigation Specification in the PBN Manual, Volume II, Parts B and C addresses the education and training appropriate for flight crew and controllers. Training should be timely and not rushed; it is an excellent vehicle for gaining acceptance of airspace users and controllers. A useful technique is to use members of the the PBN Implementation team as training champions.

Activity 16

Implementation

With proper planning and organisation, the culmination of an Airspace design project is trouble-free Implementation. Nevertheless, the Airspace design team could decide to:

[i] Ensure that there is adequate representation from among the members of the team available in the operations hall on a 24-hour basis for at least two days before implementation, during implementation and for at least one week following implementation. This would make it possible for the airspace team to:

- Monitor the implementation process;
- Support the Centre supervisor/Approach Chief or Operational Manager should it become necessary to use redundancy or contingency procedures;
- Provide support and information to operational controllers and pilots;

[ii] Enable a log-keeping system for a period similar to that in [i] above, so that implementation-related difficulties may be noted and used in future project planning.

Activity 17

Post Implementation Review

After the implementation of the airspace change which has introduced PBN, the system needs to be monitored to ensure that safety of the system is maintained and determine whether strategic objectives are achieved. If after implementation, unforeseen events do occur, the project team should put mitigation measures in place as soon as possible. In exceptional circumstances, this could require the withdrawal of RNAV or RNP operations while specific problems are addressed.

A System Safety Assessment should be conducted after implementation and evidence collected to ensure that the safety of the system is assured – see ICAO Safety Management Manual, Doc 9859.

3. LESSONS LEARNED

Note on designation of European navigation specifications

European RNAV applications were implemented before the PBN concept was developed. As a consequence, some European navigation specifications had different names to those ultimately published in the PBN Manual. Europe's Basic RNAV (B-RNAV) is known in the ICAO PBN Manual as RNAV 5 and they are identical specifications, for all intents and purposes. Europe's Precision RNAV (P-RNAV) is closest to the RNAV 1 specification in the PBN Manual. There are differences between the two specifications, but they are not really consequential, and primarily concern the use of VOR/DME (permitted in Europe but not in the ICAO specification). The differences between the RNAV 1 and P-RNAV specifications are tabled in the PBN Manual, Volume II, Part B, Chapter 3.

In Europe, it has been agreed that we would continue to use the European names in order to prevent unnecessary cost to documentation changes. Thus B-RNAV and P-RNAV continue to be used.

RNAV 5 (B-RNAV) implementation in Europe

Selecting the appropriate navigation specification

The carriage of RNAV 5 equipment (identical to B-RNAV) became mandatory in European en route airspace in April 1998. Initially, a much more advanced navigation specification had been sought (RNAV 1), but due to the retention of a significant number of older aircraft in the fleet operating in the European En route Airspace, it was only possible to require approval to RNAV 5 (which is a very basic specification which does not require a navigation database and allows the manual insertion of waypoints). This was the first lesson learned: not to aim too high in terms of equipage – and that thorough knowledge of the fleet was a must to successful implementation.

Phased Airspace Concept evolution

The second lesson learned was not to change the airspace at the same 'switch on' date that RNAV 5 became mandatory. This lesson was correctly anticipated: some 6 months elapsed after the April 1998 switch-on date, during which over 1500 'exemptions' were given to B-RNAV while aircraft still operated on the 'old' conventional route network. During this six month period, a vast number of airspace concepts were being developed, one generic at pan-European level, and more detailed ones in different countries. Route spacing studies had already been completed and planners knew that routes could be spaced between 10-15 NM apart (depending on the ATC intervention rate). A great many simulations took place in order to validate the airspace concepts for B-RNAV in various regions in Europe. Once simulations were completed and validations assured, B-RNAV was implemented in packages across the continent, at first ensuring connectivity with remnants of the conventional network and ultimately moving to a total RNAV environment with a shadow conventional network remaining in some countries. In all, the transition to a RNAV 5 ATS Route Network took four to five years; this pace of implementation was realistic and manageable. .

En Route and Terminal connectivity

Another crucial lesson learned with RNAV 5 implementation is that switching to en route RNAV should not be isolated from a switch to terminal RNAV. When the en route ATS route network changed to B-RNAV, some airspace planners did not ensure connectivity to the terminal route systems. To bridge this gap, some States sought to extend B-RNAV into terminal airspace by designing B-RNAV SIDs/STARs. B-RNAV was not designed to be deployed in Terminal Airspace as it is an en route navigation specification; it is not suited to terminal operations, and certainly not below MSA. (B-RNAV has no requirements for a navigation data base, manual insertion of waypoints is allowed, up to four waypoints per 100 NM is envisaged). This had the potential to become a safety issue that needed to be arrested. Ironically, P-RNAV followed B-RNAV by just two years, but it this was not timely enough to avoid the B-RNAV 'extension' and it took considerable time and effort to recover from this situation.

Turn Anticipation and Performance

Controllers were surprised, with the implementation of RNAV in en route airspace, that all aircraft did not turn in the same way. In fact, a spread of turn performance became more visible to the controllers; in some cases with alarming consequences. Airspace planners had also overlooked the need to widen the route spacing on the turn when designing the en route ATS route network. This had to be, and was corrected.

Turn Anticipation: is variable for ambient conditions, altitude, angle of turn, phase of flight, avionics, and aircraft

P-RNAV implementation in Europe

Mandate

In contrast to B-RNAV, P-RNAV is a navigation specification for use in the design of SIDs/STARs and it was never mandated for use in European Terminal Airspace when the operational approval became available in 2000. The debate as to whether or not to mandate P-RNAV's use was long and extensive.

Controllers, on the one hand, wanted it mandated because a mixed mode environment is difficult for controllers to handle in a high density airspace even if the controller has the means of knowing which aircraft are P-RNAV equipped and which are not (which is not the case, in many instances). The fact that different sets of clearances need to be issued and different routes published depending on the type of traffic is not really viable in busy environments (operational aspects of mixed mode are provided in Attachment 7 to this Handbook). Operators, on the other hand, were less keen on a mandate because a mandate would mean, in many cases, the need to retrofit which is costly. After an extensive debate, it was decided not to mandate P-RNAV, but rather to 'enable' its use in European terminal airspace. This created a 'chicken and egg' situation: because there was no mandate, operators did not seek operational approval for P-RNAV, and because few aircraft were approved, the ANSPs saw no point in publishing procedures for which P-RNAV was a requirement. The upshot was that P-RNAV implementation log-jammed, and various initiatives were tried to undo the logjam. To date, the uptake of P-RNAV is steadily growing (it has taken almost ten years). Whilst some 95% of aircraft in ECAC are P-RNAV capable, perhaps half that number is approved. However, Schiphol mandated the use of P-RNAV in November 2012. This is certain to increase the number of approved operators.

Is it viable to mandate a terminal navigation specification for every terminal airspace in ECAC? Most people would answer in the negative. The differences in operating requirements across ECAC mean that it is not necessarily feasible to mandate one navigation specification for use across all European terminal areas. Each TMA has different operating requirements and they certainly do not have the same needs. What would work is a P-RNAV mandate in one TMA, but this has not yet happened.

Capable vs. Approved

There is a distinction between an aircraft being capable of fulfilling the requirements of a navigation specification (i.e. RNAV 1 capable) as opposed to the aircraft being approved for RNAV 1. In the former case the aircraft is not approved. One of the offshoots of many aircraft being P-RNAV capable (but not approved) is that airspace planners are tempted to take advantage of the airborne capability and they design the airspace with routes closer than those permitted by RNAV 5. This is workable as long as all aircraft are P-RNAV approved, but it is critical to note, that in a B-RNAV mandated airspace, RNAV 5 is the only standard that the aircraft have to meet, (even if many of the aircraft have P-RNAV capability), and all it takes is one aircraft to be only B-RNAV capable to compromise the safety case.

Database storage

One of the offshoots of P-RNAV implementation was that in one State where the implementation occurred, the airspace planners saw fit to design a vast number of SIDs and STARs (because PBN makes this so easy to do). This highlighted an issue which was a lack of data storage space in some older FMS databases (one airport had some 118 SIDs/STARs which left little space for much else). In the end, the airport had to reduce the number of its SIDs/STARs.

RNAV 1 and 2 implementation in the US

At a more generic level, RNAV implementation in the US has shown that coordination with stakeholders is an essential pre-requisite for success. Amongst the parties with whom coordination should be achieved are: aircraft manufacturers, operators, air traffic control, other user groups.

In particular, controllers' expectation concerning turn anticipation caused considerable difficulties. As has been found in Europe, the introduction of RNAV in an airspace seems to fill controllers with unrealistic expectations – which may or may not be caused by a lack of understanding of what RNAV can offer. In the US (and in Europe), it was found that controller expectations for flight path conformance need to be realistic. These expectations should allow for normal variations and be limited to depictions of the nominal path, flyability or simulation results alone – particularly in those cases where the Radius to Fix (RF) functionality is not available.

A mixed navigation environment

A mixed navigation environment introduces some complexity for ATS. From an ATC workload and associated automation system perspective, the system needs to include the capability of filtering different navigation specifications from the ATC flight plan and conveying relevant information to controllers. For air traffic control, particularly under procedural control, different separation minima and route spacing are applied as a direct consequence of the navigation specification.

Mixed navigation environments can potentially have a negative impact on ATC workload, particularly in dense En Route or Terminal area operations. The acceptability of a mixed navigation environment to ATC is also dependent on the complexity of the ATS routes or SID and STAR route

structure and upon availability and functionality of ATC support tools. The increased ATC workload normally resulting from mixed mode operations has sometimes resulted in the need to limit mixed-mode operations to permitting a maximum of two navigation specifications where there is one main level of capability. In some cases, ATC has only been able to accept a mixed environment where 90% of the traffic are approved to the required navigation specification; whereas in other instances, a 70% rate has been workable. Operational aspects of Mixed Mode are discussed in Attachment 7.

PBN ATC Simulations

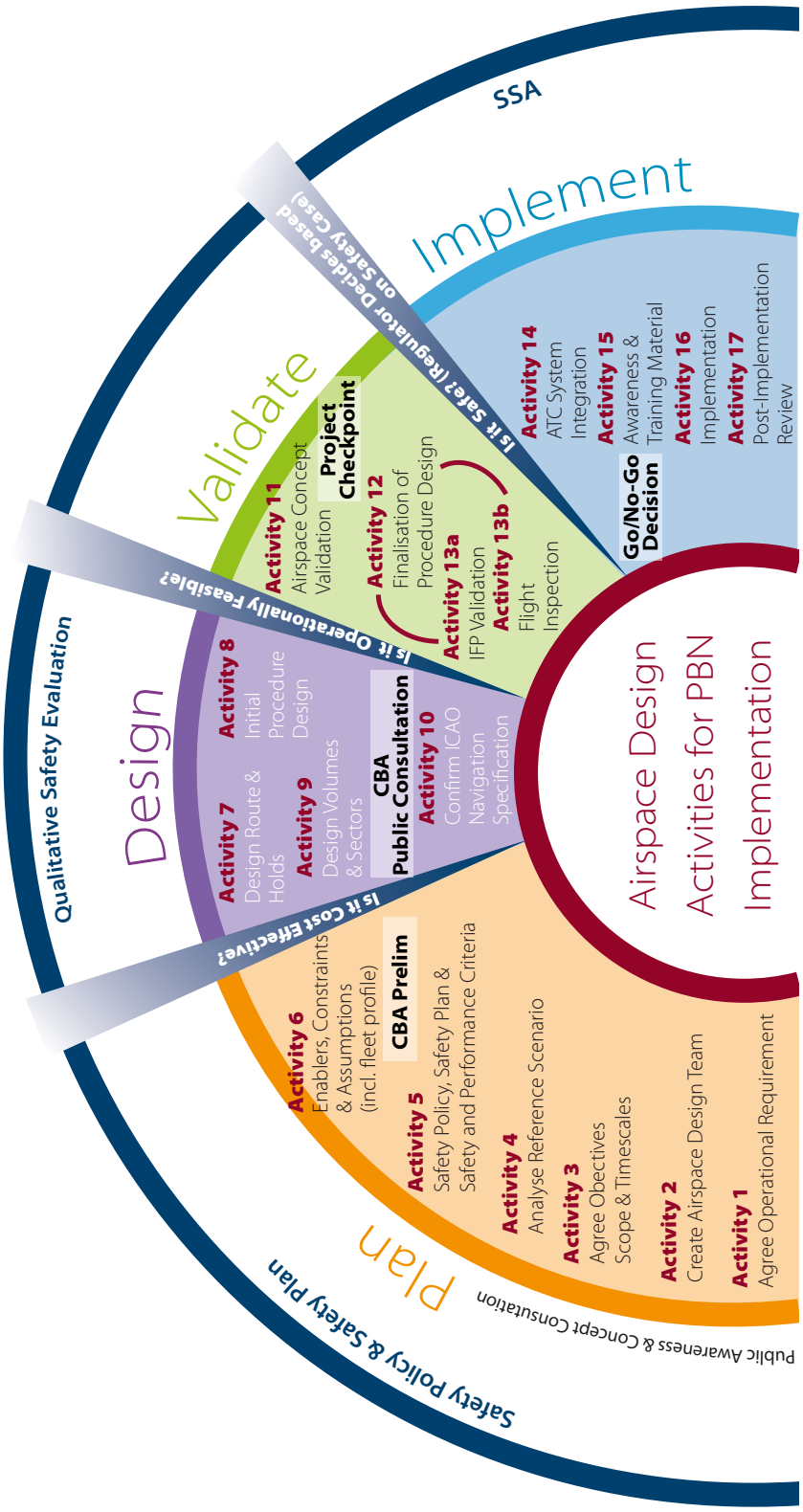
In real- and fast-time simulations, aircraft navigation accuracy is shown as being excellent because the tracks are computer generated. To make ATC simulation realistic, particularly those for route spacing, it is necessary to script in navigation errors including shallow and sharp deviations from track. Such errors would need to reflect the current error rate e.g. two errors in ten hours. Variation of turn performance should also be scripted into a simulation where neither RF or FRT are included as part of the navigation specification performance requirements.

Attachment 1:
SAMPLE PROJECT PLANNING ESTIMATION

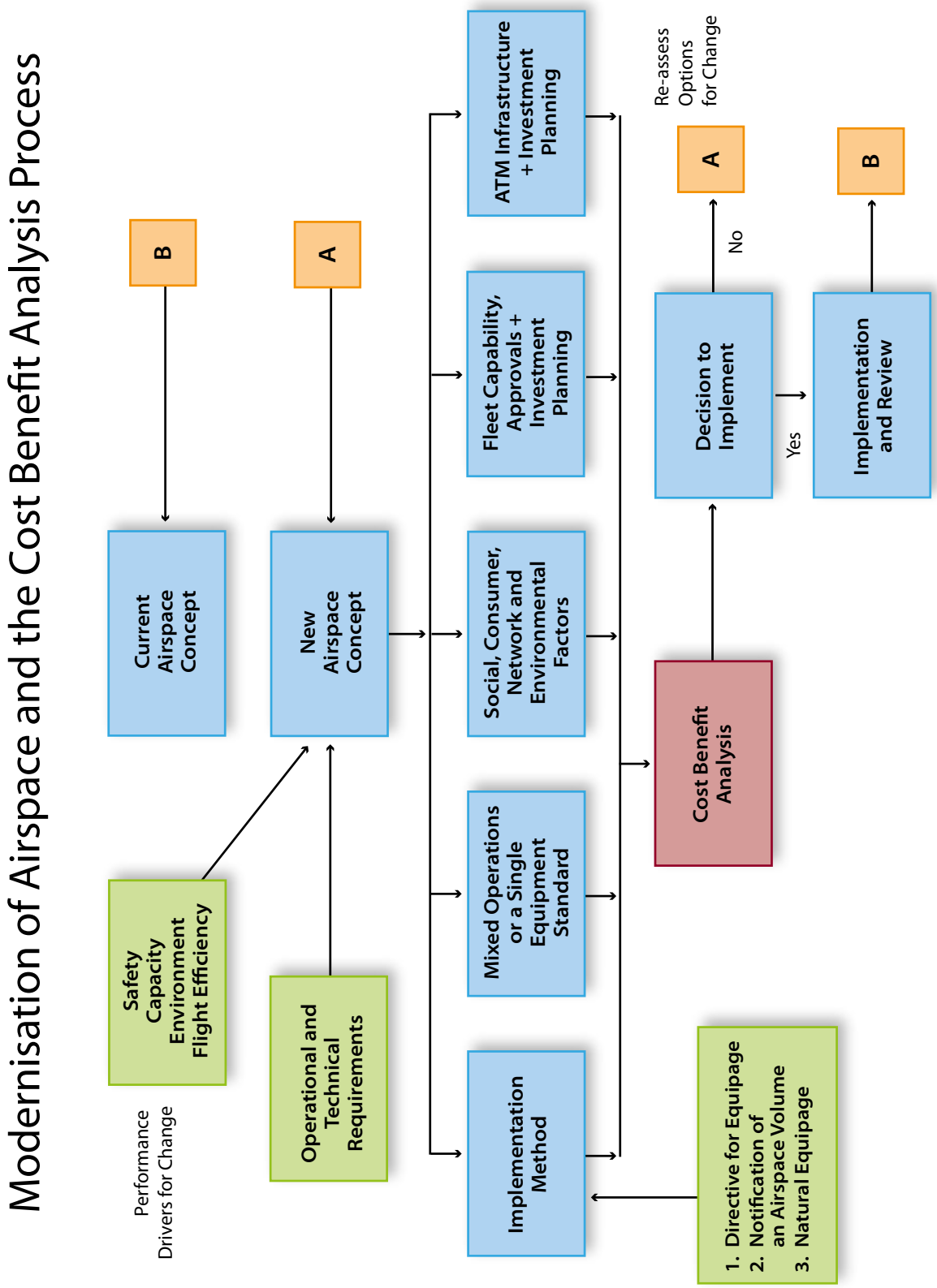
European PBN Implementation Handbook for Airspace Planners Activities 1 to 17 *with critical milestones*				
ACT	*(to be read from bottom-up)*	**No of Days**	**Key Dates** dd/mm/yy (latest)	**Notes**
17	Post Implementation Review (e.g. 6 months after project implementation)		05/08/2014	
16	Implementation of Airspace Change (Match AIRAC Cycle date)		**06/02/2014**	**<< Enter INTENDED Implementation Date here (Must match AIRAC Cycle Date)**
	Additional working day buffer to allow for unforeseen delays (±10% of total)	56	12/12/2013	
14-15	ATC System Integration - Write up LoAs - Awareness and Training	56	06/12/2013	
	GO : No-Go Decision	10	26/11/2013	
12+13a +13b	Procedure Design, Ground & Flight and Validation & Flight Inspection + 56 day (1) AIRAC cycles - ATC Training ‡	90	13/09/2013	*‡ Separate no. of days not calculated for ATC Training; Above shows that this would occur at the same time as PANS-OPS procedure design or during 56 day final AIRAC cycle*
11	Airspace Concept Validation by Real-Time Simulation (Preparation an Runs) †	100	05/06/2013	*† Assumes availability of FTS and/or RTS simulator slots, and required specialists & ATCos/pseudo pilots available*
11	Airspace Concept Validation by Fast-Time Simulation (Preparation and runs) †	70	27/03/2013	
10	Confirmation of ICAO Navigation Specification	2	25/03/2013	
6-9	Finalise Airspace Design & CBA - iteration	5	20/03/2013	
9	Airspace Design: Volumes and Sectors	5	15/03/2013	
7	2nd Iteration: Airspace Design - Routes and Holds	5	10/03/2013	
	Public Consultation with Airspace Users and other stakeholders & Comment Review	90	10/12/2012	
	Environmental Impact Assessment	50	21/10/2012	
8	Initial Procedure Design	50	19/01/2013	
7	1st Iteration: Airspace Design - Routes and Holds	10	09/01/2013	
6	Cost Benefit Analysis - fleet, infrastructure etc	25	15/12/2012	
6	Data collection and agreement on CNS/ATM assumptions incl. Fleet capability; traffic sample etc.	5	04/01/2013	
5	Select Safety Criteria; Determine Performance Criteria and understand Safety Policy Considerations	10	25/12/2012	
4	Analyse Reference Scenario (incl. Data collection of full ATM operations and critical review of current opertions)	20	05/12/2012	
1-3	Agree Operational Requirement; Project Planning; Create Airspace Design Team; Agree Project Objectives and Scope	10	**25/11/2012**	**<< This is the latest project start date**
	Total number of working days required for the PBN Implementation Project	**669**		
Pre-Start	Public Awareness and Concept Consultation with preliminary Environmental Impact Assessment and Benefits Case	180	29/05/2012	This start date for formal consultation would be decided outside the project, but would influence the project start date in green, above.
	Total number of working days needed including public consultation	**849**	***Includes the number of days needed for public consultation, if appropriate***	

Sample Project Plan								
AIRAC - Effective dates 2012-2020								
2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
12 Jan	10 Jan	9 Jan	8 Jan	7 Jan	5 Jan	4 Jan	3 Jan	2 Jan
9 Feb	7 Feb	6 Feb	5 Feb	4 Feb	2 Feb	1 Feb	31 Jan	30 Jan
8 Mar	7 Mar	6 Mar	5 Mar	4 Mar	2 Mar	1 Mar	28 Feb	27 Feb
5 Apr	4 Apr	3 Apr	1 Apr	31 Mar	29 Mar	28 Mar	27 Mar	26 Mar
3 May	2 May	1 May	30 Apr	28 Apr	27 Apr	26 Apr	25 Apr	23 Apr
31 May	30 May	20 May	28 May	26 May	25 May	24 May	23 May	21 May
28 Jun	27 Jun	26 Jun	25 Jun	23 Jun	22 Jun	21 Jun	20 Jun	18 Jun
26 Jul	25 Jul	24 Jun	23 Jul	21 Jul	20 Jul	19 Jul	18 Jul	16 Jul
23 Aug	22 Aug	21 Aug	20 Aug	18 Aug	17 Aug	16 Aug	15 Aug	13 Aug
20 Sep	19 Sep	18 Sep	17 Sep	15 Sep	14 Sep	13 Sep	12 Sep	10 Sep
18 Oct	17 Oct	16 Oct	15 Oct	13 Oct	12 Oct	11 Oct	10 Oct	8 Oct
15 Nov	14 Nov	13 Nov	12 Nov	10 Nov	9 Nov	8 Nov	7 Nov	5 Nov
13 Dec	12 Dec	11 Dec	10 Dec	8 Dec	7 Dec	6 Dec	5 Dec	3 Dec
								31 Dec

Attachment 2:
AIRSPACE ACTIVITIES FOR PBN IMPLEMENTATION



Attachment 2a:
STATE EXAMPLE OF AIRSPACE CHANGE PROCESS

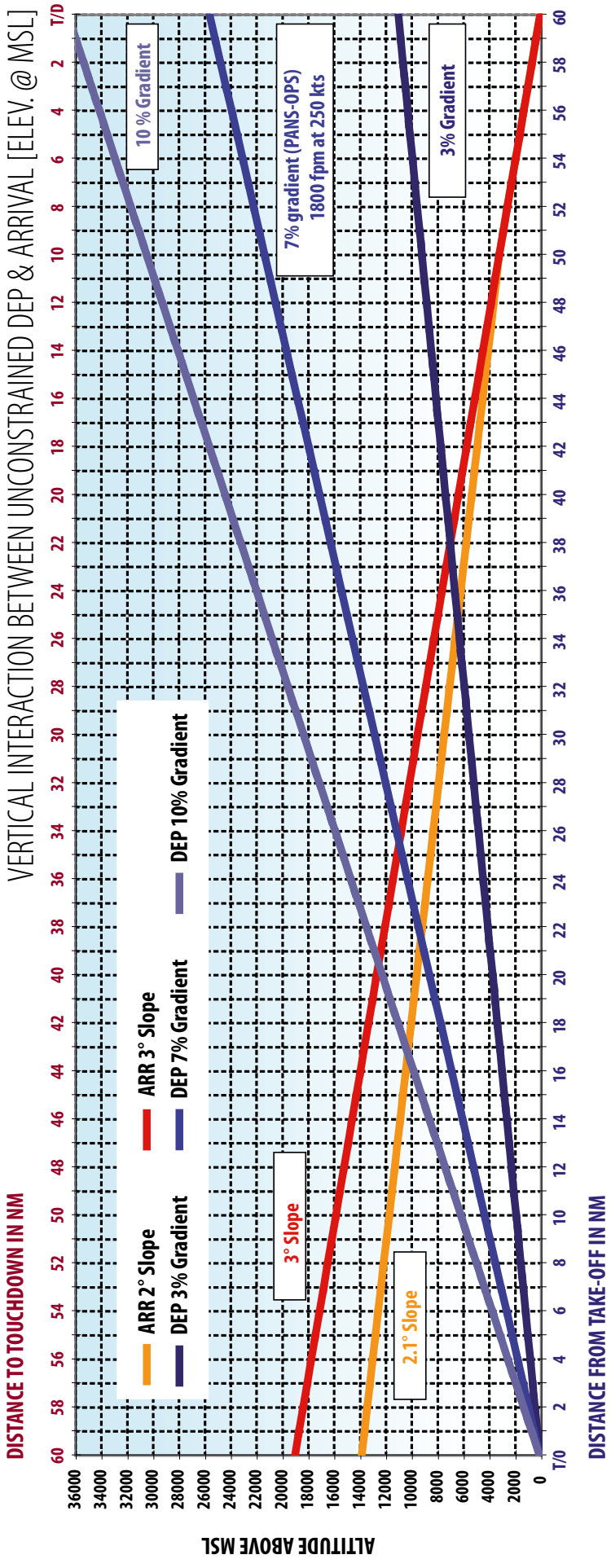


Attachment 3: SAMPLE CLIMB AND DESCENT PROFILES

This sample graph is intended as a simplistic illustration of the vertical interaction between arrivals and departures. The horizontal axis at the top shows nautical miles reducing from left to right as the aircraft descends and gets closer in track miles to the runway, the horizontal axis at the bottom shows nautical miles increasing from left to right as the aircraft increases its track miles after departure from the runway. The purpose of such a graph is to determine whether the selected crossing point between SIDs and STARs is appropriate or whether the point selected is one where both aircraft on their 'natural' profiles would be at the same level, thereby needing to level them off which is not flight efficient.

When undertaking an airspace design particularly in the terminal area, it is important for the design team to create their own graphs which can be based on input from flight crews, or, better still, on radar data showing actual vertical performance.

The correct selection of the crossing point to ensure vertical segregation of traffic flows greatly alleviates flight inefficiency. This strategic separation is what PBN so capably delivers.



Attachment 4:
FREE ROUTES AND PBN

ATS Routes as defined in the PANS-ATM include controlled and uncontrolled routes as well as SIDs and STARs. ICAO Annex 11 explains how ATS Routes are to be designated. Appendix 1 to the Annex provides the convention for designating 'en route' ATS routes whilst Appendix 3 to the Annex covers designation of SIDs and STARs.

Some ATM environments exist either with published ATS routes that are not designated as per Annex 11 Appendix 1 or 3 (instead they use the designator DCT, for 'direct'), or they exist without published ATS routes. The diagrams (at right) show examples of such environments.

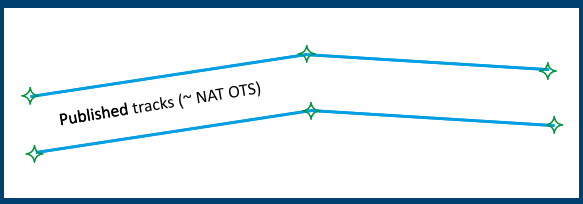
In the North Atlantic, an organised track system (known as the NAT OTS) of (movable) published ATS Routes is used – see **example A**.

The second is a particular kind of routeing used at high latitudes – shown at **example B**. These two operational environments currently connect to a fixed published continental en route ATS Route network which in turn connects to SIDs/STARs and/or instrument approach procedures. (Sample connectivity models to terminal airspace are shown on the next page).

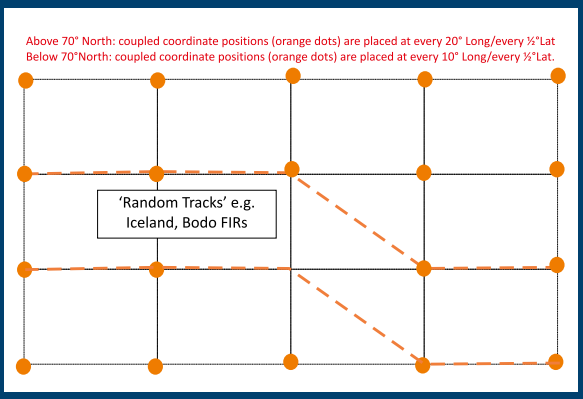
European en route airspace is seeing the increasing use of Free Routes. The EUROCONTROL Document Free Route Developments in Europe (Edition February 2012) explains the European 'Free Routes' Airspace Concept as follows: "A specified airspace within which users may freely plan a DCT route between a defined entry point and defined exit point, with the possibility to route via intermediate (published or unpublished) waypoints, without reference to the fixed, published and designated ATS Route network, subject to airspace availability. Within this airspace, flights remain subject to air traffic control." (Sample connectivity models to terminal airspace are shown on the next page).

This description matches the depiction shown at **example C**. The Free Route environment in example C shows a schema where DCT routes in the airspace are published, linking predetermined entry and exit points. A similar environment, in which no tracks of any kind are published, is shown at **example D**. This kind of implementation envisages various lower limits and is already in use in areas such as Denmark, Sweden, Portugal, Ireland i.e. European periphery and lower density.

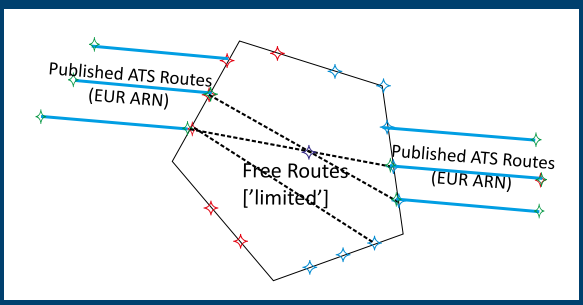
Example A: NAT OTS



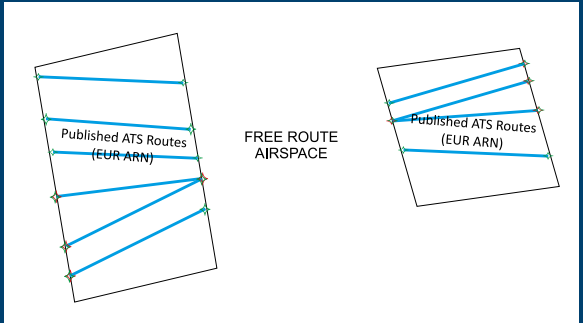
Example B: Random Tracking



Example C: Free Routes with published DCT



Example D: Free Routes without published DCT



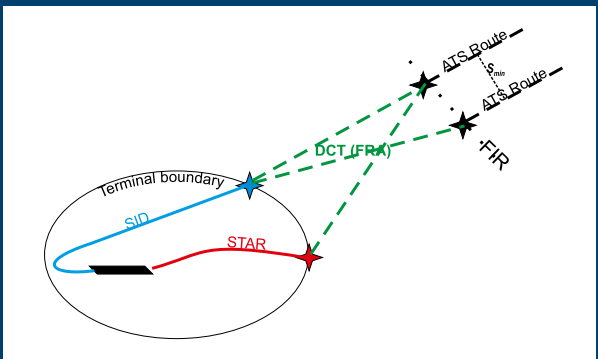
Impact of ATS route designation

The different ways in which ATS route are designated may have some impact on the RNAV or RNP system. Current ARINC 424 coding norms (used to place ATS routes in the on-board navigation database as either an 'airway' or 'airport' record) allows the specification of performance and functionality attributes of designated ATS routes to be linked to these records'. Particular navigation performance and functionality attributes are associated to these 'airway records' such as the navigation accuracy required along a flight segment e.g. RNP 1, or a particular way of executing a turn at a waypoint along the route (e.g. using Fixed Radius Transition). The extent to which such navigation performance attributes can be ascribed to a DCT 'route' (not been designated as per ICAO Annex 11 Appendix 1) is still unclear. To date, indications are that navigation performance and functionality can be ascribed to DCTs in some instances and not in others, but these conclusions are not yet definitive. For example, indications are that performance and functionality attributes assigned to the end fixes of designated ATS routes can be applied along a single DCT connecting these end fixes. For a series of subsequent DCTs for which no airway record is available in the navigation database, the system may default to a standard lateral navigation performance accuracy, e.g. 2 NM in en route.

At present, it is not possible to say how inclusive PBN is of free routes. Work needs to be completed to determine the extent to which they can work together – and the extent to which it is necessary for them to work together. This means that the way of determining minimum spacing between free route trajectories remains to be resolved.

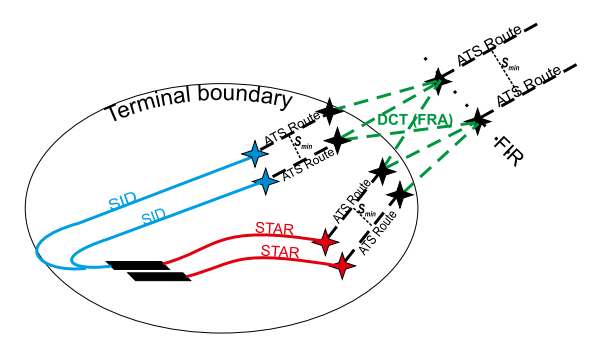
Note: *Background information on navigation performance, functionalities and routes is provided as an Appendix to this Attachment.*

Three examples of 'connectivity' models are identified:



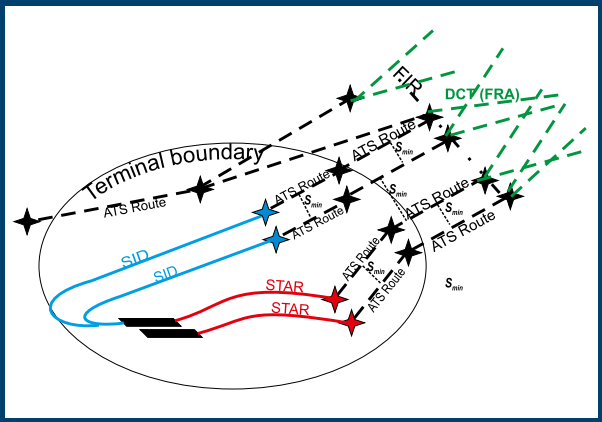
Model 1:

After last point on SID proceed DCT to FIR; from point at FIR entry, proceed DCT to first point on STAR. i.e. FRA outside SIDs/STARs (which were adapted to accommodate FRA). ***Note:*** *SIDs/STARs would be RNP.*



Model 2:

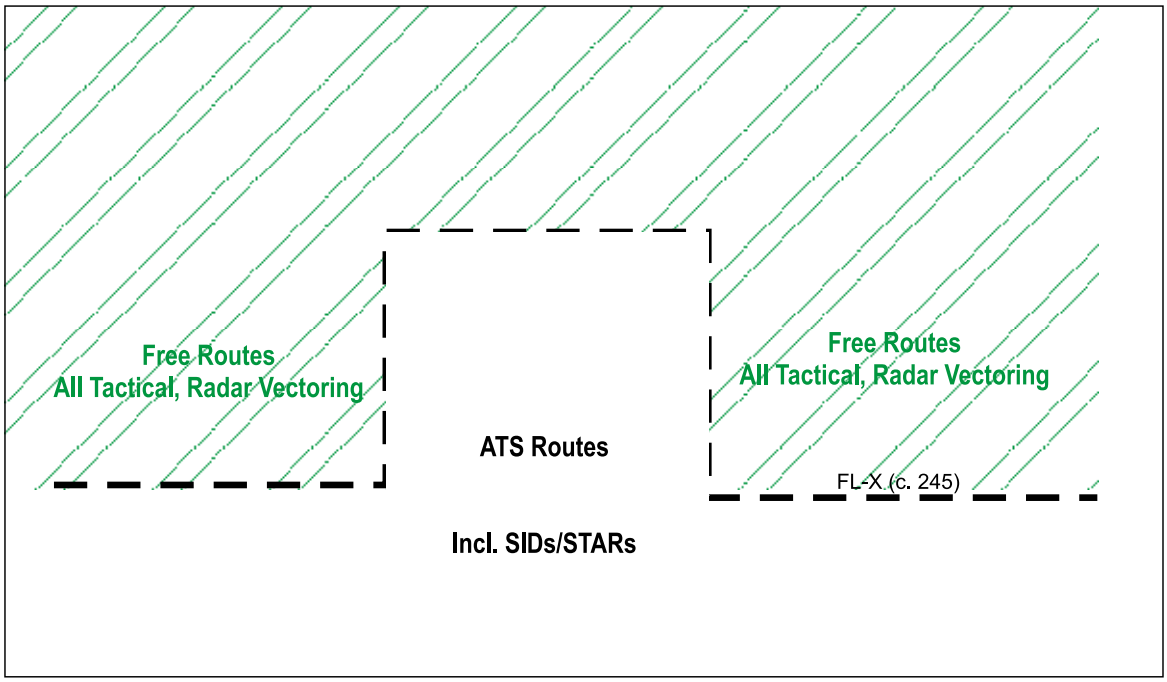
Expanded TMAs containing SIDs/STARs. After last point on SID, ATS route links to anchor WPT in FRA after which free route using DCT is employed. Conversely, inbound aircraft free route DCT TO anchor WPT where ATS Route starts and links to first point on STAR which is then followed by aircraft. Note – SIDs/STARs would be core RNP and ATS Routes between last SID/first STAR point and anchor WPT would be ATS routes requiring RNP + FRT to permit route spacing at minimum distance.



Model 3:

Full structuring of ATS Routes in congested areas to/from major TMAs with their SIDs/STARs/ATS Routes. Above and beyond can be FRA. Note – SIDs/STARs would be core RNP and ATS Routes would require core Advanced RNP + FRT to permit route spacing at minimum distance.

Cross-section



Appendix 1 to Attachment 4:
LINKING NAVIGATION PERFORMANCE, FUNCTIONAL REQUIREMENTS AND ROUTES

Navigation Performance and Navigation Functional requirements in RNAV or RNP systems are included in ICAO Performance-Based Navigation specifications.

1. Navigation Performance

Performance Based Navigation is a term used to describe how a navigation performance requirement is assigned to an application or operation and includes associated requirements for avionics systems, aircraft qualification, navigation infrastructure, ATM and airspace design in order for the application to be implementable and manageable. PBN reflects two approaches to implementation. One is based upon generic performance derived from the navigation infrastructure that aids airspace improvement and the other is based upon a level of navigation performance that must be attained and assured to address airspace and operational needs.

For RNAV systems and operations, PBN is a generic performance solution. This means that the level of navigation accuracy is derived from an available navigation infrastructure that is associated with the intended operations and airspace. The aircraft RNAV system simply performs its point to point area navigation: the direct implication is that its performance satisfies the operational requirement because that's all the referenced infrastructure allows. In the RNAV framework, the performance is reverse engineered based upon what the infrastructure provides and what the aircraft RNAV system achieves as a result. In this case, the RNAV system provides a navigation accuracy that is within the specified performance 95% of the flight time.

For RNP systems and operations, PBN is the required performance solution. It starts with what operation needs to be performed and what navigation accuracy is needed to enable it. The navigation accuracy must be supported by the navigation infrastructure but it may differ from the minimum or maximum of navigation accuracies possible. This expectation of specific performance leads to a need for operational confidence in the RNP system performance. The result is that the aircraft's RNP system or RNP system in combination with the flight crew provides the assurance through the capability to monitor that it is within the lateral navigation accuracy 95% of the flight time and alert when it fails to achieve that accuracy. Additionally, the RNP system provides confidence in the performance it achieves through an integrity check for the probability of the aircraft position being outside of 2x the lateral navigation accuracy does not exceed 1 X 10–5. (A detailed explanation of on-board-performance-monitoring and alerting is provided in the PBN Manual, Volume II, Part A, Chapter 2). Each navigation specification includes specific requirements for accuracy, integrity, continuity and, for specifications requiring GNSS, requirements related to the Signal-in-Space.

The "RNP Alerting" capability makes use of the prescribed accuracy (e.g. ±1 NM) defined for each waypoint in the airway or airport record. Where such an airway record does not exist (e.g. where a route is built up by use of individual fixes because an airway is not published as per Appendix 1 or 3 of ICAO Annex 11), it may not be possible to specify or prescribe a lateral navigation accuracy at which an alert is to be issued when the navigation accuracy is not met. In some systems, the alert level defaults to the lateral navigation accuracy applicable to the current flight phase, which may be 2 NM in en route operation, unless manually overridden by the flight crew. Where this is the case, the manually inserted lateral accuracy value may be applicable for the whole flight unless deleted upon crew action. Note however that in the absence of an airway record, not all RNP systems default to 2 NM lateral navigation accuracy in en route operations. Additionally, where a manual RNP entry is less stringent (e.g. lateral navigation accuracy of ±2 NM) than the requirement of a published route in the navigation database (e.g. lateral navigation accuracy of ±1 NM), the RNP system will alert to this condition and flight crew intervention is required when joining or rejoining the route/procedure. In this case, the pilot will be required to remove the manual entry (2 NM) so as to allow the more stringent performance requirement (1 NM) from the navigation database to apply.

2. Navigation Functions

Navigation functional requirements come in various forms, but for the purposes of this Attachment attention is drawn to those related to aircraft path steering and the ability of the airborne system to compute its flight path:

The aircraft system computed **flight path** is typically the result of aeronautical data and information contained in the system navigation database. The system uses this information to construct a flight path that for the sake of simplicity is a varied sequence of connected straight and curved path segments. The path segments, called legs, are defined in two ways, primarily for the efficiency in specifying data in a manner so it can be used by a computer-based system.

For procedures such as ATS Routes, the flight path is basically the specification of a series of fixes (called waypoints) that the navigation system connects together with a geodesic (straight line over the earth) path segment. Additionally, the navigation system may calculate a curved path that it uses to smoothly fly the turn (i.e. a transition) from one leg to the next. This type of transition, called a fly-by transition, can differ from aircraft to aircraft even if the same navigation system is used. This is due to likely differences in actual speed, wind and other flight conditions that affect the calculation of the turn required. One solution to eliminate this variability is to define as part of the Route a transition with a fixed radius (FRT).

For instrument flight procedures such as those in SIDs, STARs and Approaches, the aircraft flight path is the result of path segments known as path terminators. A path terminator is a waypoint and a specified type of path to/from the waypoint. This allows for much more variability in the definition of a flight path, which coincidentally matches many of the types of clearances and procedures issued by ATC. The result is that there are many path terminators. Examples are a Track to Fix (TF), Course to Fix (CF) and Radius to Fix (RF).

ARINC 424 is the standard used for the specification of data for procedures. This data is used by the navigation system to calculate the desired flight path.

The (new) Advanced RNP specification includes requirements for a specific subset of path terminators (including RF) and the European implementation of the Advanced RNP specification is proposing the mandatory use of FRT.

Given the topicality of FRT and RF, they are further explained in section 4.

The inclusion of navigation performance and functional requirements in RNAV or RNP specifications for operation along a (published/designated) ATS route provide certain 'guarantees' that are critical to ATM and aircraft operations. These 'guarantees' are the main ingredients in determining:

- lateral spacing between (published) ATS routes (See Attachment 5);
- procedural lateral separation minima (See Attachment 5)
- lateral and vertical separation from obstacles for instrument flight procedure design.

3. Navigation Data Records

RNAV and RNP systems have a navigation database which contains many different types of navigation data records. The kinds of navigation data records include ones for Navigation Aids, records for published and designated en Route ATS Routes (known as **Airway records**), records for airports including published and designated SIDs/STARs/Instrument approach procedures (known collectively as **Airport records**).

Key terms relating to navigation data records in the navigation database (in the context of this Attachment):

- An **Airway record** refers to a data record for a published and designated **en route ATS Route**
- An **Airport record** refers to a data record for a published and designated **SID** or **STAR** or **IAP**.

Note: *In the context of this Attachment, the terms 'Route' (used generically) or 'ATS Route' or 'SID/STAR/IAP' refer to Route(s) which have been **published** by the appropriate authority in the AIP **and designated in the AIP** in accordance with ICAO Annex 11 Appendices 1 and 3 (designation of ATS Routes and SIDs/STARs respectively). This publication ensures that the trajectory to be flown over the surface of the earth is known.*

These Airway/Airport records can include the navigation performance requirements for each Route segment making up the complete Route. The construction of a Route contains a series of fixes, possibly including path transitions for ATS Routes and a series of path terminators for SIDs/STARs/IAPs. In designing the Route, the procedure designer uses the performance capability and any combination of functionalities that are included in the navigation specification against which the aircraft must be qualified to operate along the ATS Route, SID/STAR or IAP As each published ATS Route or SID/STAR/IAP has its own airway or airport record, respectively, the navigation database can include thousands of such records. From the 'published' ATS Routes or SIDs/STARs/IAPs information, navigation data suppliers (who are the providers of navigation databases and other related services/products), build 'airway/airport records', optimise the data for the records, and use this data along with other aeronautical information (e.g. navaids, runways, etc) to create navigation databases which are used by specific aircraft operators/airlines and navigation systems, etc.

This link between airway or airport record, published Routes and navigation performance/functionality are currently the only means that an RNP system has to determine navigation performance requirements. This results in the fact that navigation performance cannot currently be ascribed 'generically' to 'RNP airspace', because navigation performance specification and associated functionality is embedded in the airway or airport record enabling an intended operation. Although the notion of 'area RNP' has been long established, the technical preparatory work for its implementation is still outstanding. For these reasons, ATC can only be assured that ATC clearances (voice or data) to an RNP certified aircraft operating in an airspace will meet the performance and functional requirements of an RNP specification (e.g. RNP 1) if the clearances are based upon the use of designated and published ATS Routes or SIDs/STARs/Approaches along with specified navigation performance requirements (i.e. RNP 1) that are contained in the airborne navigation database airway/airport records. If ATC clearances are issued to fixes and procedures which are not contained in the database, on-board performance monitoring and alerting (i.e. RNP 1) by the RNP 1 aircraft cannot be expected – see end of Section 1 of this Appendix that describes the consequences of not having an airway record.

For an RNAV system, the issue with the match between the aircraft capability and the navigation performance requirements for Routes, procedures, airspace and clearances does not exist. This is because of the generic and fixed navigation performance relationship of the aircraft's RNAV system, navigation infrastructure and procedures/Route. For example, where the navigation infrastructure for operations is predicated on VOR/DME, the density of the infrastructure supports a consistent level of aircraft flight accuracy such as ±5 NM (e.g. RNAV 5), and the placement of the Routes/procedures are based upon the VOR/DME locations, ATC can be assured that the nominal level of aircraft performance in the airspace will meet RNAV 5 whether it's for a published Route/procedure contained in the navigation database or for an ATC clearance containing fixes and procedures not contained in the database. However, lacking assurance that the aircraft will always meet the operational performance expectation without on-board performance monitoring and alerting, other means of assurance such surveillance may be needed. What this suggests is that RNAV does have some advantages if the operationally needed performance matches the RNAV system's generic performance possible. But this also requires the State/regulator to take more responsibility for the infrastructure and accepting the aircraft/systems with basic compliance assessments; the latter is becoming more difficult.

From airspace concept to airway or airport record :

1. **Airspace Concept:** Parallel tracks on both straight and turning segments spaced 7 NM apart in en Route and terminal airspace and instrument flight procedures circumnavigating environmentally sensitive areas in the terminal area, for example. Studies have demonstrated that this concept requires the performance and functionalities included in the Advanced RNP specification requiring ± 1 NM lateral accuracy with additional requirements for FRT (hereafter abbreviated to A-RNP + FRT), and is supported by the navigation infrastructure.

2. Following successful completion of Activities 1 to 17 in this Handbook, the ATS Route network with SIDs/STARs is published in the AIP with requirements for operational approval and aircraft qualification for A-RNP + FRT for operation along the Routes.

3. When building the *airway records* of the A-RNP + FRT, en Route ATS Routes and the airport records for the A-RNP SIDs and STARs, the navigation data suppliers include into the *airway or airport records* the performance and functional requirements of A-RNP + FRT. These records are a part of the navigation database that is loaded into the RNP system.

4. To operate along these routes, operators must have operational approval and aircraft qualified against the appropriate regulatory standards comparable to the A-RNP + FRT specification. Consequently

a) ATM procedures and acceptable intervention rates to control deviations are based on Advanced RNP and 7 NM Route spacing, for example. This would include reliance on aircraft performing controlled turns (see FRT and RF below).

b) Operators use instrument flight procedures which are separated from obstacles based on Advanced RNP performance and functional criteria. This would include reliance on aircraft performing controlled turns using RF outside the final approach segment, for example.

4. FRT and RF

Fixed Radius Transition (FRT) is a leg transition associated with a waypoint on ATS Routes in en route operations. A path terminator, termed Radius to Fix (RF), is associated with Terminal Instrument Flight Procedures. Although both functions differ in their definitions and intended use, they both enable a fixed, constant and predictable path to be flown by an aircraft during a turn.

In the en route phase of flight, ARINC 424 defines the transition from the inbound leg to the outbound leg from the waypoint on the route as one with a fixed radius transition (FRT) by identifying it with a waypoint in the airway record stored in the navigation database. For such a transition from in- to outbound leg to be executed as an FRT, the waypoint must have been defined as part of a route in the airway record of the navigation database. The route must have been enabled in the navigation system by calling it from the database using the appropriate route identifier e.g. UL611.

Because navigation functions have been defined but implementations in aircraft FMS are not always standardised, it is not possible to make absolute statements regarding the operational implications of an FRT implementation. In general however, it could be expected that in current implementations:

a) Where a "DCT TO" clearance has been given to a waypoint, an FRT will usually not be executed at that waypoint (even if the waypoint was initially inserted using the airway identifier). This is because the active leg in the flight plan will become a direct track between current position and the DIRECT-TO waypoint, after which the route that was originally programmed will continue.

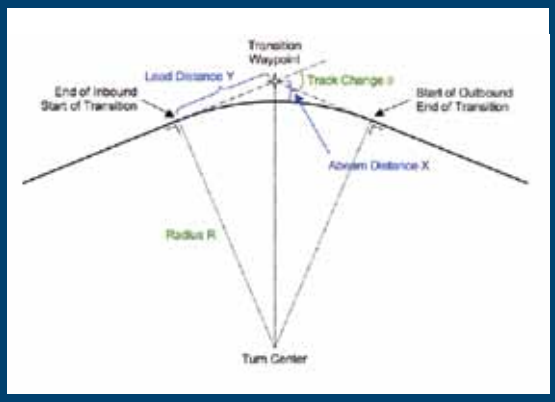
b) Where a route has been constructed wholly or partly by pilot inserted fixes (e.g. by name, place/bearing/distance or lat/long in a Free Route or published route environment – see examples B&C , in previous section) an FRT cannot be executed at the manually inserted fixes.

The leg transition at the fixes forming the junction of SIDs or STARS with ATS Routes can usually not be executed as a FRT. This could be overcome though by suitable design of the procedure, connecting it to the en route airway structure. One solution could be realised by the procedure designer creating an RF leg (the terminal equivalent of an FRT) at the end of the SID or the beginning of the STAR. For a SID, the last point of the RF leg could then be connected to the first point of the en route airway in order to ensure appropriate route spacing during the turn. For a STAR the connection would be from the last point of the en route airway to the first point of the RF leg.

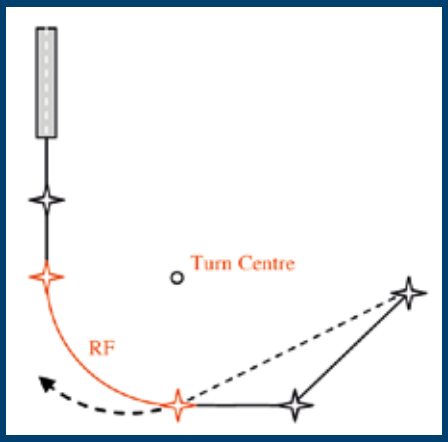
Differences between FRT and RF

The FRT is defined as a transition from one track to another at a waypoint along an en route airway. There is no start and end waypoint defined for an FRT. The FRT starts and ends where an arc with the specified radius is tangential to the inbound and outbound track of the transition waypoint.

Fixed Radius Transition (FRT)



Radius to Fix



The Radius to Fix (RF) is defined as an arc with specified radius between two defined waypoints in a procedure (SID/STAR). It is an ARINC 424 path terminator with a defined start waypoint, end waypoint and turn centre. The radius is deducted from the distance between the start or end point and the turn centre. Because of the way the RF is defined, implications of manual waypoint entry and DIRECT TO operations in a flight plan are different, as for the FRT. As long as the start and end points of the RF are not affected by these flight plan modifications, the RF will remain intact. It can be expected however that, in the case of a direct routeing to the start point of an RF (as depicted by the dotted line in the diagram above), the aircraft will deviate from the defined track because of the fact that the direct inbound track is not tangential to the beginning of the arc at the start point of the RF.

Attachment 5:
STRATEGIC DE-CONFLICTION OF RNAV OR RNP ROUTES IN A RADAR ENVIRONMENT

Note: *For brevity, this Attachment uses the generic expression 'routes' to refer variously to ATS Routes (including SIDs/STARs) as well as Instrument Approach Procedures etc. Similarly, PBN routes are those for which a navigation performance has been prescribed thus requiring aircraft operating on these routes to be qualified to the appropriate RNAV or RNP specification.*

PBN enables the systemisation of air traffic organisation through the strategic de-confliction of published routes so as to reduce the need for tactical ATC intervention. This systemisation becomes possible because route placement is no longer constrained by the location of ground-based NAVAIDS (i.e. routes no longer have to pass over these NAVAIDS which was mostly the case without PBN). In the horizontal plane, a natural way of de-conflicting routes is the use of parallel or diverging routes. If this is not possible, then the (lateral) flexibility of route placement enabled by PBN is used with crossing tracks particularly when designing terminal routes. Here, PBN's flexibility allows the airspace designer to determine the most appropriate location for the crossing point between designed tracks so as to ensure minimal vertical interaction or 'interference' between, for example, aircraft climbing and descending on crossing SIDs/STARs. (This is more fully explained in Activity 7 at sub-heading *Terminal routes leaving/joining Free Routes or ATS Routes* and supplemented by Attachment 3 to this Handbook - *Sample Climb and Descent Profiles*)

To help airspace planners appreciate the role of de-confliction of PBN routes, this attachment begins with the notions of separation and spacing in a pre- and post-PBN environment and then considers additional elements pertinent to PBN route placement. It focuses on parallel routes in order to help airspace planners know how close parallel routes may be placed in relation to each other when operation on such routes requires approval to a particular RNAV or RNP specification. However, a number of more complicated/general scenarios requiring further work are also described.

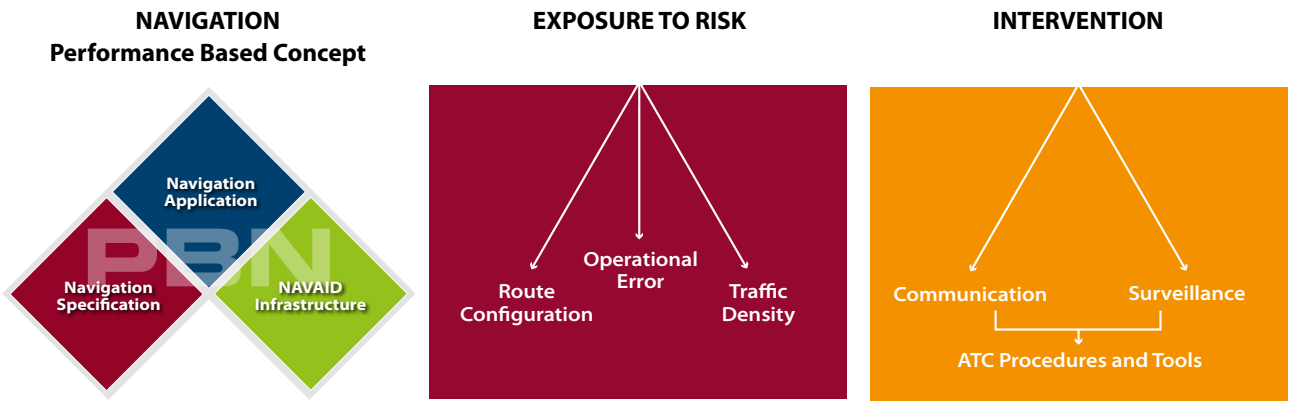
1. Notions of Separation and Spacing

Application and determination

Currently, PANS-ATM Chapter 5 contains **sensor-based separation minima** for application in a procedural environment. Application of sensor-based separation minima in a procedural style of controlling is usually achieved in a dynamic/tactical manner by ATC. For example, a 15°/15NM VOR separation minimum is likely to be applied by ATC ensuring that two aircraft are established outbound on two different VOR radials that are 15° or more apart; once the conditions for separation are satisfied, both aircraft can be cleared to the same flight level. In this kind of operation, aircraft may be tracking outbound from a common VOR and the DME must be co-located with the VOR which means that the separation minimum can only be applied in certain places where there is a co-located VOR/DME. Generally, ATS routes coinciding with these two radials are not published though may exist 'naturally' to accommodate traffic routeings. The next aircraft pair may be placed on different VOR radials 15° apart and the same separation minima applied. Thus these separation minima tend to have a more tactical application. Numerical values of these traditional separation minima were derived by technical/operational safety considerations rather than collision risk modelling (CRM).

PANS-ATM Chapter 5 will soon include **PBN separation minima** which are not sensor based. Using the 15° example, above, ATS routes with a sub-tended 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 established. There is one condition, however: to rely on PBN for the separation of aircraft, routes must be published so that they can feature in the navigation database as an airway record – as per Attachment 4). Thus the traditional 'tactical' nature of separation provision is no longer viable. This 'loss' of flexibility may have certain disadvantages, but a major advantage is that the separation can be strategically designed and built into the design of the airspace in optimum places, as frequently as needed. Numerical values for this kind of separation minima have been derived by CRM supported by technical/operational safety considerations (including hazard identification). *Note that these separation minima do not currently exist in PANS-ATM; they are under development by ICAO's Separation and Airspace Safety Panel (SASP).*

(Route) **Spacing** has traditionally referred to the spacing between parallel routes. Aircraft capable of achieving the prescribed navigation performance operate along a published route and ATC monitors the aircraft's progress either through position reports or using ATS surveillance.



More on determination

PBN separation minima and route spacing are determined by CRM supplemented by hazard identification and comprehensive safety assessments. CRM 'ingredients' include Navigation Performance, Exposure to Risk and Intervention – see Figure above. Whilst publication of routes as such is irrelevant to the CRM (which simply assumes that the routes are intersecting or parallel (mathematical) lines that one but generally more pairs of aircraft are trying to follow), PBN routes must be published so that the performance attributes of the Navigation Specification – on which the CRM relies under *navigation performance* - can be embedded in the airway record (see Attachment 4). The original Reich model or extensions thereof are basic tools of Collision Risk Modelling (CRM), linking the various elements together with the separation minimum or route spacing to the level of collision risk on a pair of intersecting or parallel routes, and 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.

Collision risk modelling relies on specific assumptions concerning the three boxes in the diagram above. 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** addresses *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). The **right-hand box** is the ATC intervention box, achieved using Communication. Surveillance and/or performance monitoring tools, e.g. by *communicating* to an aircraft to take action to correct its going astray which would be known to ATC due to surveillance.

As the various 'ingredients' change in the three boxes, the separation minima and route spacing change. B-RNAV route spacing demonstrates this:

- The original route spacing for B-RNAV (called RNP 5 under the 'old' RNP concept at the time) was based on the spacing between VOR-based routes in a procedural environment (as published in ICAO Circular 120). The logic used was: the navigation performance of B-RNAV approved aircraft was at least as good as VOR, therefore the B-RNAV route spacing could be at least the same as that between tracks based on VORs.

- To reduce the route spacing to 10 NM between either RNAV 5 or B-RNAV tracks in a high density continental airspace with radar surveillance, studies demonstrated that a high level of ATC intervention was needed (in the order of 25 interventions per hour for opposite direction tracks to two interventions per hour for same direction tracks).

- To implement B-RNAV route spacing in Oceanic airspace, outside radar surveillance where there is no VOR infrastructure, a study demonstrated 30 NM spacing.

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 radar 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.

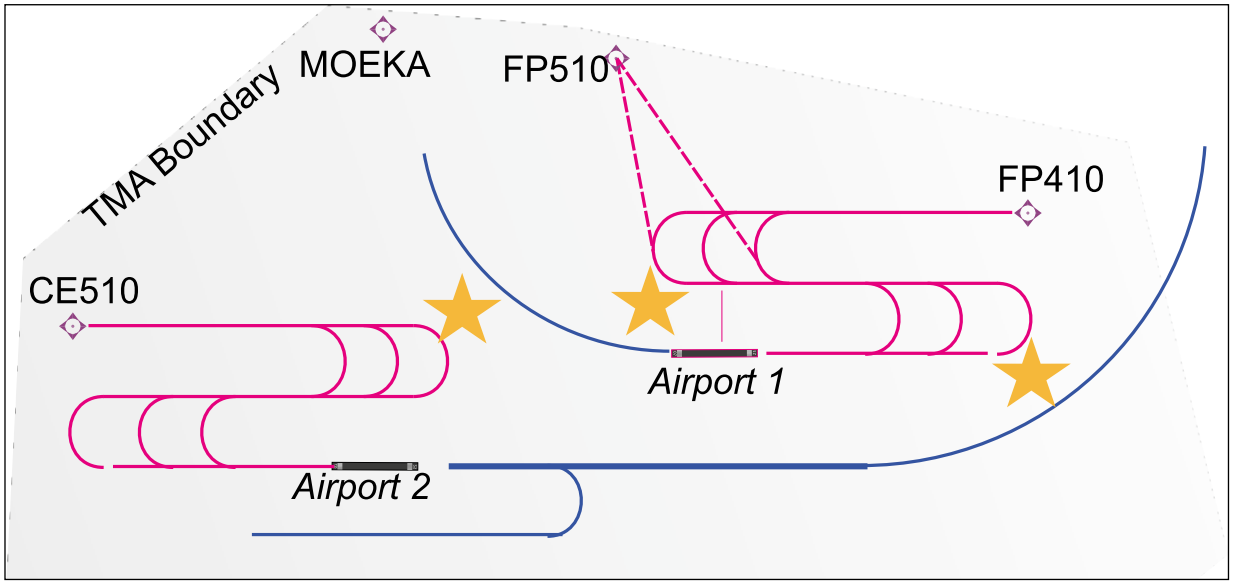
Europe, as well as other areas of the world, is moving from RNAV to RNP applications in order to exploit the additional benefits of RNP specifications.

RNP vs RNAV route spacing – is RNP better?

PBN has institutionalised the difference between RNP and RNAV, where RNP specifications include a requirement for the aircraft to have on board performance monitoring and alerting and RNAV specifications have no such requirement. The net effect of RNP in terms of route spacing is that RNP route spacing is usually smaller than RNAV route spacing (and this is to be expected also for separation minima). This improvement is attributable to the increased probability of track conformance (thanks to RNP's requirement for on-board performance monitoring and alerting which translates into the air crew being able to alert the controller that the aircraft is no longer capable of maintaining RNP). An example is the difference between P-RNAV route spacing and Advanced RNP route spacing both relying on +/- 1 NM lateral navigation accuracy: The Advanced RNP en route ATS route spacing along straight segments determined by collision risk modelling is 7 NM in contrast to 9 NM for P-RNAV. Furthermore, ICAO's PBN Manual has associated high-integrity turn performance functions with RNP specifications (which are not applicable with RNAV specifications). This means that predictable turn performance becomes the added benefit of using RNP specifications which means that the spacing between routes can remain constant between RNP routes both in the straight and turning segment.

Flyability

As route spacing distances decrease with the use of RNP specifications, it becomes important to ensure that designed SIDs and STAR's are flyable and that the track can actually be followed with the level of precision envisaged in the route spacing scenario. The non-flyability of routes is not as 'dramatic' when routes are spaced by 10 to 15 NM, as when they are spaced by 6 or 7 NM, particularly when, using RNP with RF or FRT, the spacing between the routes is maintained on the turn as well as straight segments. The orange stars (on the turns in the diagram below) show where poor flyability could compromise the spacing between proximate tracks and in some cases result in separation infringements.



The flyability of a procedure is influenced greatly by the speed of the aircraft and its ability to maintain a path within the available bank angle authority and for the effect of an adverse wind on ground speed. Establishing a design which accounts for these factors is essential and may lead to use of speed constraints, especially in turns. 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. In a poor design, whether a controller action (intervention) is required, 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.

Summary

The main points to note from the above include:

- Traditional application of pre-PBN separation minima tends to be tactical whilst PBN separation minima are strategically designed – and published for inclusion in the navigation database as an airway or airport record.
- A single navigation specification can be applied in a variety of environments with different route spacings.
- There is an increasing tendency to move from RNAV to RNP specifications, enabling tighter separation minima and route spacings thus increasing the importance of flyability in terms of separation assurance.

2. Separation Minima and Route Spacing: From Publication to Implementation

Publication

Global **Separation minima** are published in the PANS-ATM in Chapter 5. These separation minima, based on certain assumptions, are usually determined by ICAO's Separation and Airspace Safety Panel (SASP) who prepare supporting ICAO circulars which explain the calculations and assumptions used. Examples include ICAO Circular 321 *Guidelines for the implementation of GNSS longitudinal separation minima;* Circular 324 *Guidelines for Lateral Separation of Arriving and Departing Aircraft on Published Adjacent Instrument Flight Procedures;* and Circular XXX *Guidelines for the Implementation of Lateral Separation Minima*. These circulars provide crucial information in that they contain all the assumptions and operating context of the collision risk model used by the SASP, which enables any local implementation team to clearly know the starting point and how much work it still has to do to complete the local implementation safety assessment.

When separation minima are published in the PANS-ATM, ICAO has undertaken a generic safety assessment, distinguishing between collision risk due to navigation performance hazard and other hazards. That said, PANS-ATM in Chapter 2 along with Chapter 2 of Annex 11 to the Chicago Convention, stipulate that an implementation safety assessment must be completed when undertaking an airspace change such as changing the route structure (which is usually the case with PBN) or introducing significant changes to 'the system'. This means that one cannot summarily 'implant' a PANS-ATM separation minimum in a local setting but that there is a need to complete an implementation safety assessment to accommodate the actual implementation environment, thus making sure that the change to the ATM system is accomplished safely.

Route spacings are not published in the PANS-ATM as a rule. Before the introduction of PBN, RNAV route spacings were included as Attachment B (guidance material) to Annex 11 of the Chicago Convention, but this was withdrawn. These spacings are now located as an information attachment to the PBN Manual (Vol II). In the context which follows, it is implicit that any route spacing requires approval of the fleet to a specific RNAV or RNP specification e.g. RNAV 1 or RNP 4 etc.

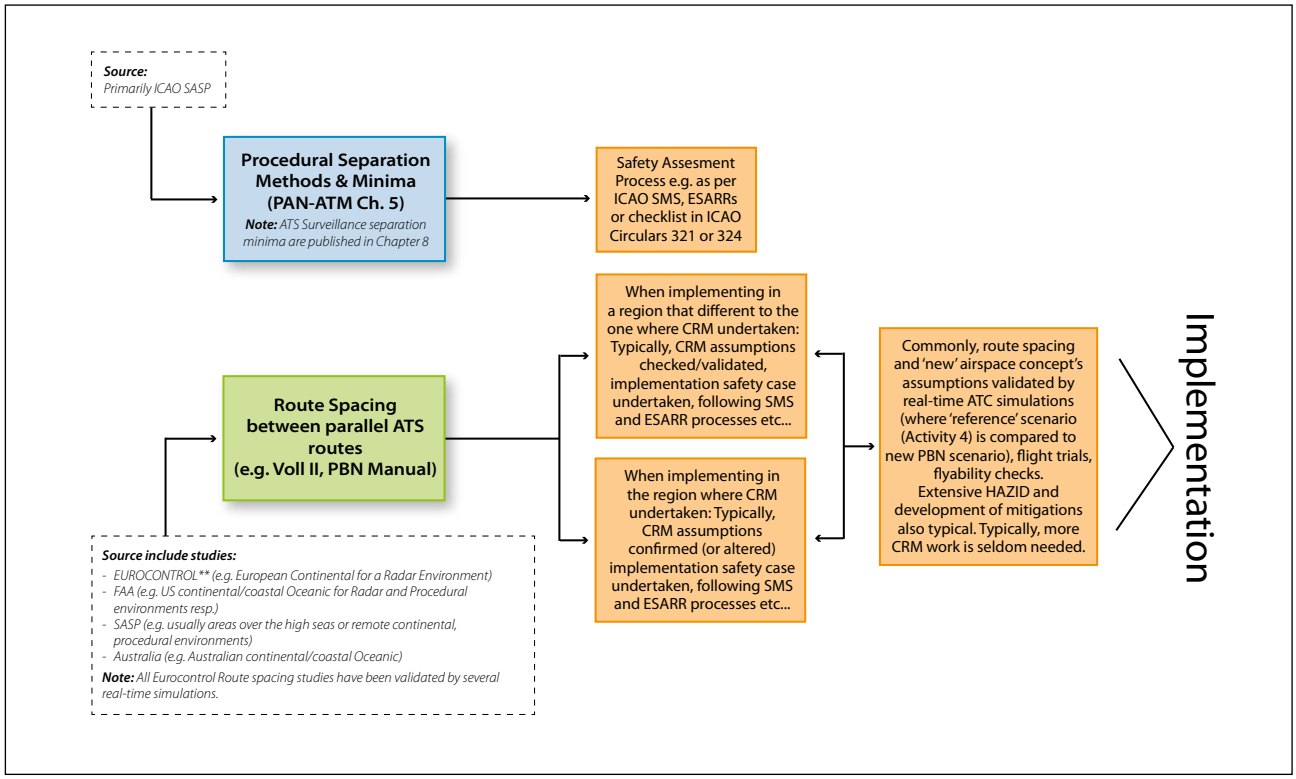
Note: *The Table in Appendix 1 to this Attachment provides a summary of the route spacings that have been determined by various studies based upon particular PBN specifications.*

For route spacings in **remote areas** or those over the **high seas**, most collision risk assessments requiring approval to a particular RNP or RNAV specification have been undertaken by the SASP given that the operating environment can be considered or rendered more or less standardised and the population of aircraft/traffic density in such areas can be easily 'averaged' for purposes of a CRM. For **continental regions**, the situation is not quite the same which is why

most RNAV and RNP route spacing studies for continental en route or terminal application have been determined by regional organisations such as EUROCONTROL or the FAA using collision risk assessment supplemented by various operational or other trials characterising the local environment. This difference can be explained (simplistically) by geography and history. Although Europe and the US's annual traffic figures may be similar, the spread of major 'core areas of traffic density' are not the same on the two continents; neither is the mix/ratio of air transport to business aircraft or the ratio between business and GA traffic and rotary craft operators. For reasons partially explained by the large number of sovereign states in Europe, there is a rich VOR and DME infrastructure across the European continent, and extensive radar surveillance coverage. European ATM Systems are not the same as those of their US counterparts (indeed, there are a variety of systems across Europe) and the training of European and US controllers is not the same and neither is the 'culture' of these controllers etc. Thus when a European route spacing study is done, the operating environment (the assumptions) cannot be entirely the same as those in the US… or South America or Australia. As a consequence, any route spacing determined for one regional implementation cannot summarily be implanted in another. Europe's B-RNAV (RNAV 5) route spacing included VOR/DME as positioning sensors that reflects its extensive NAVAID infrastructure. The 'backup' or reversion to GNSS outage could be VOR/DME and the backup to that, radar control. This reflects the European environment particularly in the core area, which is not necessarily replicated in another region seeking to implement an RNAV 5 (B-RNAV) route spacing. As such, a local implementation safety assessment would be needed were another region or state interested in implementing RNAV 5 parallel routes. Their environment (e.g. less traffic density over the pertaining planning horizon) could make it possible to reduce the route spacing from that used in Europe, or require the spacing to be increased for some other reason.

Implementation

What the above descriptions effectively mean is that any procedural separation minimum in the PANS-ATM or route spacing published in the PBN Manual cannot simply be implemented but it needs to be validated for particular local implementation. The diagram below shows how this is typically achieved:



The right-hand box in the previous diagram suggests that there are a variety of ways in which States can (and do) validate the European route spacing material for local implementation. In one State, the regulator has insisted upon more mathematical work complemented by real-time simulation to demonstrate an acceptable level of safety at implementation. Another State regulator has, with its ANSP, developed a rigorous analytical process for examining route interactions and asked the ANSP to demonstrate e.g. through real-time simulation, that the identified hazards are sufficiently mitigated. Differences due to diverse circumstances may result in different implementations as a consequence of rigorous safety assessment.

3. Route Spacing in a Radar Environment: A European quirk?

It is often wondered why one would determine a route spacing between parallel ATS routes in a radar environment. It is not immediately obvious why one would use a route spacing of 7 NM where the radar separation minimum is less i.e. 5 NM and therefore more favourable.

Route spacing cannot be the same as the radar separation minimum. This is because if the route spacing and separation minimum were the same and an aircraft deviated off its track towards the other track, the immediate consequence would be a separation infringement when this aircraft would close towards another aircraft. Thus the route spacing must always be larger than the radar separation minimum.

The route spacing determined by means of a CRM therefore provides direct evidence that the spacing is safe in the intended European environment ***with*** Radar Surveillance. With a particular design, traffic loading/density, a particular configuration of parallel routes, with particular traffic characteristics (climbing/descending), built into the CRM, collision risk modelling is an effective way of demonstrating that a selected route spacing will achieve the target level of safety (TLS) of 5 * 10-9 fatal accidents per flight hour *and* that the controller workload per sector is manageable and thus contributes to the 'safety equation'. For the strategic planning of the European airspace's extensive network of routes through some 600 sectors, it is imperative to have an operating scenario that permits a safe ATC workload and best efficiency in terms of the route design. In real time, controllers are free to alter the aircraft's flight path, and this is often the case with DCT TO instructions being given by ATC and aircraft can be tactically separated by a minimum of 5 NM. Nevertheless, the route network (and route spacing) scenario is such that if controller intervention in ATC sectors is minimum, aircraft operation along the route network is safe.

It is worth stressing what was stated in the Implementation section: regional route spacing studies are undertaken within a particular context having a particular operating environment and these two do not automatically translate from one region to the next. The route spacing that is implemented after a full local implementation safety assessment (which may include a local CRM) **can be different** to the one determined by CRM used to determine a global spacing. (Similarly, many route spacings are determined for a procedural environment, and others for a radar environment. Route spacings determined for use in a radar environment are usually smaller than those in a procedural environment. So the spacing between straight parallel routes used in a radar environment cannot be blindly 'transplanted' into to a procedural setting). Similarly, a region using a 10 NM radar separation minimum for en route could not use the 10 NM route spacing determined for European application of RNAV 5 in a radar environment.

Is there a limit to how close two routes can be spaced?

Various studies have demonstrated that when the lateral navigation accuracy prescribed in a navigation specification is equal to or less than 3 NM i.e. RNP 2, RNP 1, RNP 0.3 etc, blunder tends to dominate the route spacing rather than the accuracy.

The application of route spacing in a radar environment has recently revealed an interesting aspect related to human factors, viz. the controller's situation display and route spacing.

Most recent route spacing studies and real time simulation (RTS) validations for en route spacing have been undertaken for Advanced RNP assuming a 1 NM lateral navigation accuracy. In all RTS, the 7 NM route spacing derived by CRM for en route operations was confirmed – see Appendix 1. During the RTS, an interesting phenomenon was noted: although the controllers had asked to attempt a 6 NM route spacing in the particular en route airspace being simulated, they eventually asked that a spacing of no less than 7 NM be considered in en route for Advanced RNP. During debriefs it became evident that the size of the ATC sector and the scale of the Radar Map 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 '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.

This observation would not preclude a route spacing smaller than 7 NM being used which would be the case where the ATM operating environment so permits e.g. a different situation display scaling is used: in a terminal environment the scaling of the map, the (slower) speed of the aircraft and the distance between the radar targets usually appears larger than to the en route controller, so operating environment are different. This was demonstrated in the Budapest simulations where a 5 NM spacing was achieved in terminal operations.

For completion, the next two sections provide an overview of typical characteristics included in European route spacing studies and the real time simulations used to validate them. Identification of required future studies is also shown.

Generic European 'characteristics' included in route spacing studies

Typically, the following kind of characteristics have been included in the European operating environment when determining route spacing. This said, it is stressed that for a specific set of characteristics associated with a particular route spacing study, the individual report would need to be consulted.

- Radar coverage with monitoring continuity – see Note 1;
- Dual radio with backup frequency;
- For 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 P-RNAV, 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);
- All RNAV route spacing studies in ECAC have only been for straight parallel tracks with a need to increase the spacing between the tracks on the turns; and
- All RNP route spacing studies in ECAC have been for parallel tracks on straight *and* turning segments (with FRT or RF capability required) thereby *not* requiring to increase the route spacing on the turn.

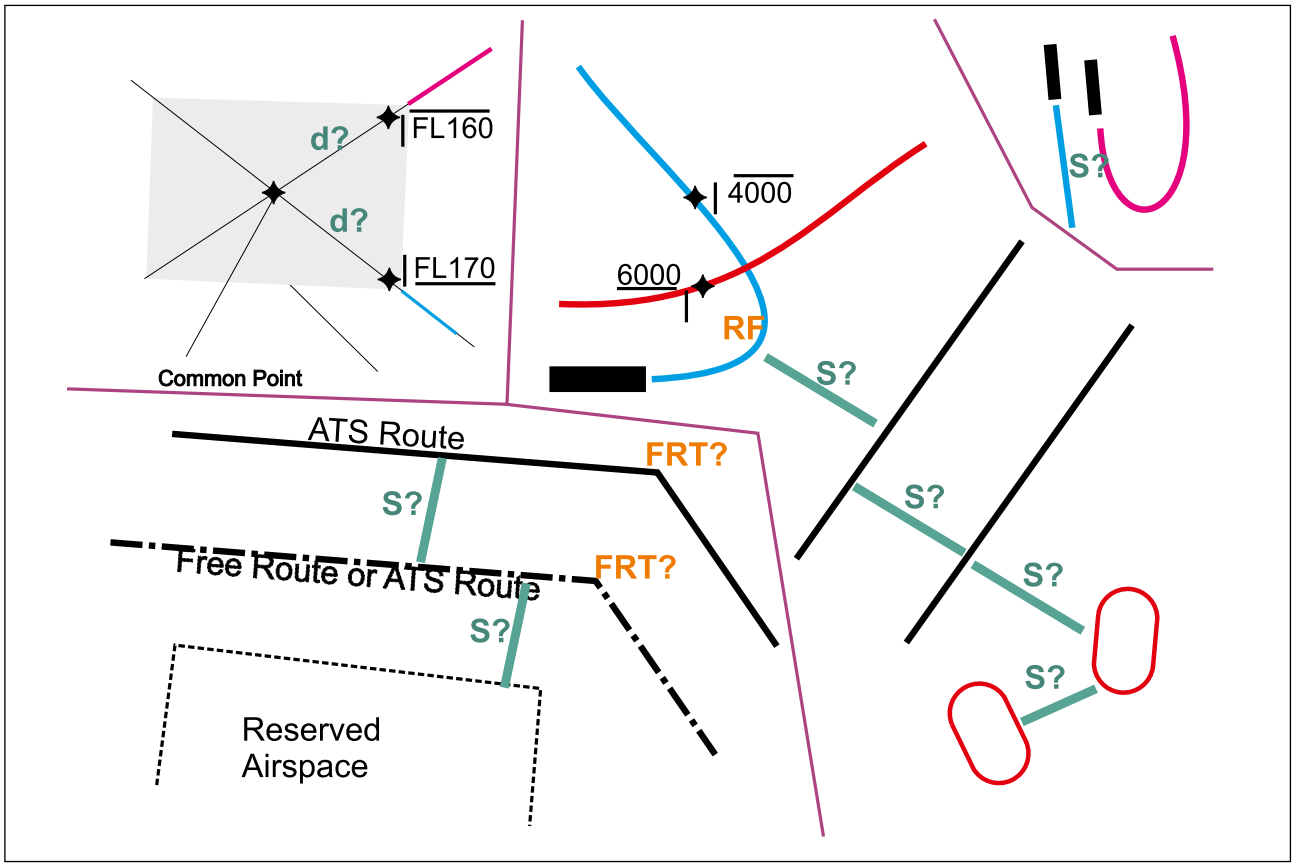
Note 1: *It is stressed that all route spacing studies undertaken in Europe have assumed (independent) Radar Surveillance and not ADS-B. If these route spacings were intended for implementation in airspace within which only ADS-B surveillance is provided, the route spacings may need to be increased due to GPS being the 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 to determine P-RNAV 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.*

European characteristics included in real-time simulations to validate route spacing studies

Typically, real-time simulations have used as background assumptions those used in the collision risk model for a particular route spacing. Where this has not been possible (e.g. a simulator has in-built route conformance monitoring which was not assumed available in the CRM), the difference in results between RTS and CRM are clearly qualified.

Route spacing studies, by definition, concern the spacing between parallel routes. No studies have yet covered scenarios not related to parallel routes in a radar environment for terminal or en route operations. As increasingly, spacing seeks to be determined between pre-defined RNP and RNAV tracks particularly in terminal operations, the following studies still need to be undertaken – see the following diagram.



4. European Route Spacing 'issues'

GNSS reversion

This Attachment has barely made a mention of the NAVAID Infrastructure needed to support route spacing. Nevertheless, the NAVAID Infrastructure in general and GNSS in particular are proving to be two high-priority challenges States have to grapple with in the application of PBN.

RNAV specifications as a basis of route design return rather large route spacings. For P-RNAV, the en route and terminal ATS route spacings were 9 NM and 7-8 NM respectively, and for B-RNAV it was 10 NM to 15 NM (with conditions). Both these specifications permit the use of VOR/DME or DME/DME or GNSS, thus the outage of one sensor (either on-board the aircraft or regionally) means that another sensor can be used or that in the 'worst case' ATC can use Radar Surveillance. The situation is slightly different as regards the Advanced RNP specification which allows a smaller route spacing of 7 NM. The difference is that GNSS is *required* **and** that a significant proportion of the European fleet cannot achieve RNP (integrity monitoring) without GNSS. The question arises, therefore, what the fallback is if GNSS fails? Differently put, what happens to the route spacing if GNSS fails?

Mindful that neither the EUR ARN nor the FMS navigation database can accommodate a dual route network where the second network would have a larger route spacing than the first in the event of GNSS outage, a reversion strategy is needed.

Several possibilities exist, given that if GNSS were to fail with Advanced RNP **all of the navigation functions** except on-board performance monitoring and alerting would continue to be available i.e. the aircraft does not suddenly get 'reduced' to P-RNAV/RNAV 1 but rather to 'Advanced RNAV' (though this, of course, is not an official designation). Work is currently ongoing to harmonise these scenarios to ensure that the operational implementation & consequences are clear to both pilots and ATC.

Reversion options	NAV Infrastructure implications	PRO	CONTRA
Excluding integrity monitoring, all remaining performance and functionality of Advanced RNP retained.	Make D/D mandatory in corresponding airspaces.	Currently best available non-GNSS reversion, probability of maintaining traffic levels for several hours reasonably high. Available below MSA.	Limited by availability of DME facilities. ***Note:*** *If a significant investment in new DME facilities would be required, it is recommended to find other means*
RNAV 5 enabled by VOR/DME.	Make VOR/DME mandatory in corresponding airspaces	Maintain RNAV operations, good situational awareness.	Poor accuracy, probably unable to sustain traffic levels for reasonable period; High ATC workload and dependence on Radar Surveillance for mitigation; rationalisation of VOR limited; Only available above MSA
Conventional navigation	Availability of corresponding aids (typically already existing); VOR, ILS, DME and even NDB.	Limited cost if facilities are already in place.	Counters purpose of PBN to design procedures for maximum airspace efficiency. Only an option in areas with little to no capacity or other environmental constraints.
Radar Control – short term	NAV Infrastructure not required	Whilst controllers remain skilled, this is a good mitigation for short term (e.g. up to one hour)	Traffic density would need to be reduced with extensive traffic regulation.
A-RNP enabled by a different GNSS element	Requires Multi-Constellation or Multi-Frequency for RNP application in ECAC	Best reversion to a fully redundant GNSS service. No change to ATC operations anticipated. Little change to ATC workload anticipated.	Not yet available, requires new standards and corresponding certification and equipage.

Note *that EGNOS cannot be used as reversion to GPS. EGNOS is a regional augmentation system for GPS that provides improved accuracy with independent integrity monitoring and is used together with GPS for the benefit of enabling RNP approaches with vertical guidance. Furthermore, EGNOS does not currently provide any ranging information.*

Appendix 1 to Attachment 5:
EUROPEAN ROUTE SPACING IN A RADAR ENVIRONMENT

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

Note *It is worth restating what is spelt out under Implementation of Section 2 of this attachment and that is that local implementation safety assessments may legitimately result in the application of different route spacings to those reflected in the above table. This is not a surprising given that the above route spacings are the result of generic route studies ('European regional level' with a generic set of assumptions) whilst implementation safety assessments are much more specific in nature, and reflect local operational conditions.*

Attachment 6:
NAVIGATION INFRASTRUCTURE ASSESSMENT FOR AIRSPACE PLANNING

The navigation infrastructure assessment process for RNAV1 is described in Eurocontrol Guide 0114: Guidance Material for P-RNAV Infrastructure Assessment. This assessment requires the most effort and tools are available to help in this process (Eurocontrol DEMETER Software). For VOR/DME to support RNAV5, all that is required is a verification of the coverage (using such tools, usually flight tests are not needed). For GNSS, the implementation process is described in the ICAO GNSS Manual (Doc 9849). The sections below describe issues associated with each type of PBN infrastructure.

VOR/DME

VOR/DME only enables RNAV5 **above MSA**, normally in en route airspace. While most modern multi-sensor FMS and even older RNAV systems provide a VOR/DME mode of operation, this is the least preferred (because it is the most inaccurate). However, it is relatively easy to achieve low-altitude coverage with a relatively small number of facilities, for example for supporting low level en route traffic.

DME/DME

To enable RNAV based on DME, multiple DME (at least 2) need to be available with a sufficient relative geometry. Due to terrain restrictions and limitations in available siting options, it may be difficult to achieve DME/DME coverage to low altitudes. For STARs, the goal should be to provide coverage down to all Final Approach Fixes or -waypoints. For SIDs, it is generally necessary to fly the initial portion based on conventional navigation, until the aircraft reaches the DME/DME coverage region. To close the gap between take-off and the RNAV portion of the SIDs, it may be necessary to require aircraft carriage of an IRS/IRU (Inertial Reference System/Unit) Unfortunately, due to the geometry requirements, current DME (such as when installed co-located with a VOR directly under the route) are often not ideally placed to support RNAV. However, stand-alone DME have significant installation flexibility compared to VOR, for example, co-located with existing surveillance or communications ground infrastructure. Three to four DMEs located in ideal positions should generally be sufficient to cover terminal airspaces.

Some air transport avionics are capable of providing RNP based on DME/DME. However, to enable all DME/DME equipped aircraft to provide an RNP1 service, considerable work is necessary. Also, current research suggests that DME/DME supporting RNP0.5 could be possible.

Some airspace users are not equipped with a DME-based RNAV capability, in particular general aviation aircraft. When using DME/DME as a mechanism to provide business continuity to air transport users in the case of a significant GNSS outage, a safe extraction (landing) possibility needs to be provided for non-equipped users (typically radar vectors onto an ILS). But once landed, it is considered that those non-equipped users would then stop operations. This operational scenario is considered acceptable provided such outages are very rare.

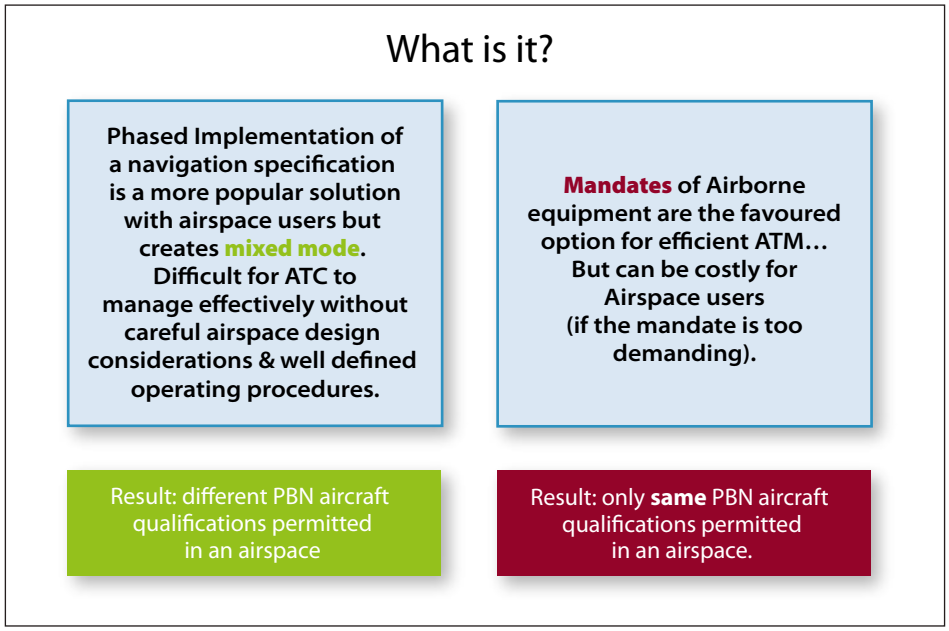
GNSS

As explained under activity 6 and discussed in Attachment 5, ANSPs planning for PBN implementation need to consider both making GNSS available for use as well as providing a mitigation in case GNSS fails. Such failure could occur due to interference originating from user segments outside of aviation. While future GNSS developments are expected to greatly increase GNSS service robustness, some form of non-GNSS mitigation will remain necessary. However, given a very low probability of occurrence, such reversions should be able to accept a lower capacity.

Summary

The navigation infrastructure assessment process starts by receiving coverage requirements from airspace planners (desired navigation specification and sensor combination depending on user fleet analysis, as well as geographic extent of the planned operations). An initial feasibility assessment is possible using software tools. The infrastructure assessment always considers the least equipped user taking into account avionics constraints relative to PBN. If facility changes are required, more detailed assessments, including all operational factors and economic considerations, will be conducted. The planning should be continuously refined by the navigation aid engineering department in cooperation with airspace experts, procedure designers and any other relevant party. The infrastructure assumptions are then formally confirmed during the validation process. The infrastructure assessment may also lead to changes in how facilities are operated (maintenance practices).

Attachment 7:
MIXED MODE OPERATIONS



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

Why have it?

The reasons for having mixed mode operations are usually related to:

- Cost: even if fleet can be retrofitted, it may cost too much
- Physical limitations of older aircraft which cannot be upgraded;
- Physical/Cost limitations of other aircraft e.g. military, business aviation and general aviation aircraft.

Mixed Mode 'models'

European experience has shown that mixed mode operations in an ATM environment are considered complex and impossible to achieve in high density operations. Over the last 15 years, virtually all real-time simulations and mixed mode operations in high-density airspace have resulted in controllers reverting to radar vectoring and PBN procedures ultimately remaining unused. As a consequence, the feeling has grown that mixed-mode operations are not feasible and not worth introducing - anywhere.

At ICAO's PBN Symposium in October 2012, this topic was chosen as the central theme of an ATM Workshop Forum. From that forum discussion, it has been possible to create the table on the next page, which 'identifies' mixed mode 'models' in use and their consequence.

A very important revelation from this Forum discussion was that, given the steep challenges presented by a State's *first* PBN implementation, introducing mixed mode operations for **low density** operations is an excellent way to learn important lessons needed to successfully implement PBN.

Model 1: Attempted in some European high-density terminal environments and in several real time simulations. **Characteristics:** Radar vectoring mixed with *one* other PBN specification in a terminal area e.g. Radar vectoring with RNAV 1 SIDs/STARs permitted or Radar Vectoring with Advanced RNP SIDs/STARs permitted. Controllers expected to allocate the PBN SID/STAR to appropriately PBN qualified aircraft and Conventional SID/STAR to the remaining traffic and to sequence all traffic normally. Furthermore, dedicated routes for RNAV 1/A-RNP qualified aircraft created and dedicated routes created for non-PBN capable aircraft.	To support this model, certain enablers needed: **a)** Separate designation for each SID or STAR requiring a particular qualification as per ICAO Annex 11, Appendix 3 e.g. KODAP 2A for RNAV 1; BINGO 3D for Conventional STAR. **b)** Available ATC system support to allow the controller to know the capability of the aircraft (this involves the Flight Data Processor (FDP) being able to extract the relevant information from Item 18 of the ICAO ATC FPL); *and* **c)** Available ATC system support that permits handling the traffic according to their navigation capability e.g. by reflecting the FDP data on the Radar Data Processer (RDP) or flight strip; *and*. **d)** In terminal areas, different SIDs/STARs and IAPs to accommodate different navigation specifications (care must be taken with designation of such 'double' routes to avoid human factor issues) – see Note. **Remarks:** Upgrade to ATC systems needed to permit ATC to handle mixed traffic is often not possible.
Model 2: Used in the US and Asia in low to high-density terminal environments for a single STAR connecting to both RNAV/RNP and conventional ILS approaches. **Characteristics:** All aircraft irrespective of their navigation qualification use a single STAR track. This single STAR track has a single designation and the onus is on the aircrew to fly the procedure using the equipment for which they have operational approval.	To support this model, certain enablers needed: **a)** A national regulatory regimen permitting the single designation of a multiple equipage/track STAR; and **b)** Regulatory acceptability of the pilot bearing the responsibility for flying the STAR with equipment for which there is operational approval **c)** The STAR design supports connection to both RNAV/RNP and conventional ILS approaches. **Remarks:** Upgrade to ATC systems not needed as regulatory regimen (especially in the US). Current US system limited to STARs.
Model 3: Used in one European medium density terminal environment. **Characteristics:** Similar to Model 1 but where aircraft declare, on first contact, whether they are RNAV 1 capable, for example, so that the correct clearance can be issued.	To support this model, certain enablers needed: **a)** Acceptance by ATC of additional Radio workload necessitated by pilot declaring whether crew has operational approval for RNAV 1, for example. **b)** Adequate procedures relating to handling of traffic. **c)** A regulatory regimen permitting the single designation of a multiple equipage STAR. **Remarks:** The application of this model is facilitated by acceptable levels of medium to low density operations and predictability of aircraft/airline/crew qualifications enabling controllers to 'learn' which aircraft are qualified for a PBN procedures.

Consequences of Mixed Mode

Without a requirement for mandatory equipage to a particular PBN specification in Models 1-2 or 3:

- There is no incentive for aircraft to obtain operational approval and as such the fleet retains its mixed flavour and the transition period can last a long time, as was shown with the P-RNAV example in Chapter 3 'Lessons Learnt'.

- The NAVAID infrastructure evolution is also slowed as all the permitted navigation specifications (or even conventional navigation) must be supported;

- In a Cost Benefit Analysis, the benefits are difficult to quantify because of the inability to optimise route spacing (i.e. it becomes necessary to retain the largest spacing for the lowest navigation performance, see Attachment 4) and the inability, in some environments, to reap the benefits of reduced obstacle clearance criteria for more high performing navigation specifications. This can mean that capacity, environmental and efficiency benefits of PBN are not necessarily realised.

In all three models, guidance material on handling mixed traffic is needed for controllers and flight crews. Such material would include airspace design considerations, allocation of the appropriate clearances etc.

As regards Model 1, mixed navigation environments have been shown to have a negative impact on ATC workload, particularly in dense en route or terminal area operations. The acceptability of a mixed navigation environment to ATC is also dependent on the complexity of the route structure and upon availability and functionality of ATC support tools. The increased ATC workload can lead to limits on mixed-mode operations to a maximum of two types, where there is one main level of capability. In some cases, ATC has only been able to accept a mixed environment where between 70 and 90 per cent of the traffic is approved to the required navigation specification. For these reasons, it is crucial that operations in a mixed navigation environment are properly assessed in order to determine the viability of such operations.

Nevertheless, Models 2 and 3 have proved workable and considered deemed a success because equipped operators at least feel that they are using their on-board equipment.

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