Performance Based Navigation (PBN)

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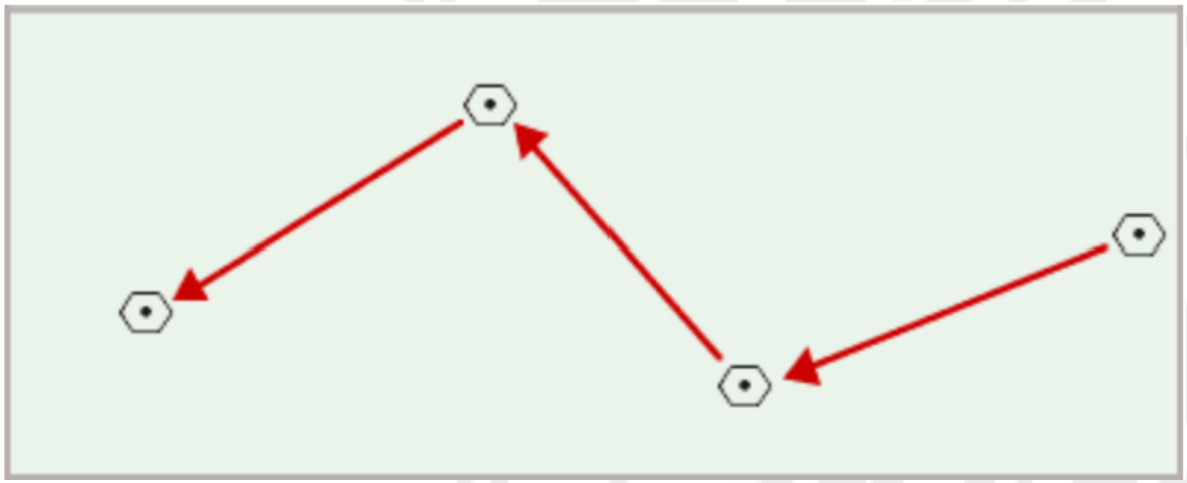
Version 1.1.b

Conventional Navigation

Aircraft normally navigate using external electronic guidance or self-contained information.

Routes were defined by the geographical positions of Navigation Aids (NAVAIDs) or fixes based on the intersection of radials from two NAVAIDs or a distance and a bearing from one. Aircraft were required to overfly these NAVAIDs and fixes.



Conventional Navigation - YouTube

Area Navigation

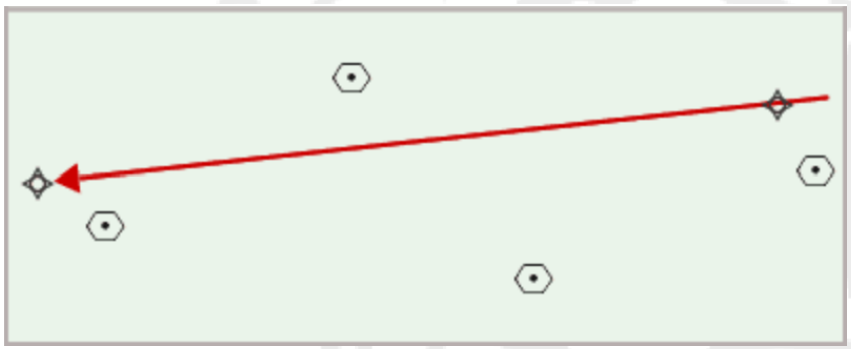
In the early 1970s, the first digital avionics were introduced on commercial aircraft. The Lockheed L-1011 TriStar is identified as the earliest civil aircraft to have this functionality.

The pilot was able to input co-ordinates into the aircraft's computer, which then provided guidance to the defined co-ordinates via a Course Deviation Indicator (CDI).

Area Navigation

The International Civil Aviation Organization (ICAO) Definition:
A method of navigation which permits aircraft operation on any desired flight path within the coverage of ground-based or space-based navigation aids or within the limits of self-contained aids, or a combination of these.

Area navigation enables the aircraft to fly a path between "waypoints", which are not necessarily co-located with ground-based navigational aids.



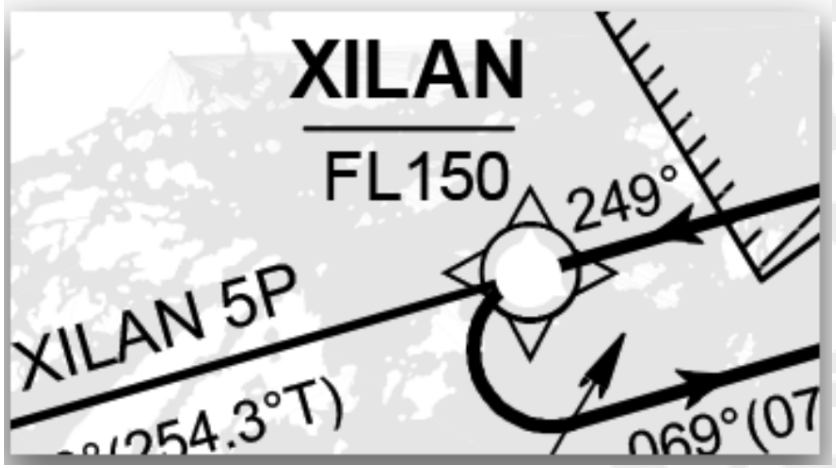
Area Navigation - YouTube

Waypoints

ICAO definition of a Waypoint:
A specified geographical location used to define an area navigation route or the flight path of an aircraft employing area navigation.

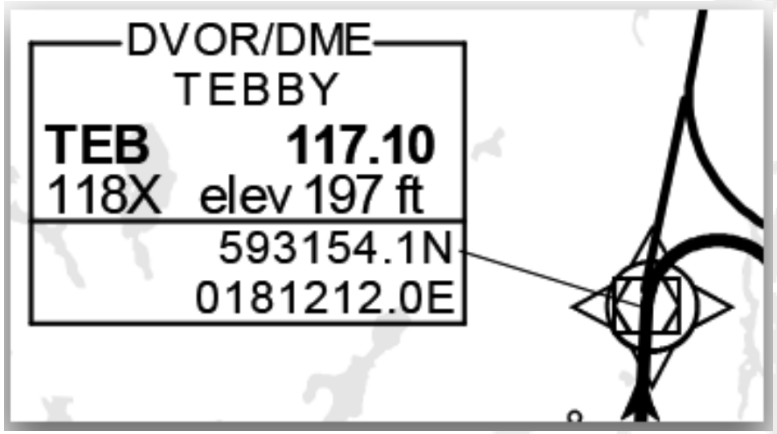
A waypoint is defined as a geographic coordinate (in WGS84) and is identified either:

- by a 5 letter unique name code.

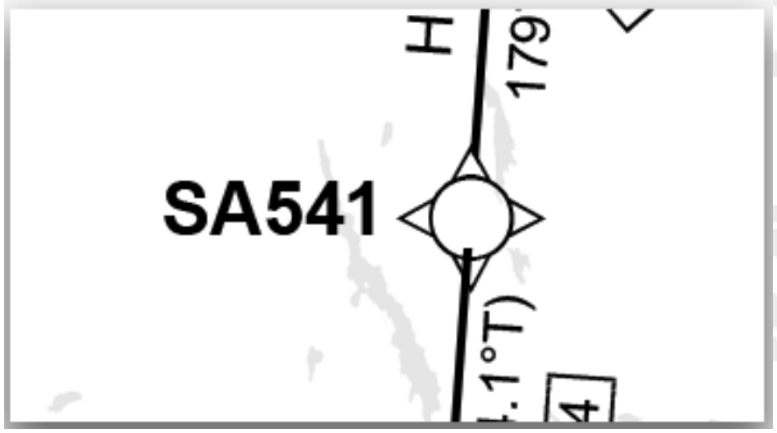


Waypoints

- if located with a ground based NAVAID by the 3 letter ICAO identifier for that station, or



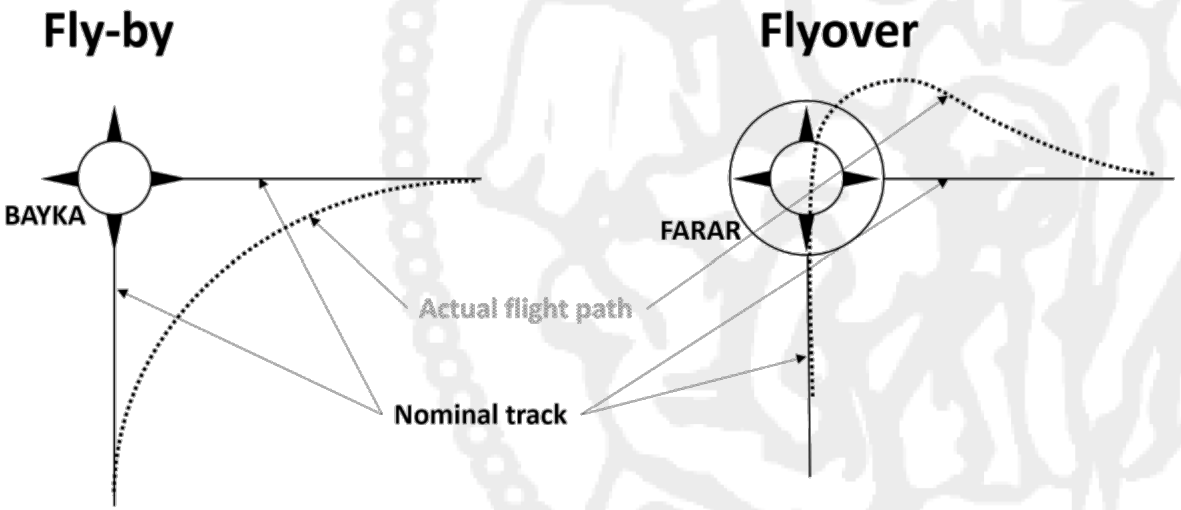
- for Terminal Airspace only, by an alphanumeric name code.



Waypoints

For terminal operations waypoints may be:

- Fly-by: A waypoint which requires turn anticipation to allow tangential interception of the next segment of a route or procedure, or
- Flyover: A waypoint at which a turn is initiated in order to join the next segment of a route or procedure.



RNAV System

An Area Navigation (RNAV) route is an Air Traffic Service (ATS) route established for the use of aircraft capable of employing Area Navigation.

RNAV routes are defined by Waypoints.

Only aircraft equipped with an RNAV system, can navigate effectively to these waypoints.

RNAV System

The intended flight path is created by the pilot by selecting or inputting a series of waypoints into the navigation computer.

The navigation computer defines the required flightpath by linking the waypoints together.

The intended flight path is then displayed to the pilot on a Navigation Display (ND).

RNAV System

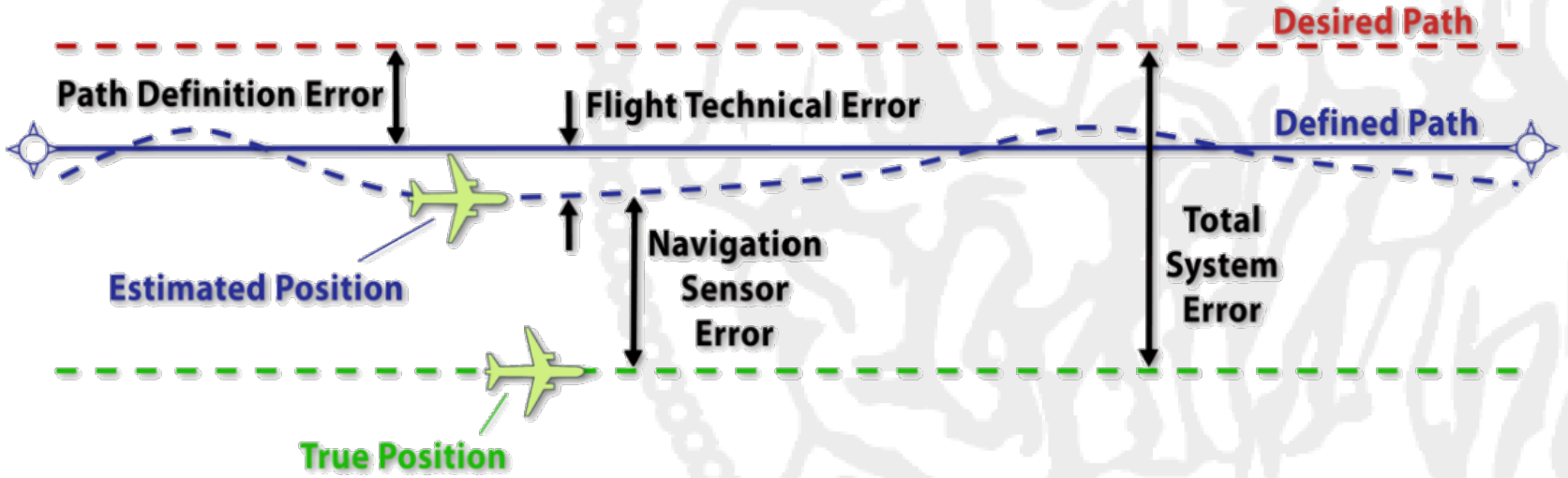
An RNAV system integrates information received from sensors, inputs from its internal database and crew entered data to provide:

- Navigation
- Flight Plan Management (referencing waypoints, not ground-based NAVAIDs)
- Guidance and Control
- Display and System Control

Total System Error

An RNAV system is designed and certified to provide a particular level of navigation accuracy with repeatable and predictable path definition.

The required navigation accuracy of an aircraft must take into account all of the errors. This is referred to as the Total System Error (TSE).



Total System Error

The causes of these errors are as follows:

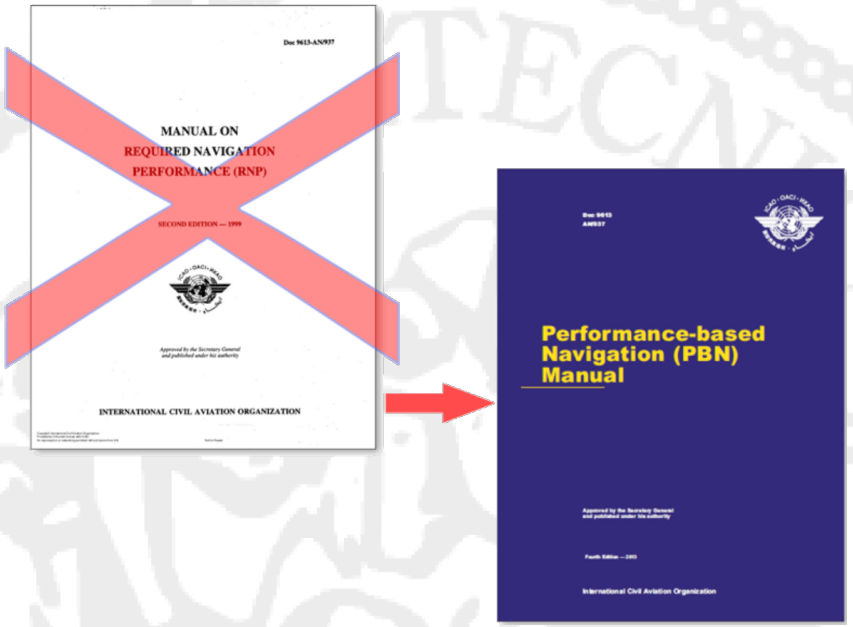
- the defined path may not exactly match the desired path,
- the aircraft's actual position may not coincide with its estimated position,
- the ability of the pilot or the avionics to fly from the estimated position onto the defined path.

When an aircraft is certified, it has been demonstrated that all of the errors combined, the aircraft is able to fly within the required performance 95% of the flight time.

Total System Error - YouTube

PBN Evolution

The original Required Navigation Performance (RNP) concept was replaced by the PBN concept in 2007.



PBN is a move from a limited statement of required performance accuracy to more extensive statements of required performance in terms of accuracy, integrity, continuity and availability of Global Navigation Satellite System (GNSS) signal, together with descriptions of how this performance is to be achieved in terms of aircraft functionality, navigation sensors and crew requirements.

PBN Benefits

The PBN concept extends beyond requiring a specific navigation accuracy, which was the case with the old RNP concept.

PBN includes identifying which flight crew procedures, RNAV system functionalities and navigation sensors are capable of achieving the required performance.

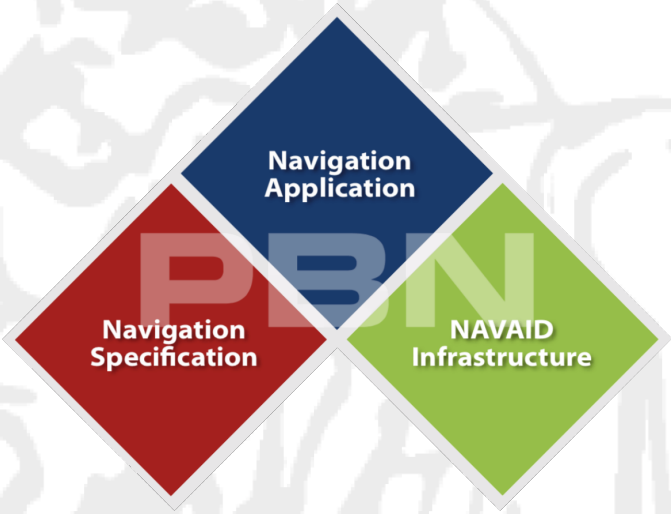
Global definitions of terms are provided that are aimed at removing any previous regional differences.

PBN Benefits

To address the weaknesses of the RNP concept, the Performance Based Navigation Manual:

- describes a coherent concept,
- provides implementation guidance,
- provides detailed Navigation Specifications, and
- provides a global framework with boundaries in which future regional Navigation Specifications and Navigation Applications can be developed.

It allows more efficient use of airspace.



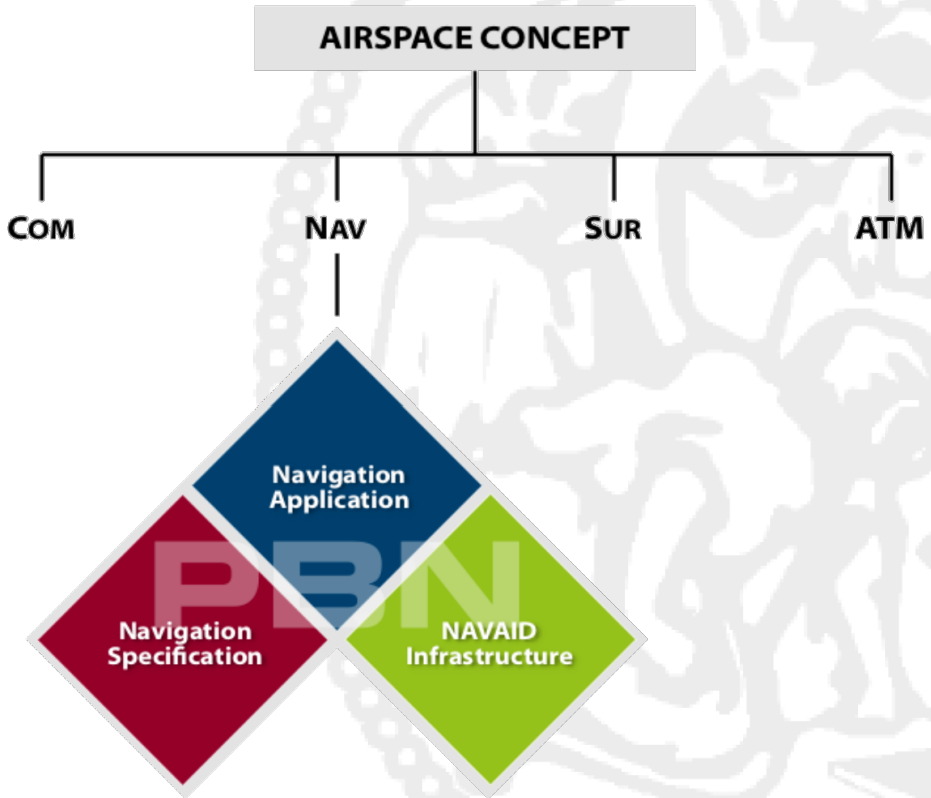
The Components Of PBN

There are three components of PBN:

- **NAVAID Infrastructure:** refers to the ground, space-based NAVAIDs or on-board capabilities which support or provide positioning capability. The Non-Directional Beacon (NDB) is not an acceptable NAVAID for PBN.
- **Navigation Specification:** details the aircraft and flight crew requirements needed to support PBN operations. They have been designed to minimise the impact on implementation costs for existing aircraft and systems.
- **Navigation Application:** the application of a Navigation Specification and the supporting NAVAID Infrastructure to specific routes, procedures and/or defined airspace volumes.

PBN Within The Airspace Concept

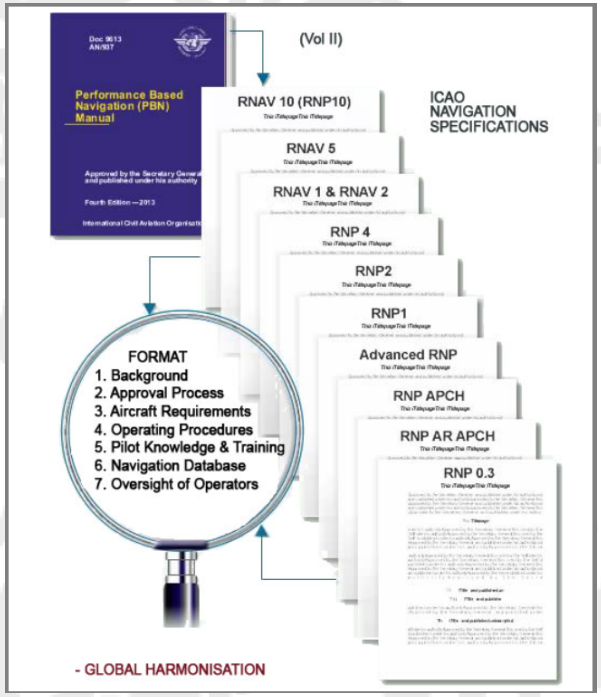
PBN is not a stand-alone concept; it is one of the elements that support the strategic objectives of the Airspace Concept, together with Communications, Surveillance and Air Traffic Management (ATM).



Navigation Specifications

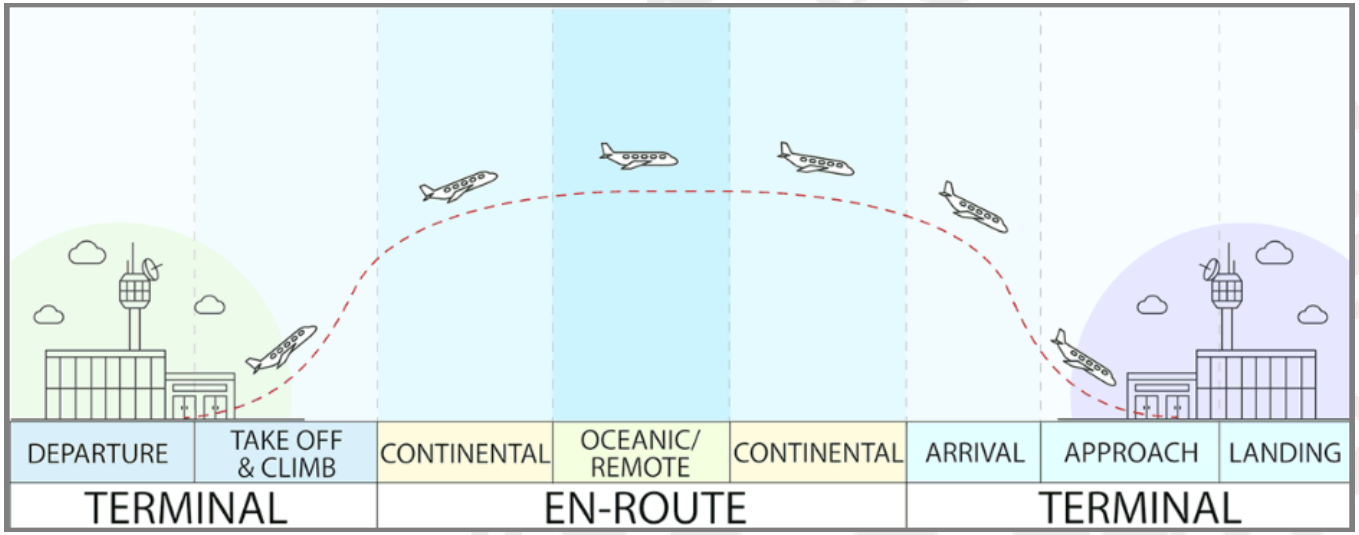
ICAO Navigation Specifications are detailed in Volume II of the Performance Based Navigation Manual. The Navigation Specification are:

- designed to satisfy global requirement
- globally compatible
- limited to provide global harmony



Navigation Specifications

The PBN Navigation Specifications relate to the different phases of flight.



Each Navigation Specification defines the performance required of the area navigation system together with any aircraft capabilities, the navigation sensors and aircrew requirements to support the defined performance level.

Navigation Specifications: Performance Requirements

- Accuracy:
  - Positioning accuracy is the difference between the actual and estimated position in fault free conditions (NSE).
  - Track-keeping accuracy is the difference between the actual and desired position in fault free conditions (TSE).
- Integrity: The degree of confidence that can be placed on the RNAV system's position estimations.
- Continuity: The ability of the navigation system to provide its service without interruption during an operation, provided it was available at the start of that operation.
- Functionality: The aircraft capabilities in terms of the avionics of the navigation computer and airframe. As a subset PBN considers the availability of the GNSS Signal In Space (SIS).

Navigation Specifications: Performance Requirements

Each Navigation Specification also details other requirements needed to achieve the specified performance level:

- **Navigation functionalities** of the RNAV system; the detailed capability of the navigation system (such as the execution of leg transitions, parallel offset capabilities, holding patterns, navigational databases)
- **Choice of navigation sensors**
- **Aircrew knowledge and training requirements**

Navigation Specifications: RNP and RNAV

RNP is a family of navigation specifications which permit the operation of aircraft along a precise flight path with a high level of accuracy and the ability to determine aircraft position with both accuracy and integrity.

Under the PBN concept, in addition to the RNP there exists the **RNAV** family of navigation specifications. RNAV and RNP are substantially very similar, they differ in relation to the performance monitoring and alerting requirement which applies to RNP only.

In normal operations, on-board performance monitoring and alerting provides the flight crew an alert "*Unable RNP*" when the required lateral track accuracy limit stipulated for the ATS route leg is exceeded.

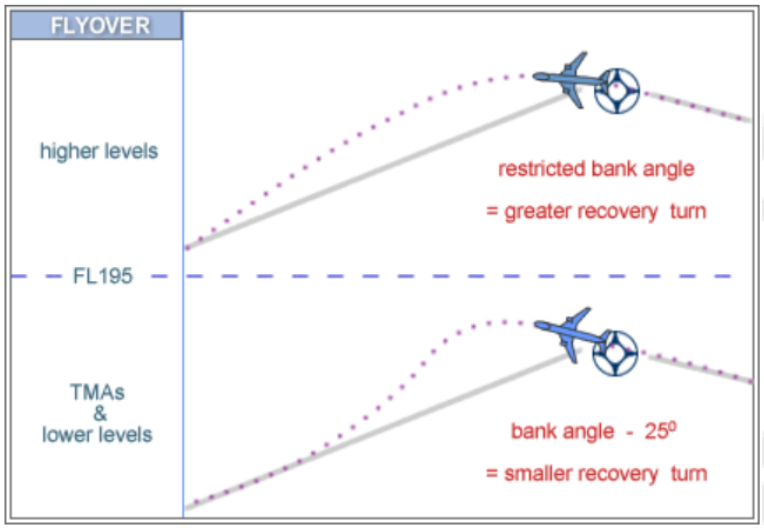
Navigation Specifications: Aircraft Functionality

Waypoints

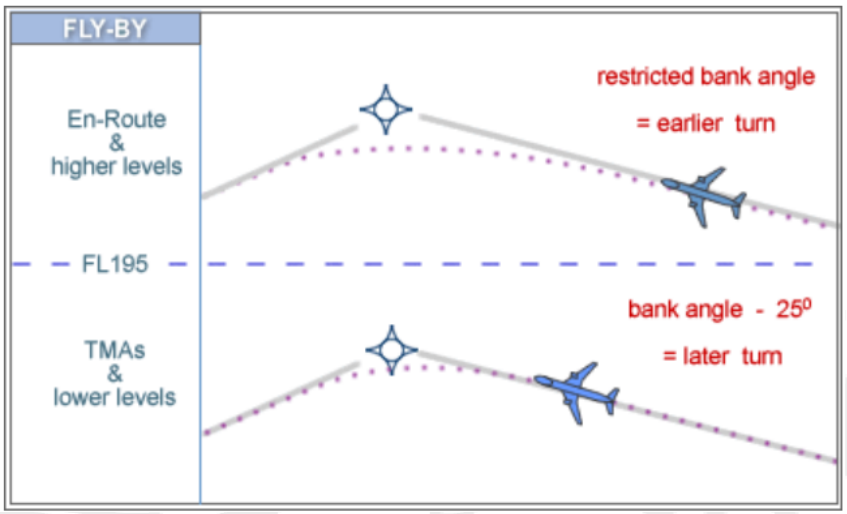
RNAV routes are defined by waypoints, which can be either Flyover or Fly-by.

Aircraft can perform turns as follows:

- Flyover



- Fly-by

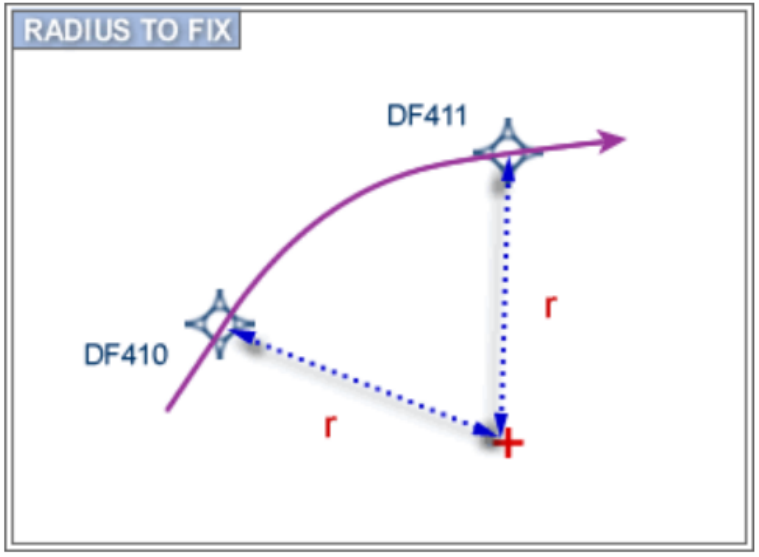


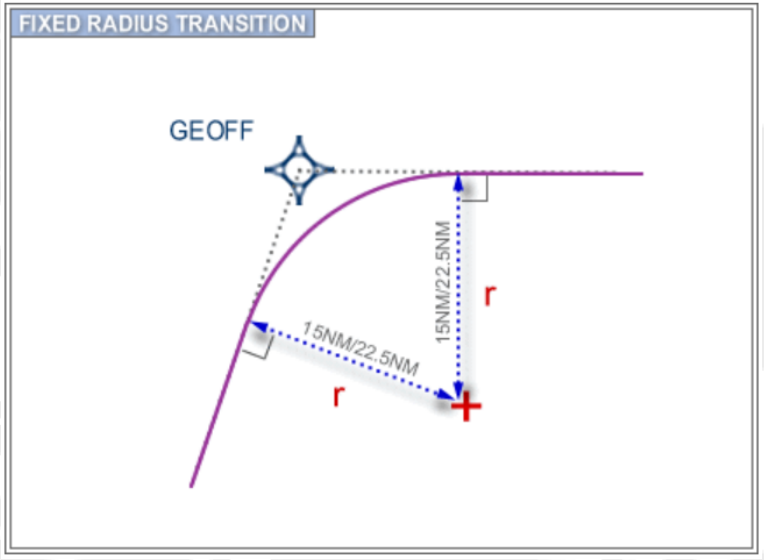
Navigation Specifications: Aircraft Functionality

Turn Performance

Fixed radius turns are used to ensure predictable and reliable track keeping in the turn. Fixed radius performance is achieved in one of two ways depending on the phase of flight:

- Radius to Fix
- Fixed Radius Transitions





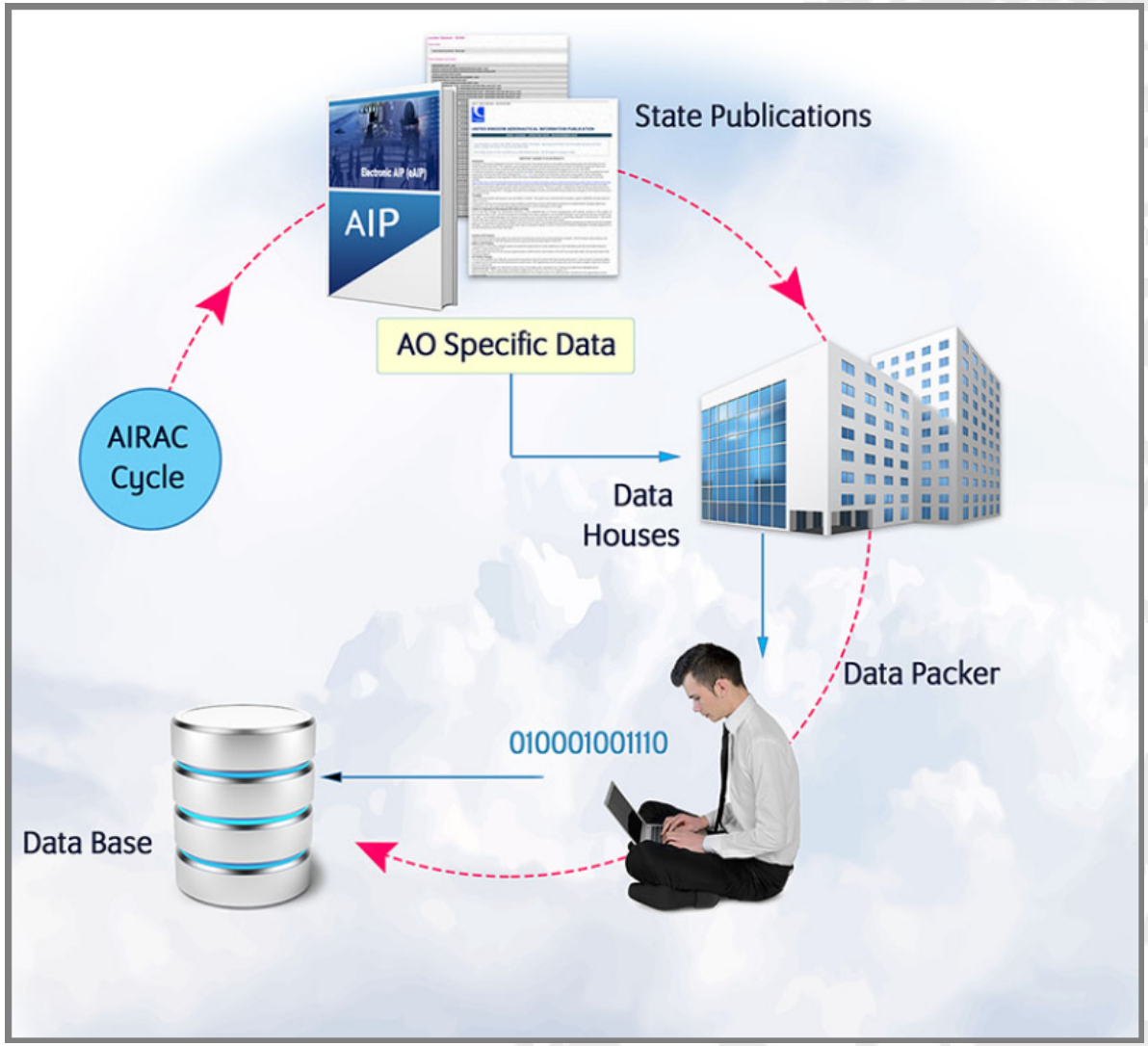
Navigation Specifications: Database

Navigation Specifications will identify if the computer is required to have a database.

Where an RNAV system has a database, the ATS routes and airport data required by that particular Aircraft Operator (AO) are stored (within the capacity limits of the database), as well as coordinates for all ground-based NAVAIDs.

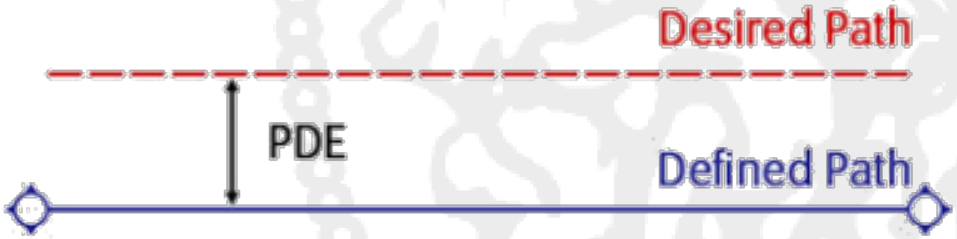
The databases are updated and validated in accordance with the ICAO Aeronautical Information Regulation And Control (AIRAC) cycle (28 days).

Navigation Specifications: Database



Navigation Specifications: Creating the Path

The Airspace Planner and the Procedure Designer design the Standard Instrumental Departures (SIDs), Standard Instrument Arrivals (STARs) and ATS routes with a sequence of waypoints. This is known as the *"Desired Path"*.
The computer links the waypoint together in order and creates a flightpath. This path is known as the *"Defined Path"*.
There can be some small computational errors called Path Definition Error (PDE).



PDE -- Path Definition Error

Navigation Specifications: Flying the Path

The aircraft uses one or more sensors to estimate its position and the RNAV system calculates the deviation from the defined path and adjusts accordingly to maintain that path. How well the 'actual' and 'desired' paths coincide depends on:

- the coding of the database
- the navigation sensors
- the capabilities and functionalities of the RNAV system
- how the aircraft is flown:
  - manually following a CDI
  - manually with the aid of a a Flight Director (FD)
  - Auto Pilot (AP)

Navigation Specifications: Cross Specifications

The ICAO Navigation Specifications are to be used by individual States, or Regions, as a basis for Certification and Operational Approval.

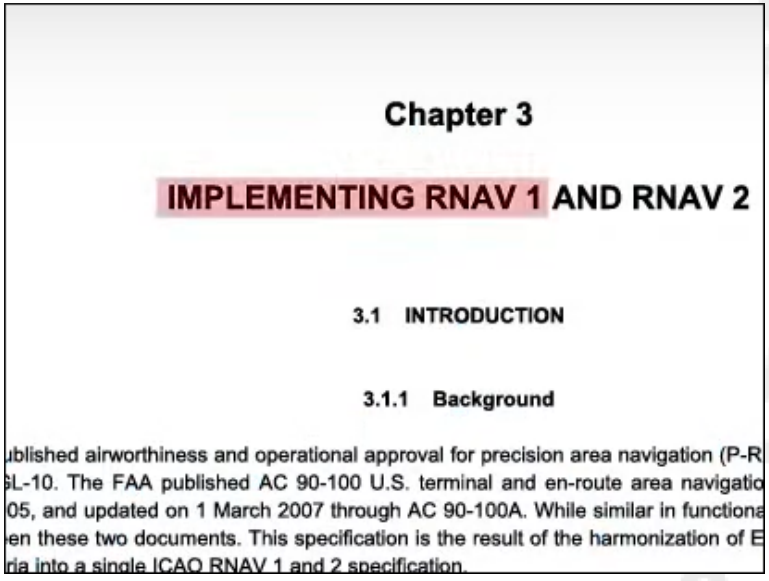
An aircraft can be certified to a particular Navigation Specification with one or more of the required navigation sensors identified in that Specification.

The criteria for carriage of specific navigation sensors as detailed in a Navigation Specification will be driven by the NAVAID infrastructure defined by the individual State or region.

As such, it is possible that the aircraft is certified to a particular Navigation Specification but cannot meet the needs of the airspace because the navigation sensors do not match the NAVAID infrastructure.

Navigation Specifications: Cross Specifications

From the Volume II of PBN Manual:



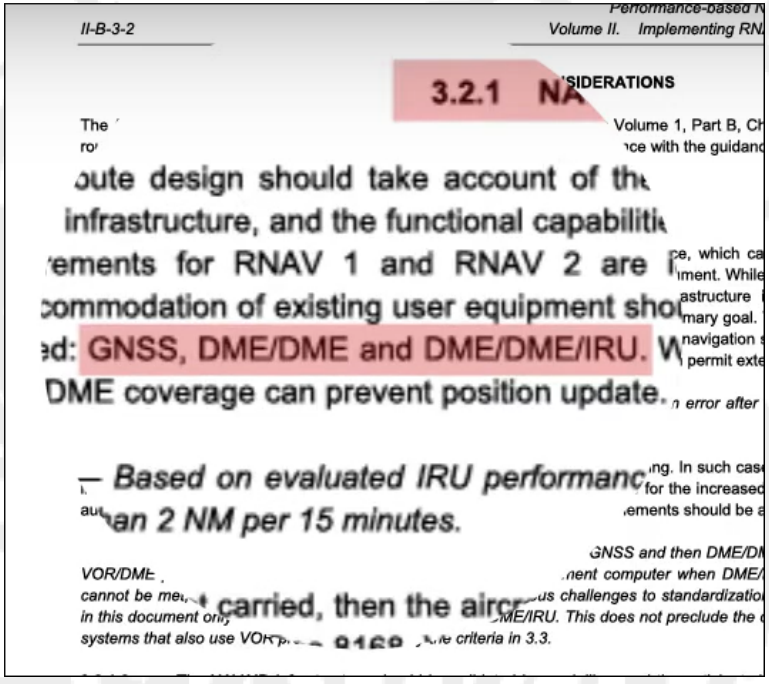
Chapter 3

IMPLEMENTING RNAV 1 AND RNAV 2

3.1 INTRODUCTION

3.1.1 Background

ublished airworthiness and operational approval for precision area navigation (P-R
GL-10. The FAA published AC 90-100 U.S. terminal and en-route area navigatio
05, and updated on 1 March 2007 through AC 90-100A. While similar in functiona
en these two documents. This specification is the result of the harmonization of E
ria into a single ICAO RNAV 1 and 2 specification.



II-B-3-2 Volume II. Implementing RN

3.2.1 NA SIDERATIONS

The Volume 1, Part B, Ch
ro ce with the guidanc

oute design should take account of th
infrastructure, and the functional capabiliti
ements for RNAV 1 and RNAV 2 are p e, which ca iment. While
commodation of existing user equipment sho astructure mary goal.
ed: GNSS, DME/DME and DME/DME/IRU. W navigation permit exte
DME coverage can prevent position update. n error after

— Based on evaluated IRU performanc ng. In such cas for the increased
au an 2 NM per 15 minutes. ements should be a

GNSS and then DME/DM
VOR/DME nent computer when DME/
cannot be me carried, then the aircr us challenges to standardizatio
in this document on ME/IRU. This does not preclude the
systems that also use VOR 9169 e criteria in 3.3.

Navigation Specifications: Cross Specifications

	RNAV1 DME/DME	RNAV1 GNSS	RNAV1 GNSS DME/DME
State A	✓	not legally allowed	✓
State B	✗	✓	✓

Navigation Specifications: Cross Specification

It should be noted that, if an aircraft and crew are certified for a particular Navigation Specification Designator, it does not imply automatic qualification for a Navigation Specification requiring less stringent accuracy. For example RNAV 5 approval does not imply RNAV 10 is satisfied.

Positioning Accuracy

The estimated horizontal and vertical position is compared against the defined path created by the navigation computer.

Position estimation accuracy is related to the type of navigation sensor used; each sensor has its own error value, called the Navigation Sensor Error (NSE).

Some sensors are better suited to PBN operations than others:

- **NDB**: is not considered in PBN as it is not accurate enough for position estimation;
- **VOR**: only supports RNAV 5;
- **DME**:cannot support RNP APCH
- **GNSS**: has the smallest error and with augmentation (integrity checking), provides a navigation solution for every Navigation Application;

Navigation Application

Navigation Application refers to the application of a Navigation Specification and the supporting NAVAID Infrastructure to specific routes, procedures and/or defined airspace volumes.

Area Navigation, which is based on the navigation computer creating paths between waypoints, is a key enabler for PBN.

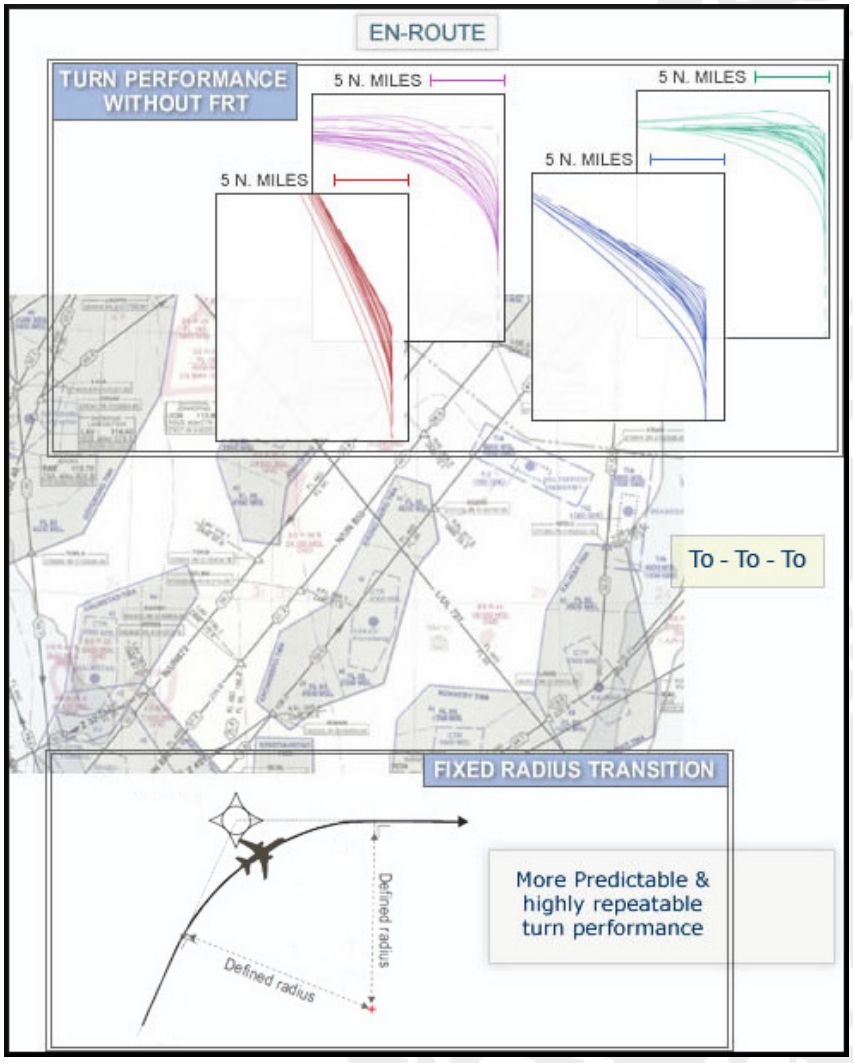
Navigation Application: En-Route Navigation

Turn performance varies depending on altitude, angle of turn, wind and speed. Systems having Fixed Radius Transiton (FRT) capability will provide better and more repeatable turn performance.

To guarantee predictable and highly repeatable flightpaths when turning, FRTs can be used.

It should be noted that the FRT functionality is only available on modern aircraft and not all aircraft can execute this type of turn.

Navigation Application: En-Route Navigation

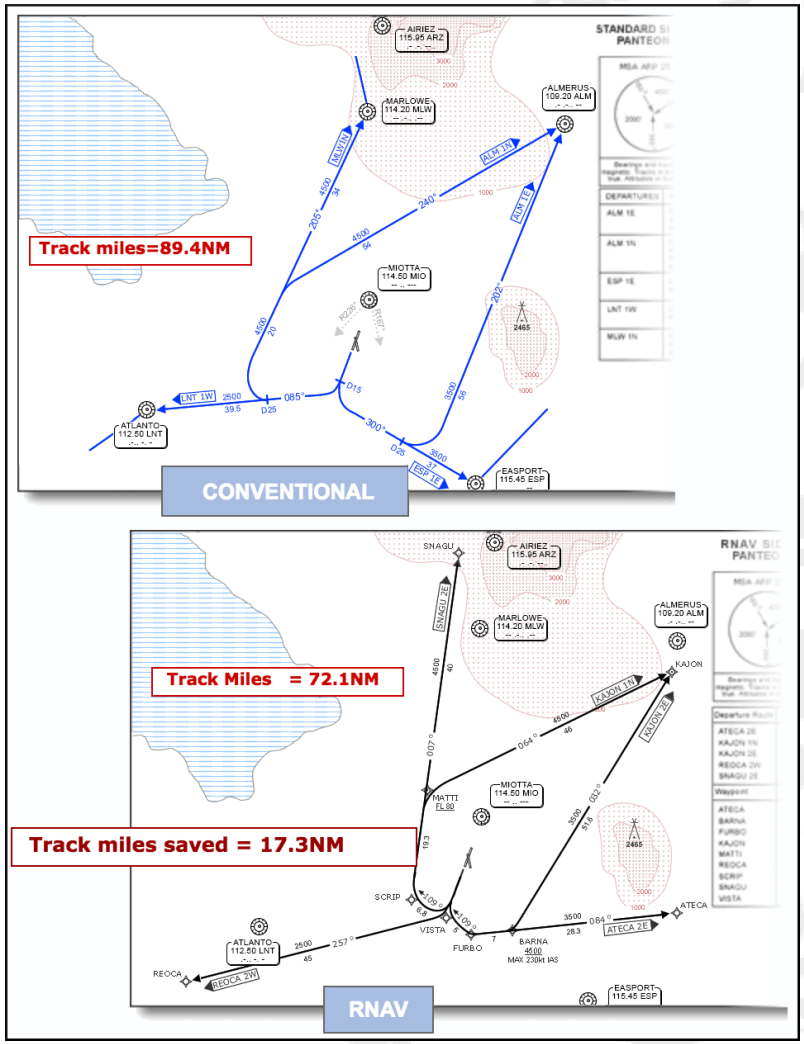


Navigation Application: Benefits of PBN

- reduced need to develop and maintain sensor-specific routes and procedures, and their associated costs;
- **more efficient use of airspace:** additional routes and improved route placement, reduced bottlenecks;
- **more predictable operations:** advance planning to support continuous descent operations;
- **environmental mitigation:** more fuel efficient and shorter routes (reduced emissions), noise and visual abatement (tranquillity issues);

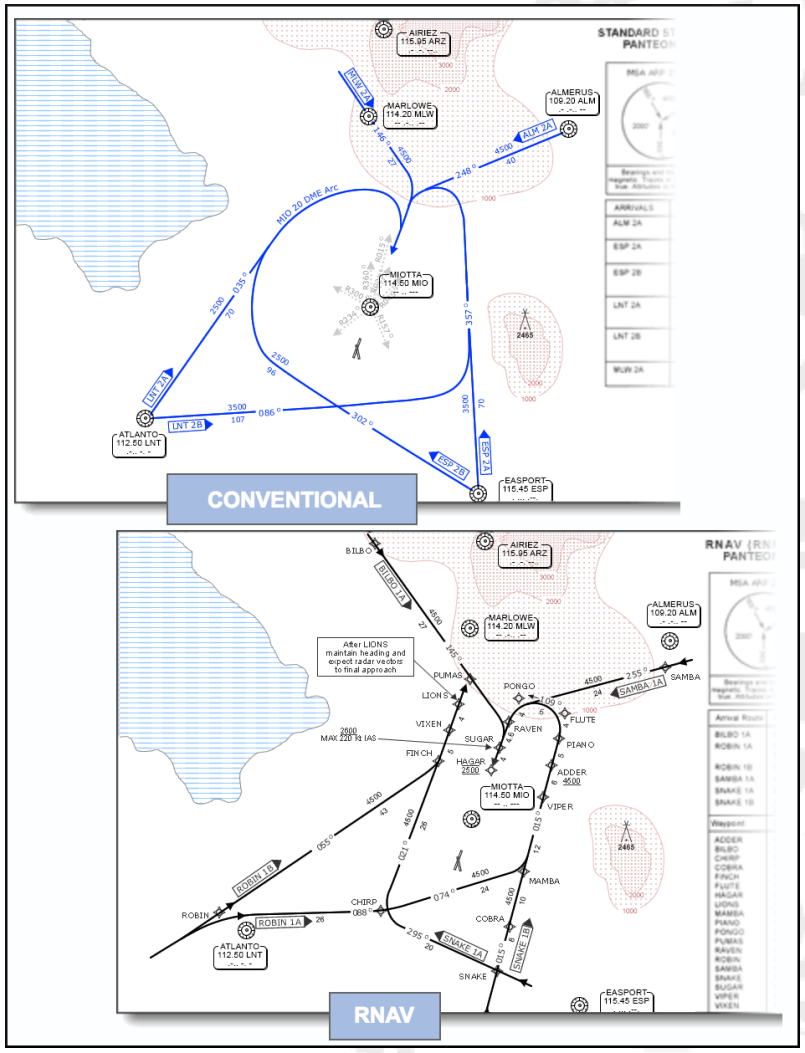
Navigation Application: Terminal Airspace Navigation

SID



Navigation Application: Terminal Airspace Navigation

STAR



Closed STARs and Open STAR

There are 2 methods used to terminate RNAV STARs

- **Closed STARs:** characterised by the publication of an uninterrupted RNAV nominal track to the final approach segment of the relevant instrument approach;
- **Open STARs:** characterised by the publication of an RNAV nominal track up to a waypoint, such as a metering Fix or a downwind waypoint, followed by ATC vectors to final approach;

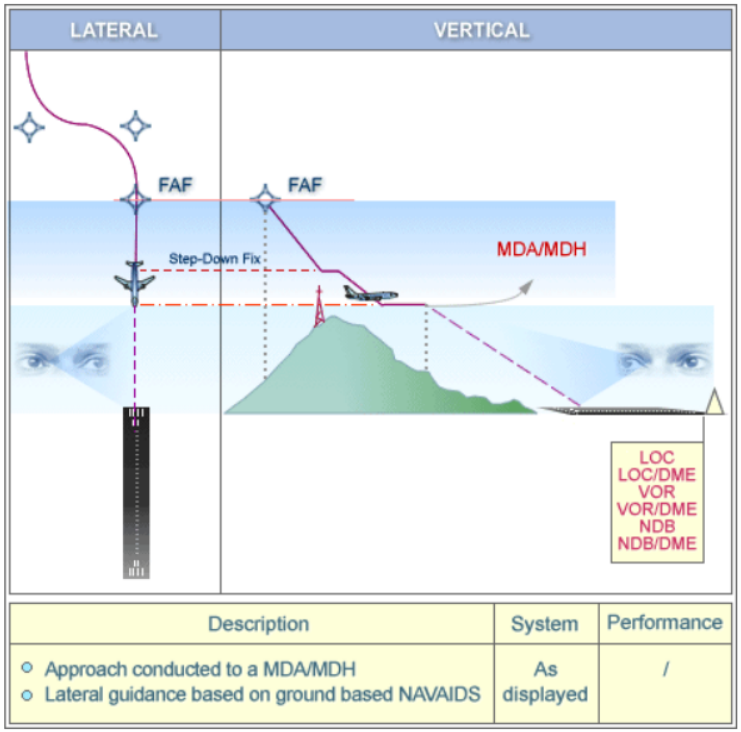
Closed STAR - YouTube

Open STAR - YouTube

Approach

Historically there were two types of approach:

- **Precision Approach (PA)** providing lateral and vertical guidance based on an ILS;
- **Non-Precision Approach (NPA)** where only lateral guidance was available from a conventional NAVAID.



Approach

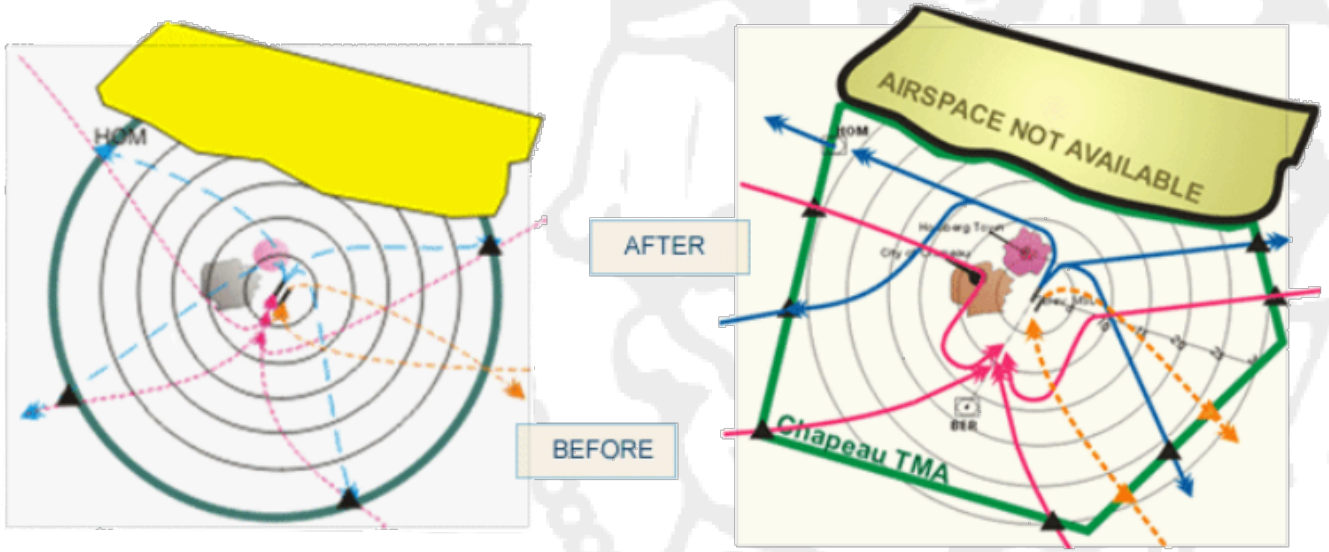
PBN offers alternatives to PA and Conventional NPA, including approaches with or without vertical guidance.

The Approach phase of flight is covered by the following Navigation Applications:

- RNP APCH
- RNP APCH with Vertical guidance (APV)
  - APV BARO VNAV
  - APV SBAS

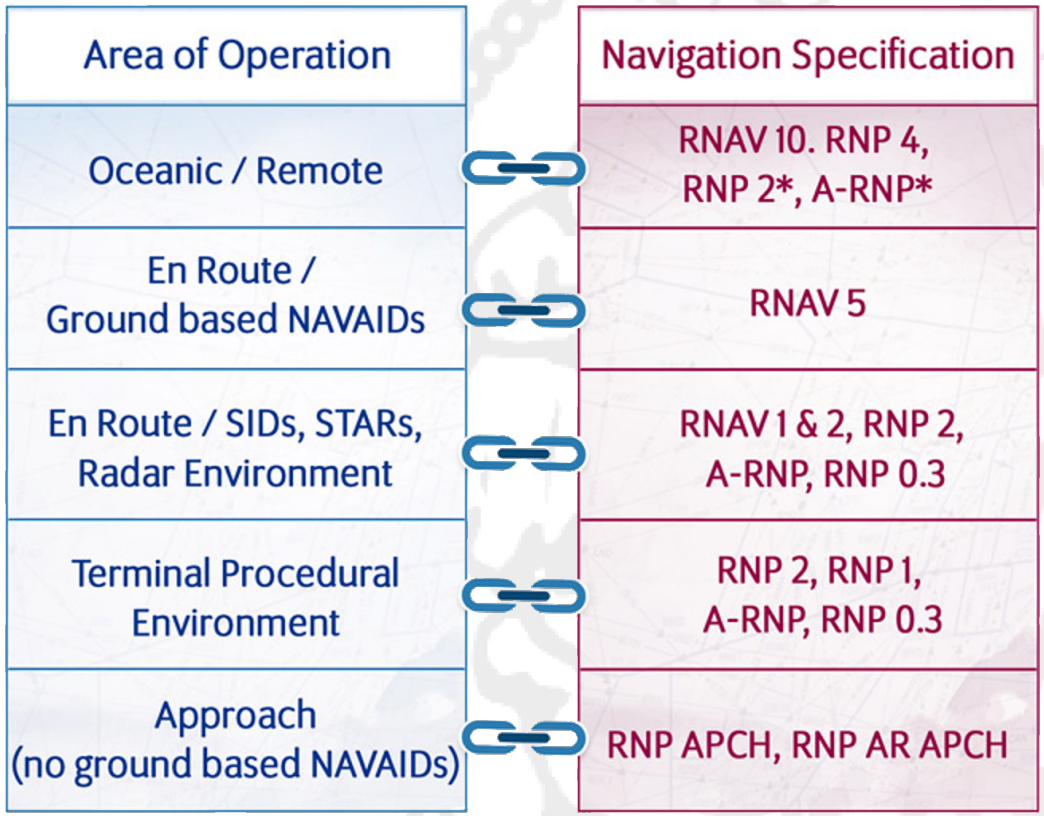
Benefits of PBN SIDs and STARs

- improves situational awareness and therefore improves overall flight safety;
- helps with access and capacity issues;
- enables strategic segregation of traffic;
- allows continuous descent, and could provide environmental mitigation;



Navigation Specifications in different areas of operation

The diagram below indicates which Navigation Specifications are typically associated with different areas of operation:



Navigation Specifications in different areas of operation

There is a strong link between an area of operation and the Navigation Specification:

	Flight Phase	Navigation Specification	Required Lateral Accuracy (TSE) 95% of the flight time	Enabling System (one or more are required)
EN ROUTE	Oceanic / Remote	RNAV 10 (RNP 10) RNP 4 RNP 2 Advanced RNP	± 10 NM ± 4 NM ± 2 NM [a] ± 2 NM [a]	GNSS, INS/IRU GNSS GNSS GNSS
	Continental	RNAV 5 [b] RNAV 2 RNAV 1 RNP 2 Advanced RNP RNP 0.3 [c]	± 5 NM ± 2 NM ± 1 NM ± 2 NM ± 2 NM or ± 1 NM ± 0.3 NM	GNSS, VOR, DME, INS/IRS GNSS DME/DME, (+IRU) GNSS DME/DME, (+IRU) GNSS GNSS, DME/DME [1] GNSS
TERMINAL	Arrival only Arrival / Departure (SIDs / STARs)	RNAV 5 [b] RNAV 2 RNAV 1 RNP 1 [d] Advanced RNP RNP 0.3 [c]	± 5NM ± 2 NM ± 1 NM ± 1 NM ± 0.3 NM ± 0.3 NM	GNSS, VOR, DME, INS/IRS GNSS DME/DME, (+IRU) GNSS DME/DME, (+IRU) GNSS, DME/DME [1] GNSS GNSS
	Approach	Advanced RNP	± 0.3 NM in Initial and Intermediate phases only	GNSS, (+IRU)
		RNP APCH [f]	± 1 NM in Initial and Intermediate phases ± 0.3 NM in Final Approach phase	GNSS, DME/DME [1]
		RNP (AR) APCH	± 1 to 0.1 NM in Initial and Intermediate Approach phases ± 0.3 to 0.1 NM in Final Approach phase	GNSS (+IRU if required for extraction)
		RNP 0.3 [c]	± 0.3 NM	GNSS

Approach and Landing

Approach and Landing in Queenstown, New Zealand - YouTube

Credit where credit is due

The present material has been prepared as part of the contribution to the *Flipped Class-innovative didactic* initiative during academic year 2021/2022 by the following students:

- Claudia Ranieri
- Francesco Marini
- Pietro Marini

List of Acronyms

AIRAC	Aeronautical Information Regulation And Control
AO	Aircraft Operator
AP	Auto Pilot
ATS	Air Traffic Service
CDI	Course Deviation Indicator
FD	Flight Director
FRT	Fixed Radius Transiton
NAVAID	Navigation Aid
NDB	Non-Directional Beacon
NPA	Non-Precision Approach
NSE	Navigation Sensor Error
PA	Precision Approach
PBN	Performance Based Navigation
PDE	Path Definition Error
RNAV	Area Navigation
RNP	Required Navigation Performance
SIS	Signal In Space
STAR	Standard Instrument Arrival
TSE	Total System Error
ATM	Air Traffic Management
GNSS	Global Navigation Satellite System
ICAO	International Civil Aviation Organization
ND	Navigation Display
SID	Standard Instrumental Departure