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Flight crew basic theoretical training for

RNP APCH down to LPV minima

European Satellite Services Provider S.A.S.
Service Provision Unit

Issue 1.3 – April 2019

Introduction

- This training package is focussed in covering the **theoretical knowledge syllabus** for RNP APCH to LPV minima for an Instrument Rated pilot in accordance with:

Appendix to Annex I to ED Decision 2018/001/R

'Acceptable Means of Compliance (AMCs) and Guidance Material (GM) to Part-FCL Amendment 4'

- To complement it, it also covers the **theoretical knowledge syllabus** for Global Navigation Satellite Systems

- This training shall be complemented with:
  - Operating Procedures training
  - Specific Aircraft System theoretical training
  - Practical in aircraft or simulator training

Introduction

Some notes:

- All paragraphs intended to cope with Learning Objectives (LOs) sub-references are numbered following the same EASA's Syllabus Reference i.e. (01), (02), (03), etc

- Certain contents and/or slides are not part of formal LOs but have been included to provide additional information. This are not marked in any way.

- A significant number of LOs are not applicable to CB-IR(A) and EIR. Only those marked with a **CE** symbol are applicable

- Text referring to BK LOs has been marked with a **BK** symbol. Explanatory Note to Decision 2018/001/R, which states that:

  "Several LOs have been categorised as comprising 'Basic Knowledge (BK)' in a newly added column in the LO tables"

  "These LOs will no longer be the subject of dedicated examination questions"

  "However, student pilots will still be required to assimilate the specific knowledge required by the BK LOs"

Target audience: all IR pilots

Commission Regulation (EU) 2016/539, amending Regulation (EU) No 1178/2011 as regards pilot training, testing and periodic checking for performance-based navigation

- Introducing the necessary changes to Air Crew regulations as to incorporate PBN in the regular training and checking requirements for pilots

- Requesting all ATOs to **introduce PBN privileges to their IR courses by 25 August 2020 at the latest, date from which PBN will become mandatory to all IR pilots**

List of acronyms

ABAS	Airborne Based Augmentation System	FTE	Flight Technical Error	LP	Localiser Performance	RDH	Reference Datum Height
AAIM	Aircraft Autonomous Integrity Monitoring	GAGAN	GPS Aided Geo Augmented Navigation	LPV	Localiser Performance with Vercial Guidance	RNAV	Area Navigation
AIRAC	Aeronautical Information Regulation And Control	GBAS	Ground Based Augmentation System	LTP	Landing Threshold Point	RNP	Required Navigation Performance
AMC	Acceptable Means of Compliance	GCS	Galileo Control Segment	MEL	Minimum Equipment List	SBAS	Satellite Based Augmentation System
ANSP	Air Navigation Service Provider	GLONASS	Global Navigation Satellite System	MEO	Medium Earth Orbit	SDCM	System for Differential Corrections and Monitoring
APV	Approach with Vertical Guidance	GMS	Ground Mission Segment	MLS	Microwave Landing System	SNAS	Satellite Navigation Augmentation System
ATS	Air Traffic Services	GNSS	Global Navigation Satellite System	MSAS	Multi-functional Satellite Augmentation System	SPS	Standard Positioning Service
CDFA	Continuous Descent Final Approach	GPS	Global Positioning System	NDB	Non-Directional Beacon	TAWS	Terrain Awareness Warning System
CRC	Cyclic Redundancy Check	GSA	European GNSS Agency	NM	Nautical Mile	TK	Theoretical Knowledge
DME	Distance Measuring Equipment	HAL	Horizontal Alert Limit	NSE	Navigation System Error	TTFF	Time To First Fix
DOP	Dillution Of Precision	ICAO	International Civil Aviation Organisation	OM	Operations Manual	UHF	Ultra High Frequency
EGNOS	European Geostationary Navigation Overlay Service	ILS	Instrument Landing System	PBN	Performance Based Navigation	UTC	Universal Time Coordinated
ESSP	European Satellite Services Provider	IRS	Inertial Reference System	PDE	Path Definition Error	VAL	Vertical Alert Limit
FAF	Final Approach Fix	IRU	Inertial Reference Unit	PinS	Point in Space	VDB	VHF Data Broadcast
FAP	Final Approach Point	LAAS	Local Area Augmentation System	PL	Protection Level	VHF	Very High Frequency
FAS DB	Final Approach Segment Data Block	LNAV	Lateral Navigation	PPS	Precise Positioning Service	VOR	VHF Omnidirectional Range
FD	Fault Detection	LNAV/VNAV	Lateral Navigation / Vertical Navigation	PRN	Pseudo-Range Noise	VPA	Vertical Path Angle
FDE	Fault Detection and Exclusion	LO	Learning Objective	RAIM	Receiver Autonomous Integrity Monitoring	WAAS	Wide Area Augmentation System

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ESSP

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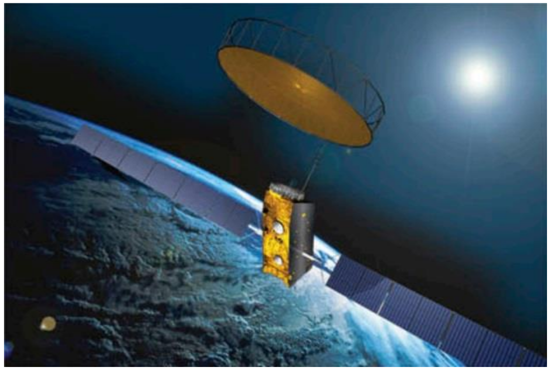
Course contents: TK /LO's

062 06 00 00	**GLOBAL NAVIGATION SATELLITE SYSTEMS**
062 06 01 00	Global navigation satellite systems (GNSSs)
062 06 01 01	General
062 06 01 02	Operation
062 06 01 03	Errors and factors affecting accuracy
062 06 02 00	Ground-, Satellite- and Airborne-based augmentation systems



Course contents: TK /LO's

062 07 00 00	**PBN**
062 07 01 00	PBN concept
062 07 01 01	PBN principles
062 07 01 02	PBN components
062 07 01 03	PBN Scope
062 07 02 00	Navigation Specifications
062 07 02 01	RNAV and RNP
062 07 02 02	Navigation functional requirements
062 07 02 03	Designation of RNP and RNAV specifications
062 07 03 00	Use of PBN
062 07 03 03	Specific RNAV and RNP system functions

062 07 00 00	**PBN**
062 07 04 00	PBN operations
062 07 04 01	PBN principles
062 07 04 02	On-board performance monitoring and alerting
062 07 04 03	Abnormal situations
062 07 04 04	Database management
062 07 05 00	Requirements of specific RNAV and RNP specifications
062 07 05 05	RNP APCH
062 07 05 09	PBN Point In Space (PinS) Approach

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062 06 00 00

GLOBAL NAVIGATION SATELLITE SYSTEMS

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062 06 01 00 – GPS / GLONASS /GALILEO / BeiDou

062 06 01 01 – General

CE (01) There are four main Global Navigation Satellite Systems (GNSS)

- USA NAVSTAR **GPS** (NAVigation System with Timing And Ranging Global Positioning System)
- Russian **GLONASS** (GLObal Navigation Satellite System)
- European **GALILEO** (more info here), to become fully operational in the coming years
- Chinese **BEIDOU**, to become fully operational in the coming years

CE **BK** (02) All these systems:

- Consist of a constellation of satellites which can be used by suitably equipped receivers to determine position
- Are interoperable

Unlike GPS and GLONASS, ***Galileo*** *and BeiDOU are run by civil, not military, authorities*

GPS-III-A satellite (source: United States Government)

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062 06 01 02 – Operation

Modes of operation

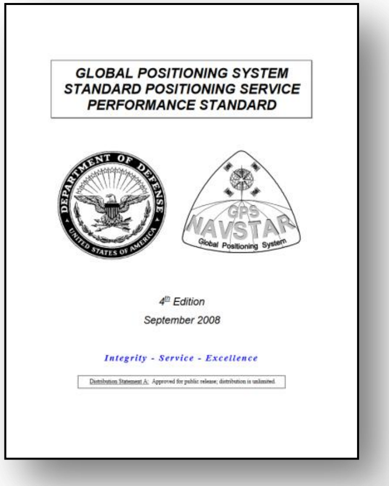
CE (1) GNSS can operate in two different modes:

- SPS (Standard Positioning Service): civilian users
- PPS (Precise Positioning Service): authorised users

CE (2) **SPS** is a positioning and timing service originally designed to provide civilian users with a less accurate positioning capability than **PPS**

CE BK (3) GNSS are composed of 3 main **segments**:

- space segment
- control segment
- user segment

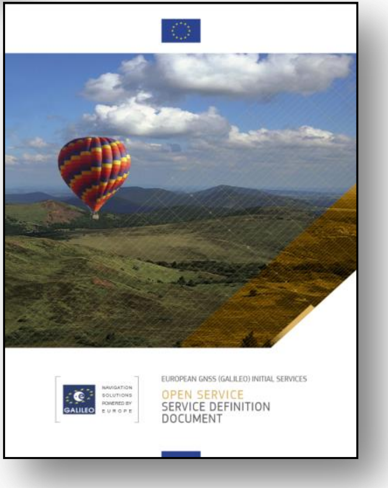


GLOBAL POSITIONING SYSTEM
STANDARD POSITIONING SERVICE
PERFORMANCE STANDARD

4th Edition
September 2008

Integrity - Service - Excellence

Distribution Statement A: Approved for public release; distribution is unlimited.



EUROPEAN GNSS (GALILEO) INITIAL SERVICES
OPEN SERVICE
SERVICE DEFINITION DOCUMENT

062 06 01 02 – Operation

SPACE SEGMENT – example NAVSTAR GPS

(04) Each satellite broadcasts ranging signals on two UHF frequencies

L1	1575,42	MHz
L2	1127,60	MHz

GPS can operate in two different modes:

- SPS (Standard Positioning Service): civilian users
- PPS (Precise Positioning Service): authorised users

(05) **SPS is** a positioning and timing service **provided on L1** frequency

(06) **PPS uses both** L1 and L2 frequencies. 2 frequencies → higher accuracy

062 06 01 02 – Operation

SPACE SEGMENT – example NAVSTAR GPS

BK (07) Satellites transmit a coded signal used for ranging, identification (<u>satellite individual PRN code</u>), timing and navigation

BK (08) The navigation message contains:

- satellite clock correction parameters
- Universal Time Coordinated (UTC) parameters
- an ionospheric model
- satellite health data

CE **BK** (09) Its ionospheric model is used to calculate the time delay of the signal travelling through the ionosphere

Whenever a GPS satellite is retired, its PRN code is assigned to future replacements

SATELLITE STATUS
EPU 0.05NM
HDOP 0.9
HFOM 23FT
VFOM 33FT
POSITION N 13°04.62' E077°35.62'
TIME 06:34:22UTC
ALTITUDE 3023FT
GROUND SPEED 0.0KT
TRACK ___°

GPS STATUS
ACTIVE GPS GPS1
GPS SOLUTION 3D NAV
SBAS ACTIVE

SBAS SELECTION
☑ EGNOS
☑ MSAS
☑ WAAS

GPS status page showing PRN-identified satellites

(source: http://theflyingengineer.com/)

The ionosphere acts as a refractive means (hence a delay is caused) for the GPS signal.

The C/A code is a pseudo random noise (PRN) code sequence. It repeats every millisecond and is unique to identify each satellite (PRN 01, PRN 02, PRN 03…)

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062 06 01 02 – Operation

SPACE SEGMENT – example NAVSTAR GPS

BK (10) Two codes are transmitted on the L1 frequency: C/A (Coarse Acquisition) and P (Precision)

Code	**Used by**	
C/A	SPS (civil)	PPS
P (precision)		PPS

CE **BK** (11) Satellites are equipped with atomic clocks, which allow the system to keep very accurate time reference

Atomic clocks on-board satellites are based on Cesium or Rubidium

An error of 1 µs (10^{-6} sec) in the user clock can produce a positioning error of up to 300m

062 06 01 02 – Operation

CONTROL SEGMENT

CE

BK

(12) The control segment comprises:

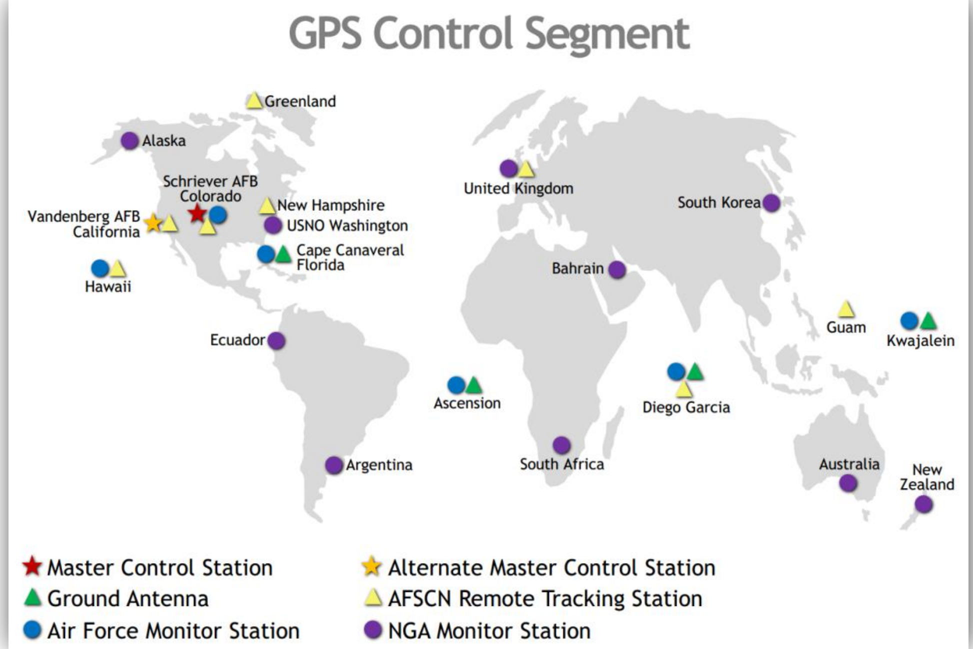
- A master control station (may have alternative master control station/s)
- Command and control ground antennas
- Monitoring stations

CE

BK

(13) The control segment provides:

- Monitoring the constellation status
- Correction of orbital parameters
- Navigation data uploading



Example: GPS Control Segment

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062 06 01 02 – Operation

USER SEGMENT

CE **BK** (14) GNSS supplies three-dimensional position fixes and speed data, plus a precise time reference

CE **BK** (15) A GPS receiver is able to determine the distance to a satellite by determining the difference between the time of transmission by satellite and the time of reception

BK (16) The initial distance calculated to the satellites is called “pseudo range” as it is biased by the lack of time synchronisation between GPS satellite and receiver clocks. In addition, the “pseudo range” is also biased by other effects such as ionosphere, troposphere and signal-noise

Pseudo range modelling:

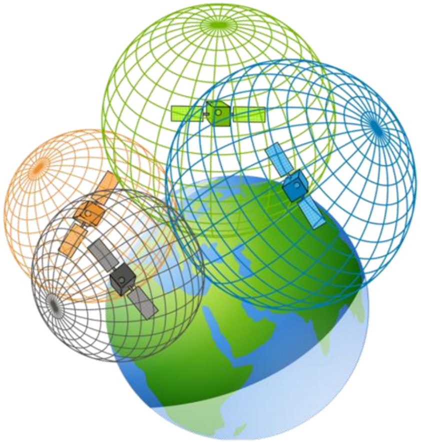
$$P\lambda = \rho + d\rho + c(dT–dt) + d_{tropo} + d_{iono} + M + e$$

ρ is the geometric range or geometric distance between the satellite and the receiver
$d\rho$ is the orbital error
dt is the receiver clock error
dT is the satellite clock error
d_{ion} is the iono delay
d_{trop} is the tropo delay
M multipath
e noise

062 06 01 02 – Operation

USER SEGMENT

CE **BK** (17) Each range defines a sphere with its centre at the satellite



CE **BK** (18) To resolve **4 unknown parameters** (X, Y, Z, ΔT) and calculate the position, we require the measurement of ranges to four different satellites.

Rationale ΔT (receiver clock offset): **the 3 spheres do not intersect in a single point**. Hence **ΔT** constitutes a new variable to be determined.

CE **BK** (19) The GPS receiver synchronises to the correct time base when receiving four satellites

BK (20) The receiver is able to calculate aircraft groundspeed using the SV Doppler frequency shift and/or the change in receiver position over time

062 06 01 02 – Operation

More info in these slides

NAVIGATION System with Timing And Ranging Global Positioning System (NAVSTAR GPS) Integrity

CE
BK

RAIM (Receiver Autonomous Integrity Monitoring) provides integrity over GPS-only navigation

CE
BK

(21) RAIM is a technique that ensures the integrity of the provided data by redundant measurements

CE
BK

(22) RAIM is achieved by consistency check among range measurements → when a sufficient number of satellites is tracked by the receiver, individual faulty pseudo ranges can be isolated

CE
BK

(23) Basic RAIM requires 5 satellites. A 6th satellite is required for isolating a faulty satellite from the navigation solution

When the GPS receiver is fed with barometric altitude, the number of satellites needed for the receiver to perform RAIM function may be reduced by one

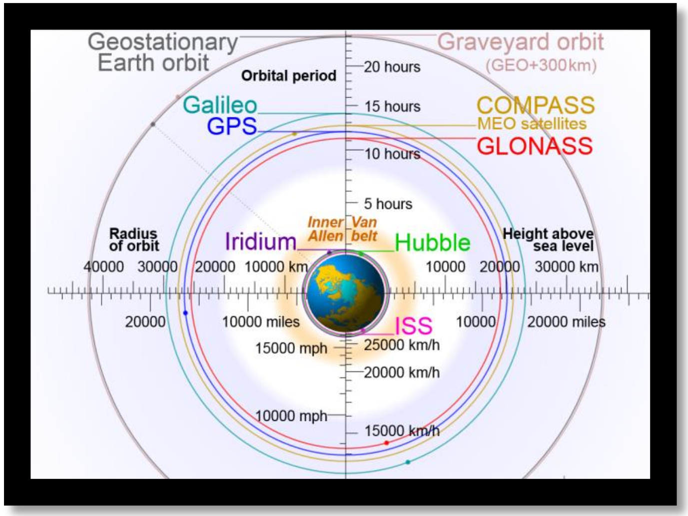
062 06 01 02 – Operation

More info in these slides

NAVIGATION System with Timing And Ranging Global Positioning System (NAVSTAR GPS) Integrity

(24) Agreements have been concluded between the appropriate agencies for the compatibility and **interoperability** by any approved user of NAVSTAR and GLONASS systems

BK (25) Even if…different GNSSs may use different data with respect to reference systems, orbital data, and navigation services.



Animation available in *https://upload.wikimedia.org/wikipedia/commons/b/b4/Comparison_satellite_navigation_orbits.svg*

062 06 01 03 – Errors and Factors affecting accuracy

(01) The most significant factors affecting accuracy of GNSS positioning are:

		GPS	GPS + SBAS
CE	- Ionospheric propagation delay (IPD)	2 m	0,3 m
	- Dilution of position (horizontal)	1,1 m	1,1 m
	- Satellite clock errors	1 m	0,5 m
	- Satellite orbital variations		
	- Multipath	0,2 m	0,2 m
	- Tropospheric propagation delay	0,25 m	0,25 m
	- Receiver noise	0,5 m	0,5 m

(02) A user equivalent range error (UERE) can be computed from all these factors

062 06 01 03 – Errors and Factors affecting accuracy

BK (03) (04) Ionospheric propagation delay (IPD)

- The IPD constitutes the most significant error, it can achieve several tens of meters
- It can be almost eliminated if using two frequencies → this is the main reason why GPS PPS is today more precise than SPS
- The IPD can be reduced by modelling, using a model of the ionosphere

In GPS SPS receivers, IPD is currently corrected by using a ionospheric model contained in the navigation message. However the error is only reduced by 50%

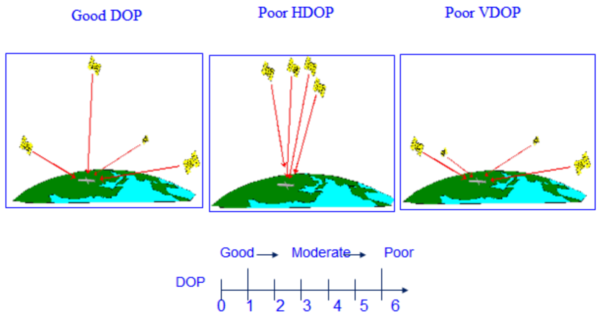
062 06 01 03 – Errors and Factors affecting accuracy

- Dilution of Precision

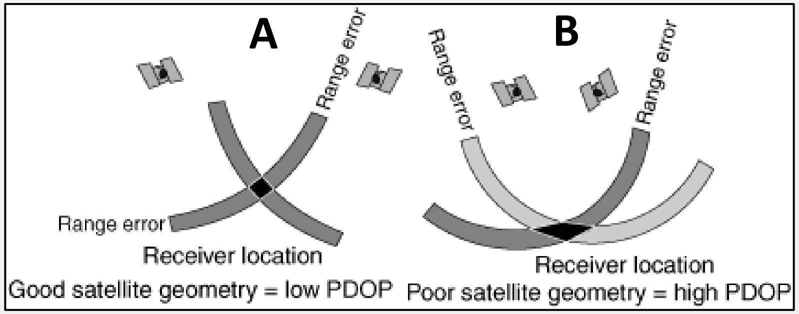
(05) Arises from the geometry and number of satellites in view. It is called the **Geometric Dilution of Precision (GDOP)**

(06) The UERE, in combination with the geometric dilution of precision (GDOP), allows for an estimation of position accuracy

DOP is an indicator of the geometrical distribution of the satellites *used to compute the navigation solution*



A bad geometry (high DOP) contributes to a bigger error in the estimated position.



In **A** the measurement has some error bounds, and the true location will lie anywhere in the black area. In **B** the measurement error is the same, but the error on the position has grown considerably due to the arrangement of the satellites.

Source: adaptation from Wikipedia and Academic

062 06 01 03 – Errors and Factors affecting accuracy

BK (07) The errors in the satellite orbits are due to:

- Solar winds
- Gravitation effects of the sun and the moon (and planets)

062 06 02 00 – Ground, Satellite and Airborne based augmentation systems

GBAS

SBAS

ABAS

Source: Honeywell

Source: SES

Source: Cirrus

062 06 02 01 – Ground-based augmentation systems

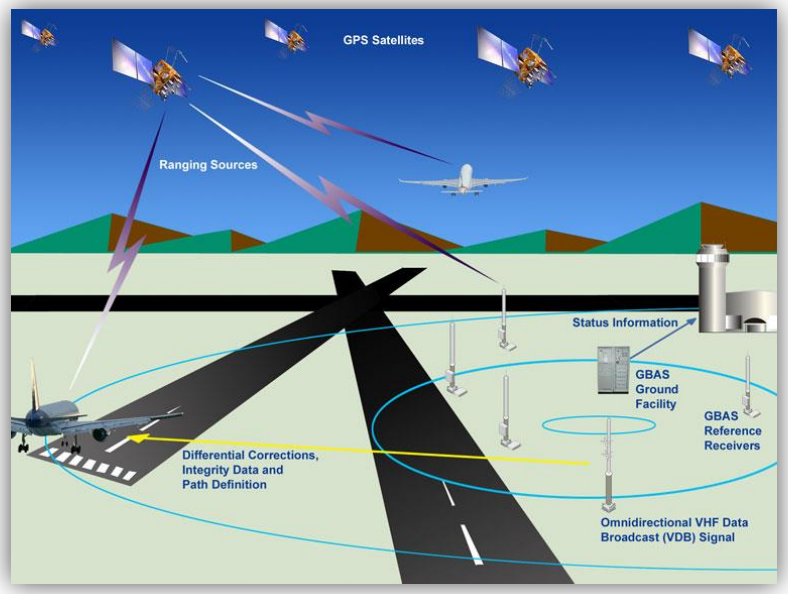
GBAS SBAS ABAS

GROUND BASED AUGMENTATION SYSTEMS

CE (01) Its main principle is to measure on ground the signal errors transmitted by GNSS satellites and relay the measured errors to the user for correction

CE **BK** (02) The ICAO GBAS standard is based on this technique through the use of a data link in the VHF band of ILS-VOR systems (108-118 MHz)

(05) One ground station can support all the aircraft subsystems within its coverage providing the aircraft with approach data, corrections and integrity information for GNSS satellites in view via a VHF data broadcast (VDB)



Source: FAA

CE ***(03)** The coverage of the GBAS station is of about 20 NM / 30 km*

062 06 02 01 – Ground-based augmentation systems

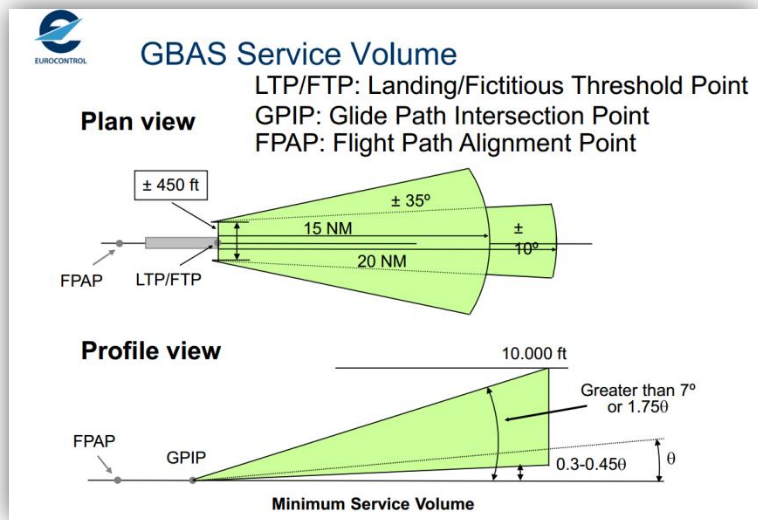
GROUND BASED AUGMENTATION SYSTEMS

CE (04) GBAS provides (1) information for guidance in the terminal area, and (2) for three-dimensional guidance in the final approach segment (FAS) by transmitting the FAS data block

BK (06) The minimum software designed coverage area is (aka **GBAS Service Volume)** is 10° on either side of the final approach path to a distance between 15 and 20 NM, and 35° on either side of the final approach path up to a distance of 15 NM

(07) Outside this area, FAS data (2) is not used

BK (08) GBAS based on GPS is sometimes called Local Area Augmentation System (LAAS)

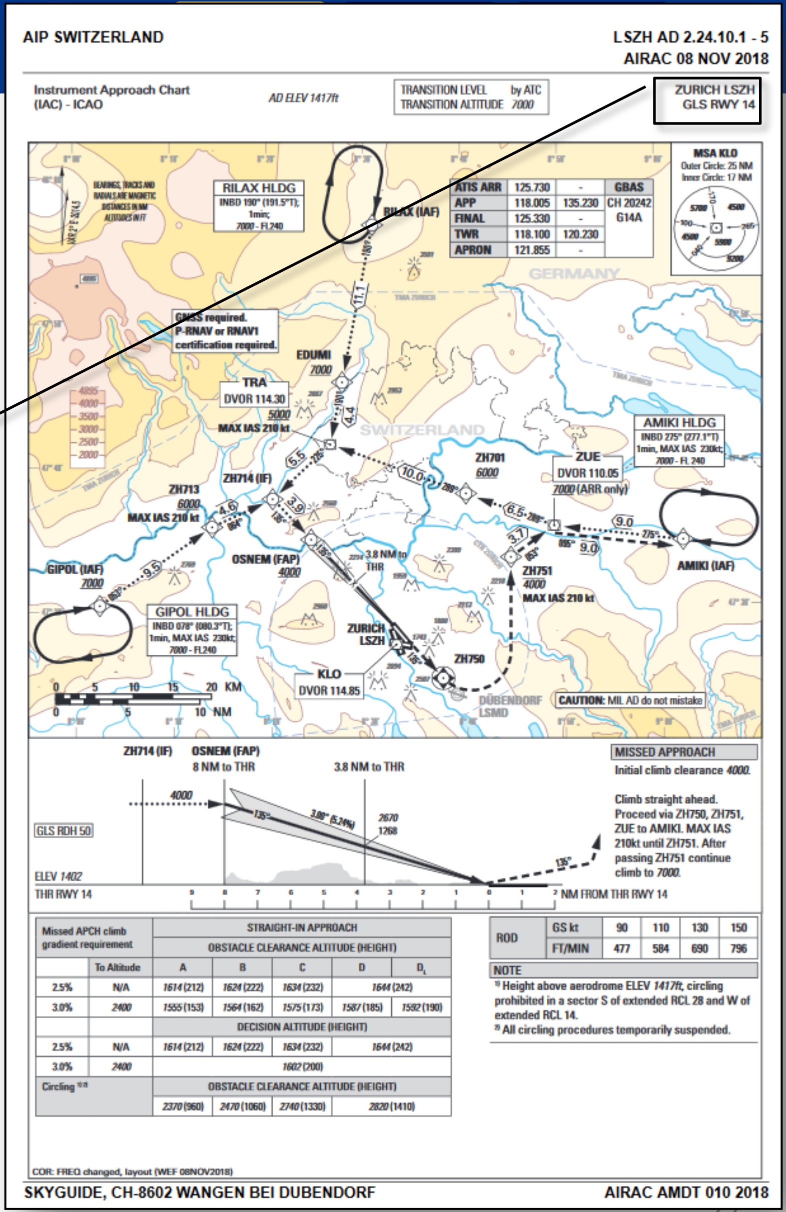


062 06 02 01 – Ground-based augmentation systems

GROUND BASED AUGMENTATION SYSTEMS

(09) A GBAS-based approach is called GLS approach (GLS-GNSS landing system)

ZURICH LSZH
GLS RWY 14



AIP SWITZERLAND

LSZH AD 2.24.10.1 - 5
AIRAC 08 NOV 2018

Instrument Approach Chart
(IAC) - ICAO

AD ELEV 1417ft

TRANSITION LEVEL by ATC
TRANSITION ALTITUDE 7000

ZURICH LSZH
GLS RWY 14

ATIS ARR	125.730	-	GBAS
APP	118.005	135.230	CH 20242 G14A
FINAL	125.330	-	
TWR	118.100	120.230	
APRON	121.855	-	

MSA KLO
Outer Circle: 25 NM
Inner Circle: 17 NM

RILAX HLDG
INBD 190° (191.5°T);
1min;
7000 - FL240

GNSS required.
P-RNAV or RNAV1
certification required.

AMIKI HLDG
INBD 275° (277.1°T)
1min, MAX IAS 230kt;
7000 - FL 240

GIPOL HLDG
INBD 078° (080.3°T);
1min, MAX IAS 230kt;
7000 - FL240

CAUTION: MIL AD do not mistake

MISSED APPROACH
Initial climb clearance *4000*.

Climb straight ahead. Proceed via ZH750, ZH751, ZUE to AMIKI. MAX IAS 210kt until ZH751. After passing ZH751 continue climb to *7000*.

Missed APCH climb gradient requirement		STRAIGHT-IN APPROACH				
		OBSTACLE CLEARANCE ALTITUDE (HEIGHT)				
	To Altitude	A	B	C	D	D$_L$
2.5%	N/A	*1614* (212)	*1624* (222)	*1634* (232)	*1644* (242)	
3.0%	*2400*	*1555* (153)	*1564* (162)	*1575* (173)	*1587* (185)	*1592* (190)
		DECISION ALTITUDE (HEIGHT)				
2.5%	N/A	*1614* (212)	*1624* (222)	*1634* (232)	*1644* (242)	
3.0%	*2400*	*1602* (200)				
Circling [1] [2]		OBSTACLE CLEARANCE ALTITUDE (HEIGHT)				
		2370 (960)	*2470* (1060)	*2740* (1330)	*2820* (1410)	

ROD	GS kt	90	110	130	150
	FT/MIN	477	584	690	796

NOTE
[1] Height above aerodrome ELEV *1417ft*, circling prohibited in a sector S of extended RCL 28 and W of extended RCL 14.
[2] All circling procedures temporarily suspended.

COR: FREQ changed, layout (WEF 08NOV2018)

SKYGUIDE, CH-8602 WANGEN BEI DUBENDORF

AIRAC AMDT 010 2018

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Global Navigation
Satellite Systems
Agency

062 06 02 02 – Satellite-based augmentation systems

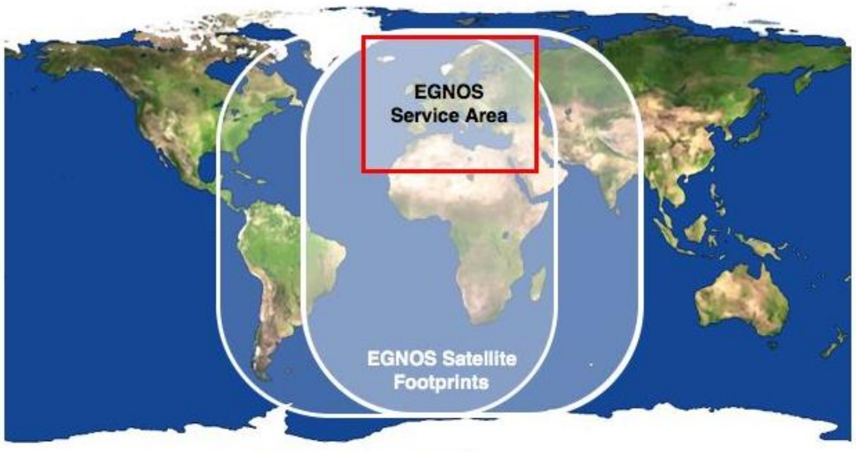
GBAS SBAS ABAS

SBAS BASED AUGMENTATION SYSTEMS

CE BK (01) Its main principle is to measure on the ground the signal errors transmitted by GNSS satellites and transmit differential corrections and integrity messages through geostationary satellites

CE BK (02) The frequency band of the data link is identical to that of the GPS signals

Note the difference in the below image between the GEOs coverage area (footprints) and the Service Area



EGNOS GEO footprints

CE BK (03) The use of geostationary satellites enables messages to be broadcast over very wide areas

CE BK (04) The pseudo-range measurements to these geostationary satellites can also be made, as if they were GPS satellites

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062 06 02 02 – Satellite-based augmentation systems

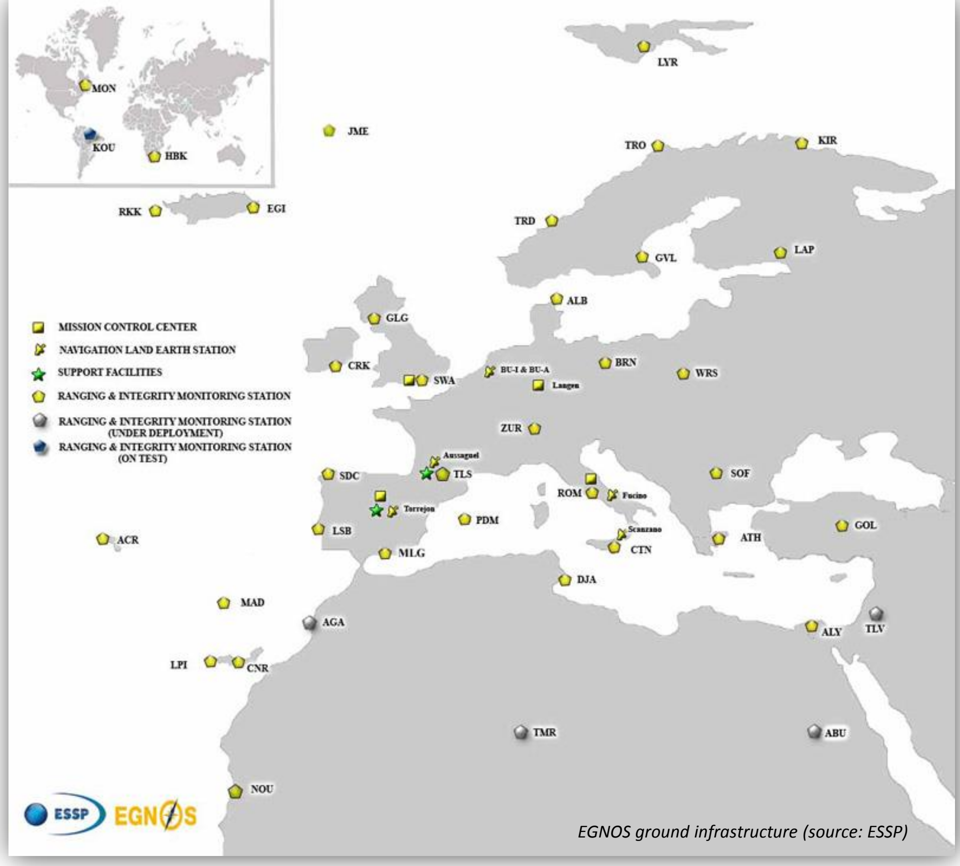
GBAS | **SBAS** | ABAS

SBAS BASED AUGMENTATION SYSTEMS - Elements

CE
BK

(05) SBAS consists of 2 elements:

- The ground infrastructure (network of monitoring and processing stations)
- The SBAS satellites



EGNOS ground infrastructure (source: ESSP)

062 06 02 02 – Satellite-based augmentation systems

GBAS SBAS ABAS

SBAS BASED AUGMENTATION SYSTEMS

CE (06) SBAS allows the implementation of three dimensional Type A and Type B approaches

- 3D Type A: DH ≥ 250ft
- 3D Type B: DH ≥ 200ft

CE BK (07) SBAS examples:

- European Geostationary Navigation Overlay Service (EGNOS) in western Europe and the Mediterranean
- Wide Area Augmentation System (WAAS) in the USA
- Multi-functional Transport Satellite (MTSAT)-based augmentation system (MSAS) in Japan
- GPS and geostationary earth orbit augmented navigation (GAGAN) in India

(Others under development: SDCM in Russia, SNAS is China)

062 06 02 02 – Satellite-based augmentation systems

GBAS SBAS ABAS

SBAS BASED AUGMENTATION SYSTEMS

CE BK (08) SBAS is designed to significantly improve accuracy and integrity

CE (09) The integrity and safety are improved by alerting SBAS users within the following Time To Alert (TTA) if a GPS malfunction occurs

- 3D Type A:	10 seconds (in Europe, EGNOS reduces this figure to 6 seconds)
- 3D Type B:	6 seconds

062 06 02 02 – Satellite-based augmentation systems

GBAS SBAS ABAS

EGNOS

EGNOS, it's there. Use it.

- The European Geostationary Navigation Overlay Service
- EGNOS uses 3 geostationary satellites and a network of ground stations to receive, analyse and augment, and then re-transmit GPS and eventually Galileo signals
- The system is designed to improve accuracy to 1-2 m horizontally and 3-5 m vertically
- Integrity and safety are improved by alerting users within 6 seconds if a GPS malfunction occurs (up to 3 hrs GPS alone)

You can find more information about the status of the EGNOS Space Segment in
http://www.essp-sas.eu/download/service_notices/essp_com_11851_01_00_service_notice_11_prn124_decommisioning.pdf

062 06 02 02 – Satellite-based augmentation systems

GBAS SBAS ABAS

EGNOS - benefits

EGNOS, it's there. Use it.

- More landings under severe atmospheric conditions
- More landings at less well-equipped airports
- Increased capacity, benefiting both airport and airline operators
- Curved approaches and more efficient routes → fuel and noise savings
- Possibility to phase-out some expensive ground based navaids infrastructure and to free valuable radio spectrum that can be exploited for new/other services

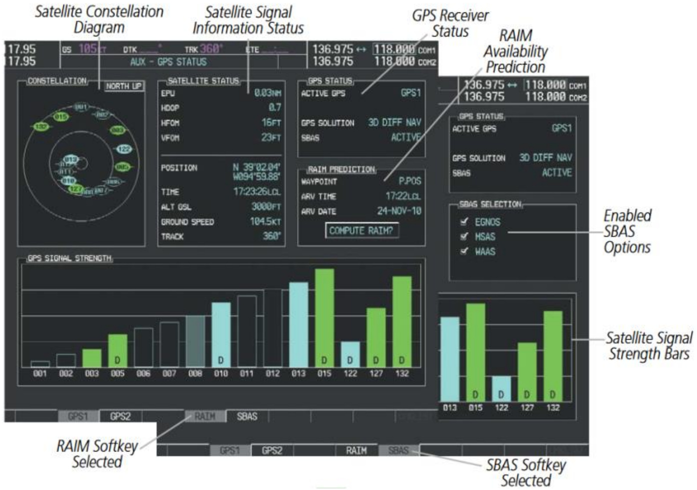
062 06 02 04 –Airborne-based augmentation systems

GBAS SBAS **ABAS**

AIRBORNE BASED AUGMENTATION SYSTEMS

CE (01) Its main principle is to use redundant elements within the GPS constellation (e.g. multiplicity of distance measurements to various satellites) or the combination of GNSS measurements with those of other navigation sensors (such as inertial systems), to develop integrity control

Unlike GBAS and SBAS, ABAS does not provide corrections to improve positioning accuracy



GPS Status page for a Garmin G1000 (source: Garmin)

062 06 02 04 –Airborne-based augmentation systems

GBAS SBAS ABAS

AIRBORNE BASED AUGMENTATION SYSTEMS

CE (02) The type of ABAS using only GNSS information is RAIM (Receiver Autonomous Integrity Monitoring)

CE (03) The type of ABAS using addition information from on-board sensors is named AAIM (Aircraft Autonomous Integrity Monitoring)

CE (04) Typical sensors used in AAIM are barometric altimeter, clock and inertial navigation system (IRS)

- Barometric altimetry sources are used sometimes to improve the TTFF (Time to First Fix), which refers to the time required to acquire satellite signals and navigation data and calculate a position solution

062 06 02 04 –Airborne-based augmentation systems

GBAS SBAS **ABAS**

CE (05) The Receiver Autonomous Integrity Monitoring (RAIM) is a **technique that ensures the integrity of the provided data by redundant measurements**

- *The GPS ground stations monitor GPS satellites and detect faults*
- *It can take too much time to detect a fault and update the navigation messages sent to the users to declare a particular satellite SIS erroneous*

CE (06) To solve this, GPS receivers have an *autonomous* way of assuring the *integrity* of GPS pseudo-ranges: the RAIM algorithm, which is ***achieved by consistency checks among range measurements***

- *GPS receivers require a minimum set of 4 satellites to compute a 3D position*

CE ***(07) With additional satellites, the "RAIM algorithm" comes into play***

- ***A 5th satellite provides Fault Detection (FD)*** *capability: the receiver recognises a faulty satellite, but is not able to identify which one in particular (aka* ***basic RAIM****)*
- ***A 6th satellite provides Fault Detection and Exclusion (FDE)*** *capability: the receiver is able to isolate the faulty satellite*

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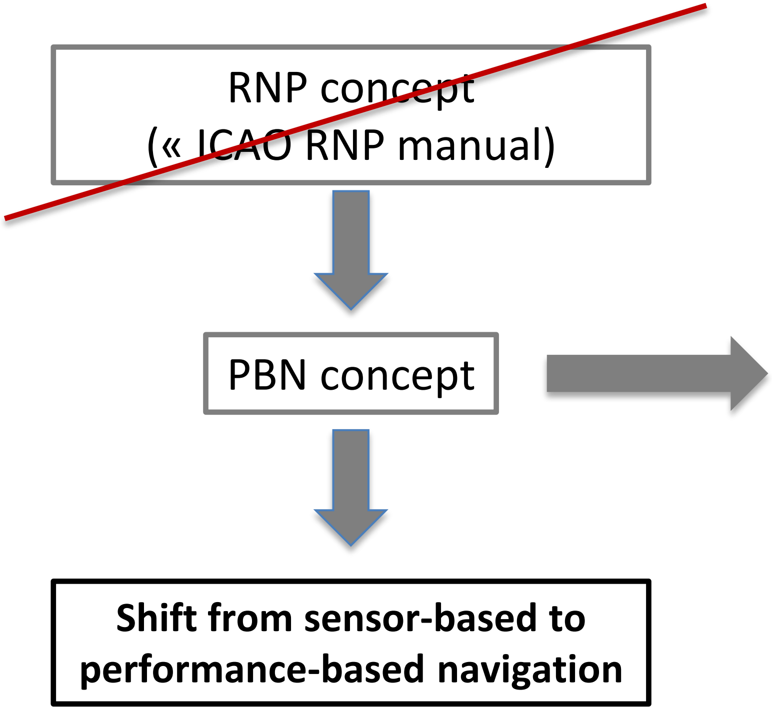
062 07 00 00

PERFORMANCE-BASED NAVIGATION

062 07 01 00 – PBN concept

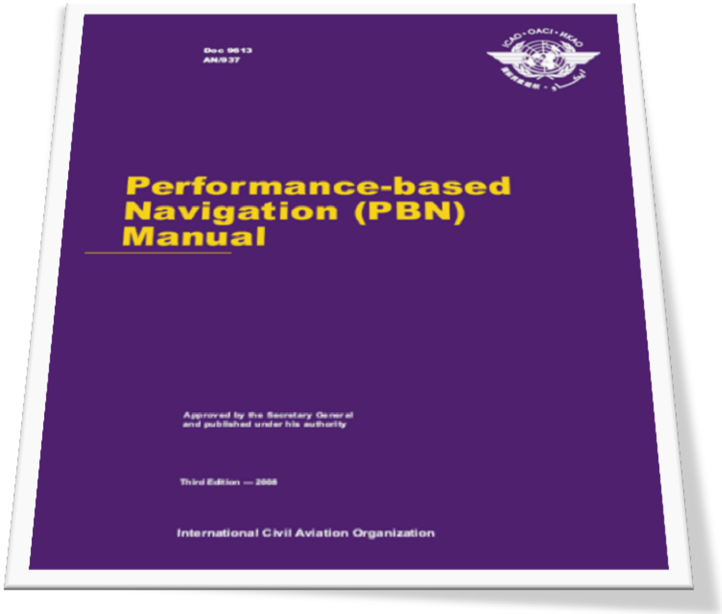
- **Performance-based navigation**: area navigation (RNAV) based on performance requirements for aircraft operating along an ATS route, on an instrument approach procedure or in a designated airspace



~~RNP concept~~
~~(« ICAO RNP manual)~~

PBN concept

Shift from sensor-based to performance-based navigation



Doc 9613
AN/937

Performance-based Navigation (PBN) Manual

Approved by the Secretary General and published under his authority

Third Edition — 2008

International Civil Aviation Organization

ICAO Doc 9613

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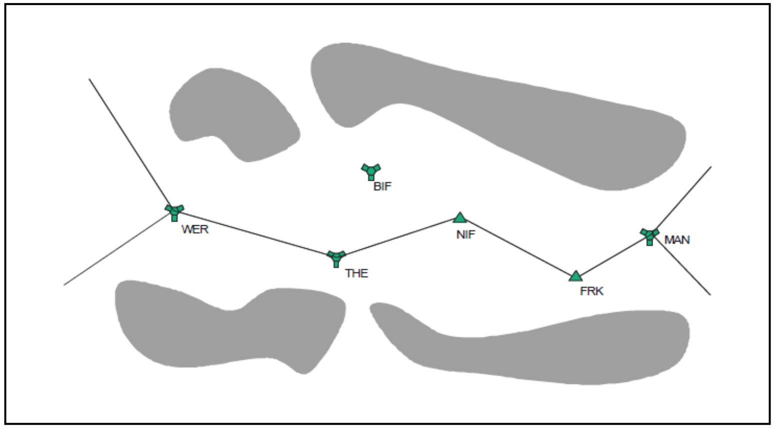
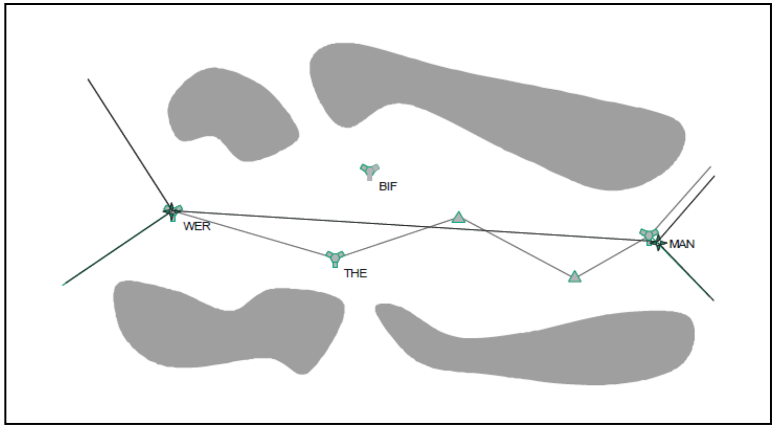
062 07 01 00 – PBN concept

Conventional navigation



- Aircrafts navigate based on direct signals from ground-based radio NAVAIDs
- Navigation relies on aircraft crossing radio beacons and tracking to and from them directly
- Routes are dependent on the location of the navigation beacons, resulting in longer routes

Area Navigation



- Within the coverage of the available navaids → AREA
- Aircrafts compute their latitude-longitude position
- Navigation relies on aircraft crossing fixes defined by name, latitude and longitude
- Routes are no or less dependent on the location of NAVAIDs, resulting in much more flexible route designs

Images from ICAO

062 07 01 01 – PBN principles

CE (01) The PBN concept specifies that aircraft RNAV and RNP system performance requirements be defined in terms of:

- **Accuracy**
- **Integrity**
- **Availability**
- **Continuity**

- Performance requirements are identified in navigation specifications, which also identify the choice of navigation sensors and equipment that may be used to meet the performance requirements

Difference between RNAV and RNP is explained later

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062 07 01 01 – PBN principles

BK (02) RNAV and RNP systems are necessary to optimise the utilisation of airspace, which is a limited resource

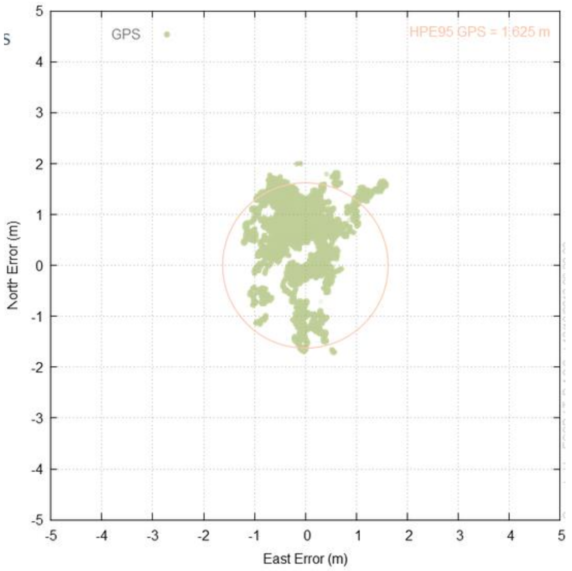
(03) Both the flight crew and air traffic controllers need to be aware of the on-board RNAV or RNP system capabilities in order to determine whether the performance of the RNAV or RNP system is appropriate for the specific airspace requirements

- Information for ATC is contained in the flight plan

062 07 01 01 – PBN principles

ACCURACY

(04) Definition “*conformance of the true position and the required position*”



Example of GPS static measurements

062 07 01 01 – PBN principles

CE **AVAILABILITY**

(09) Definition "percentage of time (annually) that the services of the system are usable by the navigator"

- *(Alt: proportion of time during which reliable navigation information is presented to the crew, autopilot, or other system managing the flight of the aircraft)*

The availability of a system (or service) establishes the percentage of time during when the operation (for example a final approach) can be started.

CE **CONTINUITY**

(05) Definition "*capability of the system to perform its function without unscheduled interruptions during the intended operation*"

- (*Alt from ICAO SARPS: It relates to the capability of the navigation system to provide a navigation output with the specified accuracy and integrity during the approach, assuming that it was available at the start of the operation*)

The continuity of the system guarantees that once an operation (for example a final approach) is initiated, it will not be interrupted.

062 07 01 01 – PBN principles

INTEGRITY

CE (06) Definition *“a measure of the trust that can be placed in the correctness of the information supplied”*

- The system must have the ability to provide timely and valid alerts to the user

Loss of Integrity Alert for a Garmin G1000 (source: Garmin)

062 07 01 01 – PBN principles

INTEGRITY (extra info not included in official LOs)

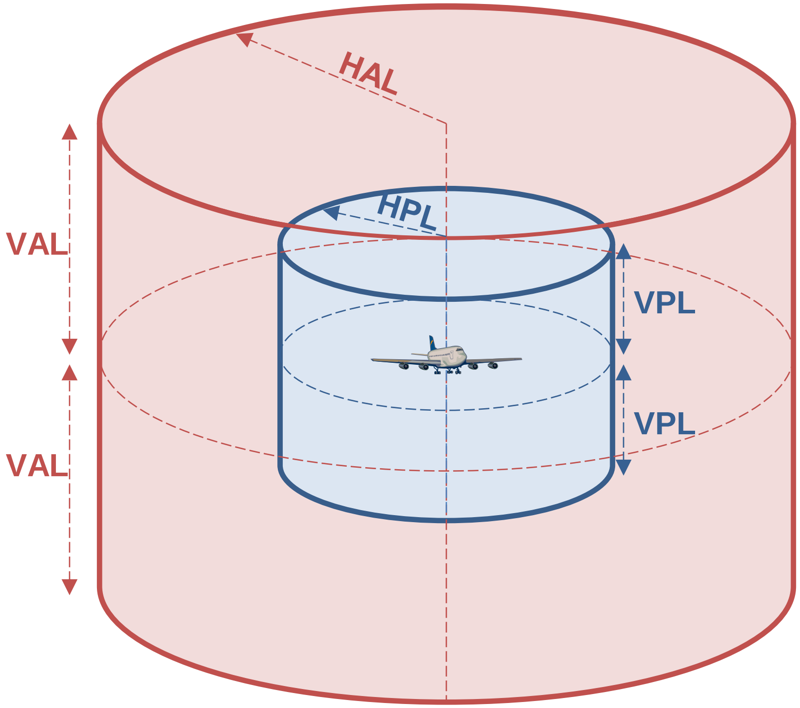
- The parameters defining the integrity are:
  - **Alert Limit (AL)**: the error tolerance not to be exceeded without issuing an alert
    - Means the region (horizontal and vertical) which is required to contain the indicated position with the required probability for a particular navigation mode
    - Required ALs depend on the type of operation
  - **Time to Alert**: the maximum allowable time elapsed from the onset of the navigation system being out of tolerance until the equipment enunciates the alert
  - **Integrity Risk**: probability that, at any moment, the position error exceeds the Alert Limit
  - **Protection Level**: statistical bound error computed so as to guarantee that the probability of the absolute position error exceeding said number is smaller than or equal to the target integrity risk
    - Means the region (horizontal and vertical) assured to contain the indicated position. It defines the region where the missed alert requirement can be met
    - PLs are computed by the on board receiver

062 07 01 01 – PBN principles

INTEGRITY cont. (extra info not included in official LOs)

if during an operation the PLs exceed the required ALs, the operation cannot continue

- VPL only used for operations with vertical guidance (e.g. LPV)



xAL: fixed value during operation

xPL: value calculated by on-board receiver (varies depending on aircraft and satellite geometry and SBAS corrections)

The integrity of the system (or service) establishes to which degree the navigation source can be trusted during the flight.

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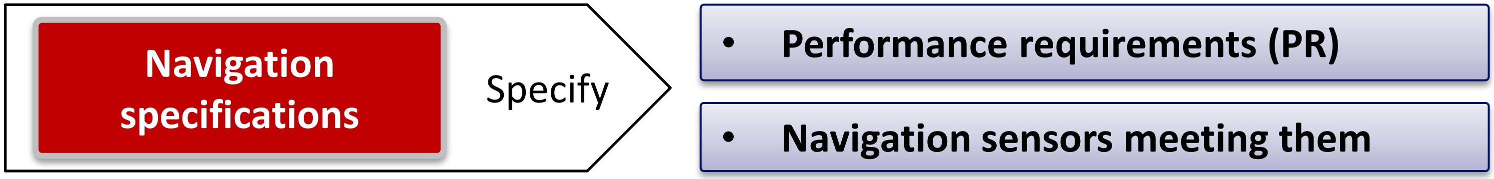
062 07 01 01 – PBN principles

CE (07) Unlike conventional navigation, PBN is not sensor-specific

- The **PBN concept** represents a shift from sensor-based to PBN



Navigation specifications

Specify

- **Performance requirements (PR)**
- **Navigation sensors meeting them**

A certain set of PRs may be met by more than one sensor.

- Advantages of PBN over sensor-specific methods of developing airspace:
  - reduces the need to maintain sensor-specific routes and procedures, and their associated costs;
  - avoids the need for developing sensor-specific operations with each new evolution of navigation systems, which would be cost-prohibitive;
  - allows for more efficient use of airspace (route placement, fuel efficiency and noise abatement);
  - clarifies how RNAV and RNP systems are used; and
  - facilitates the operational approval process for operators by providing a limited set of navigation specifications intended for global use.

062 07 01 01 – PBN principles

CE (08) **Computed vs raw data**

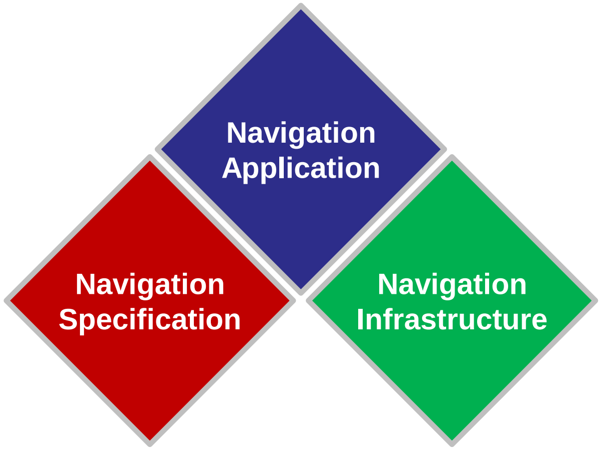
Conventional navigation

- The *navigation performance* data used to determine the separation minima or route spacing depend on the accuracy of the **raw data** from specific NAVAIDs such as VOR, DME or NDB

PBN

- Requires an RNAV or RNP system that integrates raw navigation data to provide a positioning and navigation solution. In determining separation minima and route spacing in a PBN context, this integrated navigation performance “output” **(computed data)** is used
- Area navigation system will confirm the validity of the individual sensor data and, in most systems, will also confirm the consistency of the **computed data** before they are used.

062 07 01 02 – PBN components



Adapted from Eurocontrol

(01) **PBN is composed of 3 constituents**

- **Navigation Specification**: set of aircraft and aircrew requirements needed to support a navigation application within a defined airspace concept
- **Navigation Infrastructure**: ground based NAVAIDS or space based NAVAIDS
- **Navigation Application**: application of a navigation specification and the supporting NAVAID infrastructure, to routes, procedures, and/or defined airspace volume, in accordance with the intended airspace concept

062 07 01 02 – PBN components

EXAMPLE – RNAV 1

Navigation Specification

- **RNAV 1** refers to an RNAV **navigation specification** which includes a requirement for 1 NM navigation accuracy (among other requirements)

Navigation Infrastructure

- In terms of **navigation infrastructure**, the following systems enable RNAV 1: GNSS, DME/DME and DME/DME/IRU

Navigation Application

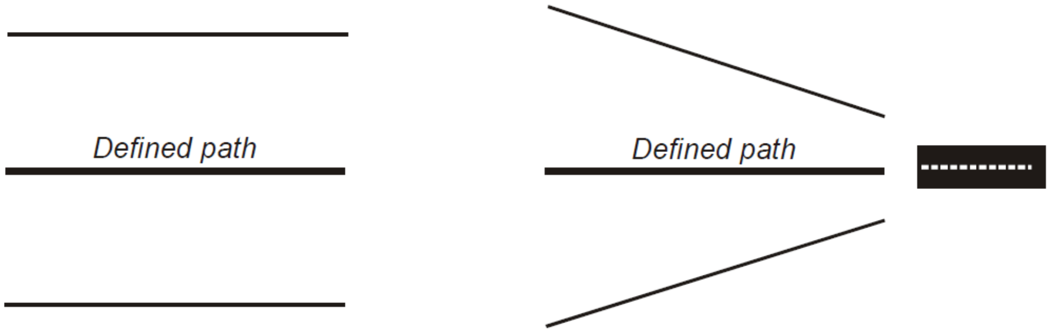
- RNAV 1 can support en-route and terminal **navigation applications**, like SIDs or STARs

State A's AIP could stipulate GNSS as a requirement for its RNAV 1 specification because State A only has GNSS available in its NAVAID infrastructure.
State B's AIP could require DME/DME/IRU for its RNAV 1 specification (policy decision not to allow GNSS).

062 07 01 03 – PBN scope

(01) For Oceanic/remote, en-route and terminal operations, PBN is limited to operations with linear lateral performance requirements and time constraints

(02) For Approach operations, PBN accommodates both linear and angular laterally guided operations

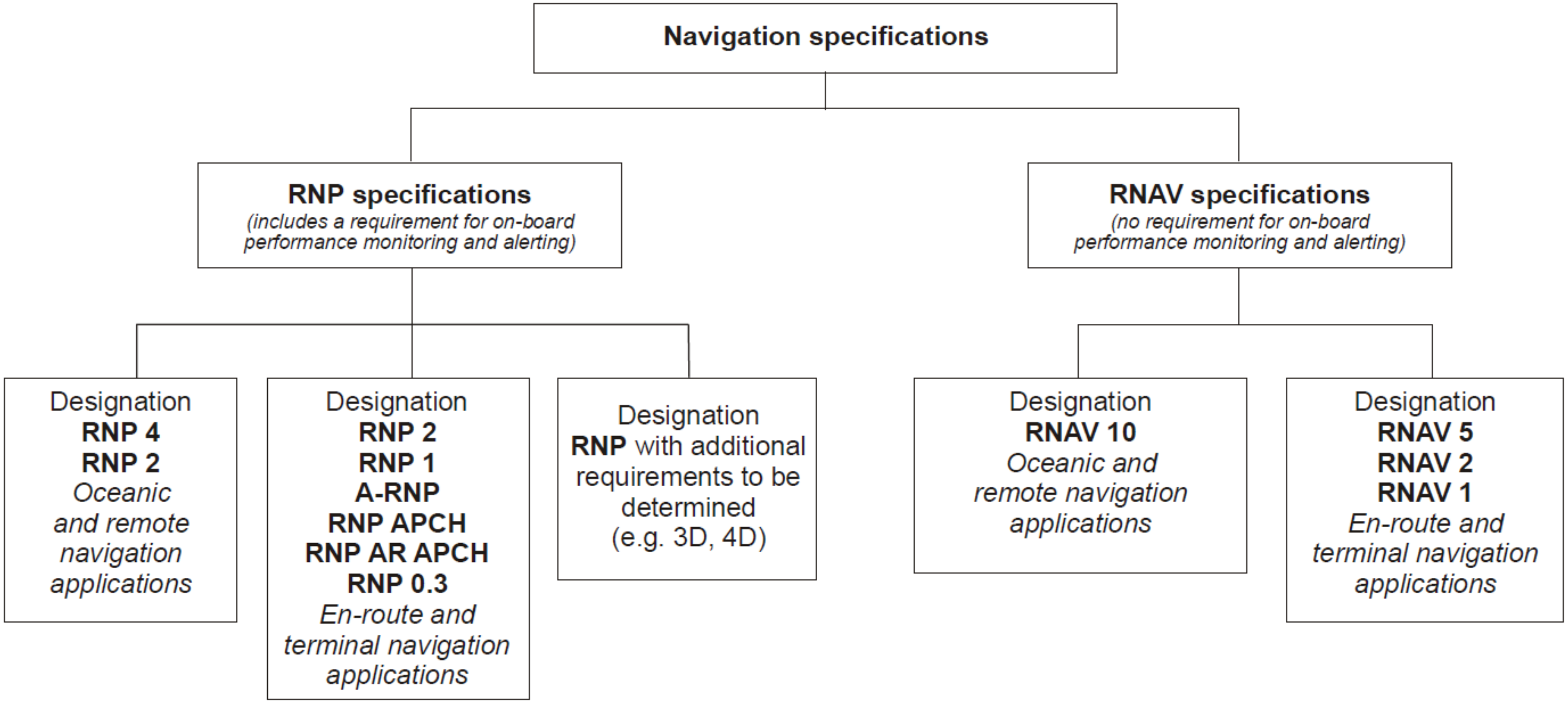


a) Linear lateral performance requirements using an RNP system, e.g. RNP and RNAV specs

b) Angular lateral performance requirements using an RNP system, e.g. RNP APCH to LPV minima

Image from ICAO

062 07 02 00 – Navigation specifications



Navigation specifications

RNP specifications
(includes a requirement for on-board performance monitoring and alerting)

RNAV specifications
(no requirement for on-board performance monitoring and alerting)

Designation
RNP 4
RNP 2
Oceanic and remote navigation applications

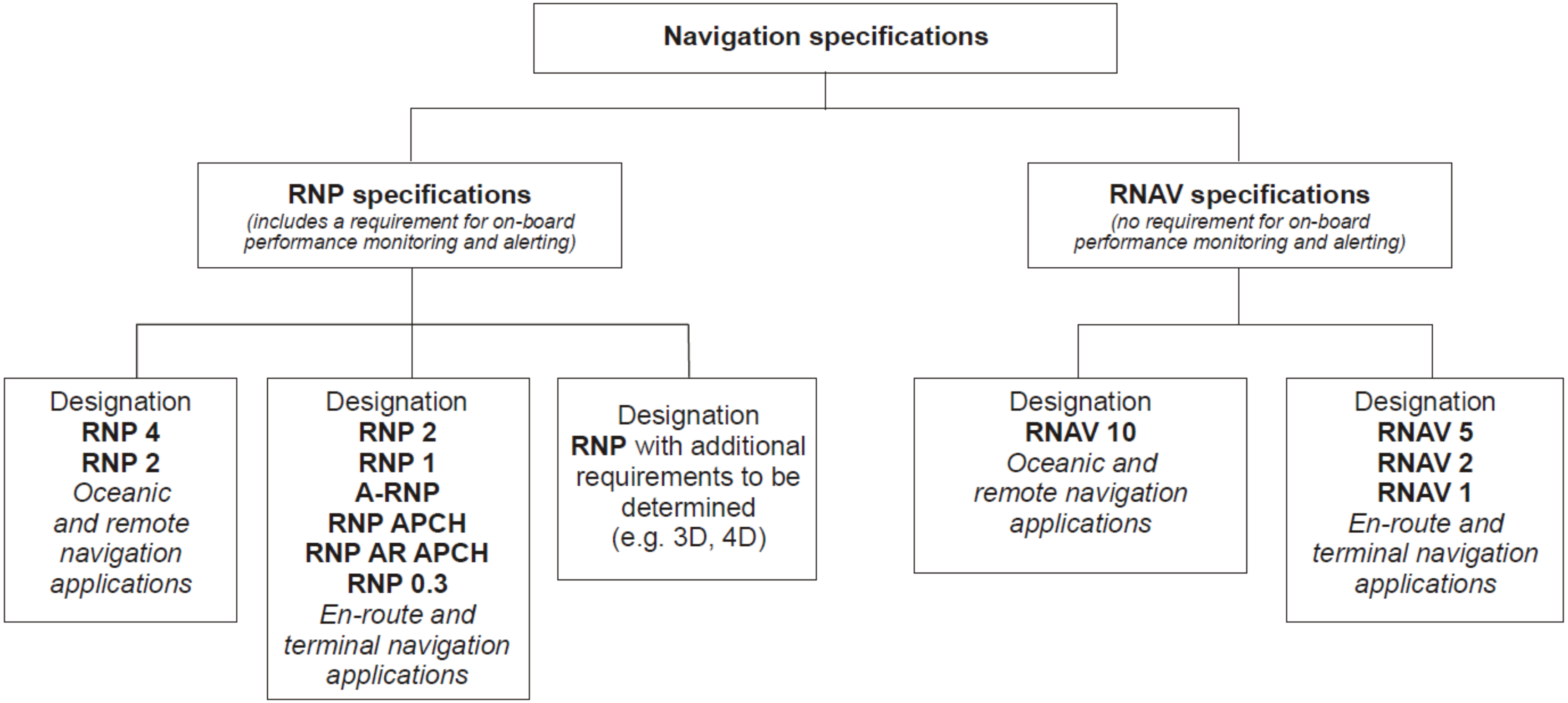
Designation
RNP 2
RNP 1
A-RNP
RNP APCH
RNP AR APCH
RNP 0.3
En-route and terminal navigation applications

Designation
RNP with additional requirements to be determined
(e.g. 3D, 4D)

Designation
RNAV 10
Oceanic and remote navigation applications

Designation
RNAV 5
RNAV 2
RNAV 1
En-route and terminal navigation applications

062 07 02 01 – RNAV and RNP



Navigation specifications

RNP specifications
(includes a requirement for on-board performance monitoring and alerting)

Designation
RNP 4
RNP 2
Oceanic and remote navigation applications

Designation
RNP 2
RNP 1
A-RNP
RNP APCH
RNP AR APCH
RNP 0.3
En-route and terminal navigation applications

Designation
RNP with additional requirements to be determined
(e.g. 3D, 4D)

RNAV specifications
(no requirement for on-board performance monitoring and alerting)

Designation
RNAV 10
Oceanic and remote navigation applications

Designation
RNAV 5
RNAV 2
RNAV 1
En-route and terminal navigation applications

(01)

CE

RNAV and RNP systems are fundamentally similar. The key difference between them is the ***requirement for on-board performance monitoring and alerting****.*

A navigation specification that includes a requirement for on-board navigation performance monitoring and alerting is referred to as an RNP specification.

062 07 02 02 – Navigation functional requirements

BK (01) RNAV and RNP specifications include requirements for certain navigation functionalities. At the basic level, these functional requirements may include:

a) continuous indication of **aircraft position relative to track** to be displayed to the pilot flying on a navigation display situated in his primary field of view;

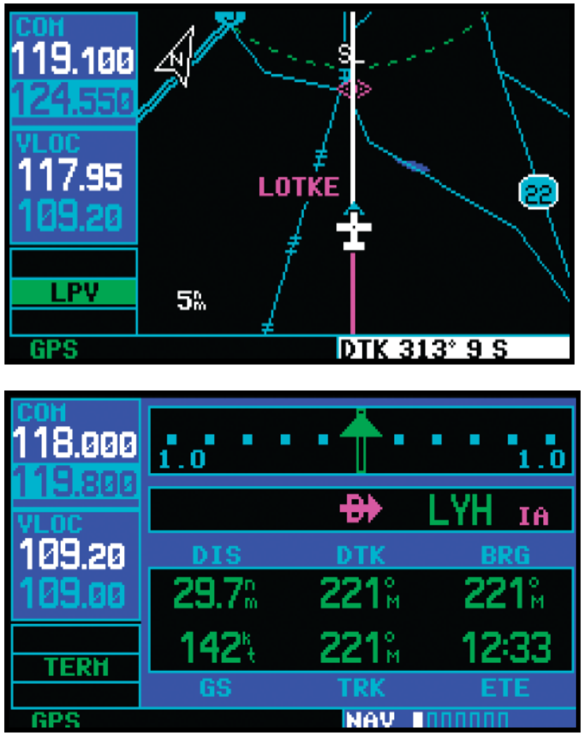
b) display of **distance and bearing to the active** (To) waypoint;

c) display of **ground speed or time to the active** (To) waypoint;

d) navigation **data storage function**; and

e) appropriate **failure indication** of the RNAV or RNP system, including the sensors.

Example: Garmin GNS 430W



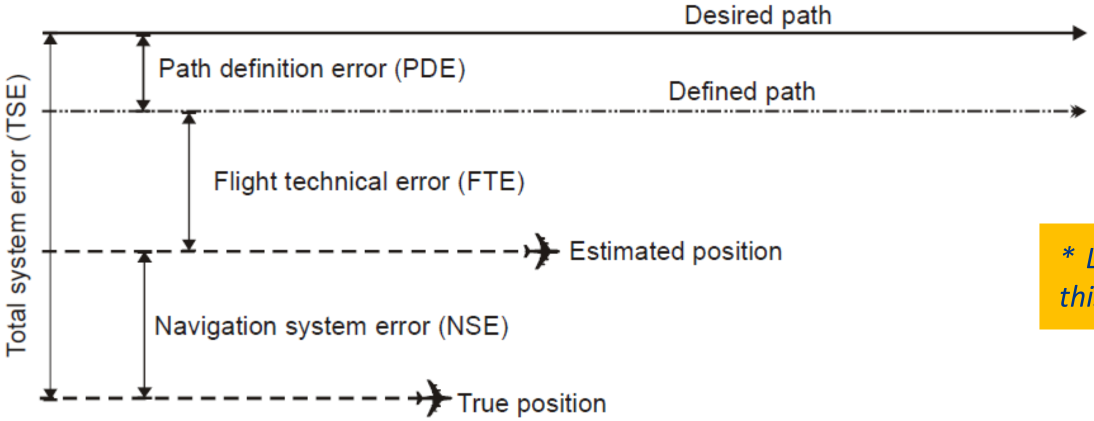
Source: Garmin

062 07 02 03 – Designation of RNP and RNAV specifications

RNAV **X**
RNP **X**

(01) The expression "X" means a lateral navigation (LNAV) accuracy* in Nautical Miles (NM), expected to be achieved 95% of the flight time by the population of aircraft operating within the airspace, route or procedure

- Navigation systems are specified in terms of NSE, and therefore hypotheses on the FTE and PDE contributions to the TSE are made to qualify a system for a given navigation specification



** Lateral navigation accuracy referring in this context to Total System Error (TSE)*

062 07 02 03 – Designation of RNP and RNAV specifications

CE (02) Because specific performance requirements are defined for each navigation specification, an aircraft approved for a particular navigation specification is not automatically approved for any other navigation specification, even if the later has a less stringent accuracy requirement

- In other words: an aircraft approved for an RNP or RNAV specification having stringent accuracy requirements (e.g. RNP 0.3 specification) is not automatically approved for a navigation specification having a less stringent accuracy requirement (e.g. RNP 4).

RNAV Specifications	
Oceanic/Remote	RNAV 10
En-route/ Terminal/Approach	RNAV 5, RNAV 2, RNAV 1

RNP* Specifications	
Oceanic/Remote	RNP 4
En-route/ Terminal/Approach	Basic RNP 1, RNP APCH, RNP (AR) APCH

** Includes on-board navigation performance monitoring and alerting*

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062 07 02 03 – Designation of RNP and RNAV specifications

RNAV 10

(03) Oceanic / remote phases of flight

- Without on-board performance monitoring and alerting function, even when operationally approved as “RNP 10”
- Lateral TSE must be within ±10 NM for at least 95 per cent of the total flight time
- 50NM lateral and 50NM longitudinal separation
- Based on INS, IRS FMS or GNSS

RNP 4

(03) Oceanic / remote phases of flight

- With on-board performance monitoring and alerting function (usually RAIM)
- Lateral TSE must be within ±4 NM for at least 95 per cent of the total flight time
- 30 NM lateral and 30 NM longitudinal separation
- Primarily based on GNSS

062 07 02 03 – Designation of RNP and RNAV specifications

CE

RNAV 5*

(04) En-route and arrival** phases of flight

- Without on-board performance monitoring and alerting function
- Lateral TSE must be within ±5 NM for at least 95 per cent of the total flight time
- Route spacing may vary among regional implementations
- Based on VOR/DME, DME/DME, INR, IRS or GNSS

** Almost equivalent to Basic RNAV (B-RNAV) within ECAC*
***may be used for the initial part of a STAR outside 30 NM and above MSA.*

062 07 02 03 – Designation of RNP and RNAV specifications

(05) RNAV 2 and RNP 2 also used as navigation specifications

RNAV 2

(07) <u>En-route continental, arrival and departure phases of flight</u>

- Without on-board performance monitoring and alerting function
- Lateral TSE must be within ±2 NM for at least 95 per cent of the total flight time
- Based on DME/DME, DME/DME/IRU and GNSS

RNP 2

(06) <u>En-route and oceanic/remote phases of flight</u>

- With on-board performance monitoring and alerting function (usually RAIM)
- Lateral TSE must be within ±4 NM for at least 95 per cent of the total flight time
- Based on GNSS

062 07 02 03 – Designation of RNP and RNAV specifications

CE

RNAV 1*

(08) Arrival and departure phases of flight

- Without on-board performance monitoring and alerting function
- Lateral TSE must be within ±1 NM for at least 95 per cent of the total flight time
- Based on DME/DME, DME/DME/IRU and GNSS

RNP 1

(08) Arrival and departure phases of flight

- With on-board performance monitoring and alerting function (usually RAIM)
- Lateral TSE must be within ±1 NM for at least 95 per cent of the total flight time
- For terminal airspace with no or limited ATS surveillance, with low to medium density traffic
- Based on GNSS

**Almost equivalent to Precision RNAV (P-RNAV) within ECAC*

062 07 02 03 – Designation of RNP and RNAV specifications

CE

RNP APCH

(09) Approach phase of flight

- With on-board performance monitoring and alerting function (usually RAIM or SBAS)
- Lateral TSE varies with minima and approach segment (initial, intermediate, final missed)
- Based on:
    - GNSS for LNAV minimum
    - GNSS + barometric VNAV for LNAV/VNAV minimum*
    - GNSS augmented by SBAS for LP and LPV minima

RNP AR

(10) Approach phase of flight

- With on-board performance monitoring and alerting function (usually RAIM)
- Cross-track error must be lower than the lateral applicable accuracy value for 95 per cent of flight time
- For terminal airspace with no or limited ATS surveillance, with low to medium density traffic
- Based on GNSS + (usually) barometric-based VNAV

**GNSS-based vertical guidance may be used*

062 07 02 03 – Designation of RNP and RNAV specifications

RNP 0.3

(11) All phases of flight except oceanic/remote and final approach

- With on-board performance monitoring and alerting function (usually RAIM or SBAS)
- Lateral TSE must be within ±0.3 NM for at least 95 per cent of the total flight time
- Primarily for helicopters
- Based GNSS

Helicopter Operations

(12) RNAV 1, RNP 1 and RNP 0.3 may also be used in en-route phases of **low-level** instrument flight rule (IFR) helicopter flights.

062 07 03 00 – Use of PBN

- Generic navigation requirements are defined based on operational needs
- Operators then evaluate options in respect of available technology and navigation services
- PBN brings the opportunity to **select cost-effective options**

062 07 03 03 – Specific RNAV and RNP system functions

FB/FO | Path Terminators | Fixed radius paths | Off/Hold

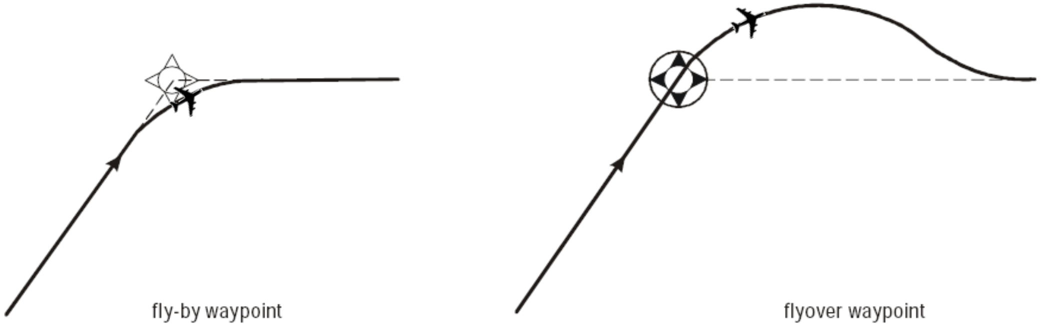
(05) The standard that fixes database formats and contents is the **ARINC 424 'Navigation System Data Base Standard'**

Allows coding the SIDs, STARs and instrument approach procedures (IAPs) from the official published government source documentation into the ARINC navigation database format

CE (04) Waypoints coordinates are loaded in the on-board aircraft's database. Types:

- ***Fly-by***: *the navigation system anticipates the turn onto the next leg*
- ***Fly-over***: *the aircraft overflies the waypoint before starting the turn onto the next route leg*

Note that the depiction of fly-by and fly-over waypoints is different



062 07 03 03 – Specific RNAV and RNP system functions

FB/FO | **Path Terminators** | Fixed radius paths | Off/Hold

(06) **ARINC 424** also defines the **Path Terminator**: define a specific type of termination of the previous flight path.

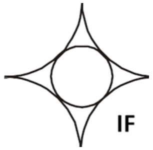
- The Path Terminator is a two-letter code, which defines a specific type of flight path along a segment of a procedure and a specific type of termination of that flight path
- Path terminators are assigned to all RNAV SID, STAR and approach procedure segments in an airborne navigation database
- This allows translating into computer language (FMS) the procedures designed for clock & compass manual flight
- Charted procedures are translated into a sequence of ARINC 424 legs in the database
- There are 23 different path terminators defined in ARINC 424. Those which can be expected in RNAV or RNP charts are depicted in next slide

062 07 03 03 – Specific RNAV and RNP system functions

FB/FO | **Path Terminators** | Fixed radius paths | Off/Hold

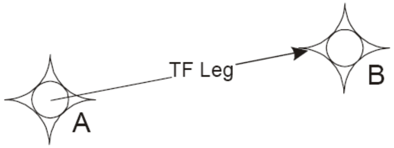
Initial Fix (IF)

- It defines a point in space
- The coding of RNAV procedures starts at an IF



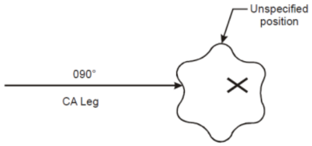
Track to a fix (TF)

- Preferred type for straight legs
- Geodesic path between two waypoints



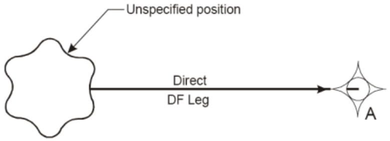
Course to an altitude (CA)

- Course that terminates at an altitude with an unspecified position
- For departures or Missed App



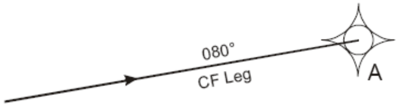
Direct to a fix (DF)

- Segment from an unspecified position to a known waypoint



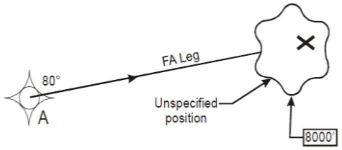
Course to a Fix (CF)

- Course that terminates at a waypoint
- CF legs are subject to magnetic variation issues



Course from a fix to an altitude (FA)

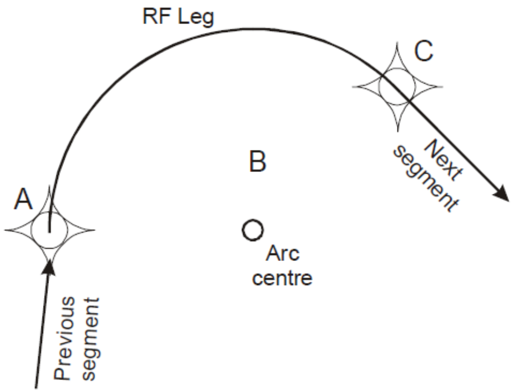
- Begins at a fix and terminates when aircraft altitude is at, or above, a specified altitude



062 07 03 03 – Specific RNAV and RNP system functions

FB/FO | Path Terminators | **Fixed radius paths** | Off/Hold

There are two types of **FIXED RADIUS PATHS**



CE (01) **Radius to Fix (RF)**

- *Is also a type of Path Terminator*
- *Specific curved path radius in a terminal or approach procedure*
- *Is defined by radius, arc length, and fix*

CE (02) **Fixed radius transition (FRT)**

CE *(03) It is essential to respect the flight director guidance and the speed constraints associated with an RF leg.*

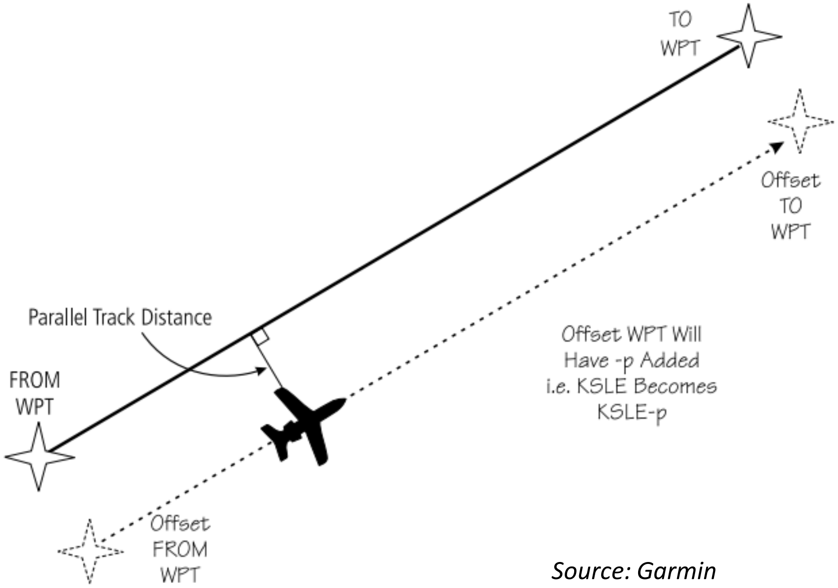
- *To be used* with en-route procedures*
- *It falls upon the RNP system to create it between two route segments*
- *These turns have two possible radii, 22.5 NM for high altitude routes (above FL 195) and 15 NM for low altitude routes. Using such path elements in an RNAV ATS route enables improvement in airspace usage through closely spaced parallel routes*

** The "Concept of Use" of FRT is currently being evaluated by ICAO, who is carefully addressing promulgation, airspace design and avionics capabilities aspects, among others. No State has published yet any ATS Routes that require the FRT function*

062 07 03 03 – Specific RNAV and RNP system functions

CE (07) Many aircraft have the capability to fly a path parallel to, but offset left or right from, the original active route → **offset flight path**

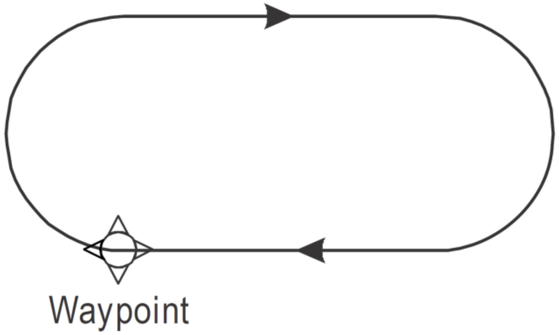
- *The purpose of this function is to enable offsets for tactical operations authorized by ATC*
- *Capability for the flight crew to specify a lateral offset from a defined route (generally in increments of 1NM to 20 NM)*



Source: Garmin

062 07 03 03 – Specific RNAV and RNP system functions

- Many aircraft have the capability to execute a **holding pattern** manoeuvre using their RNAV system, which can provide flexibility to ATC in designing RNAV operations.
  - *The RNAV system facilitates the holding pattern specification by allowing the definition of the inbound course to the holding waypoint, turn direction and leg time or distance on the straight segments, as well as the ability to plan the exit from the hold*



062 07 04 00 – PBN operations

- What pilots need to know about PBN operations is whether the aircraft and flight crew are qualified to operate in the airspace, on a procedure or along an ATS route

- The flight operations element considers:

  - *The operator’s infrastructure for conducting PBN operations and flight crew operating procedures, training and competency demonstrations*

  - *The operator’s MEL, OMs, checklists, navigation database validation procedures, etc*

062 07 04 01 – PBN principles

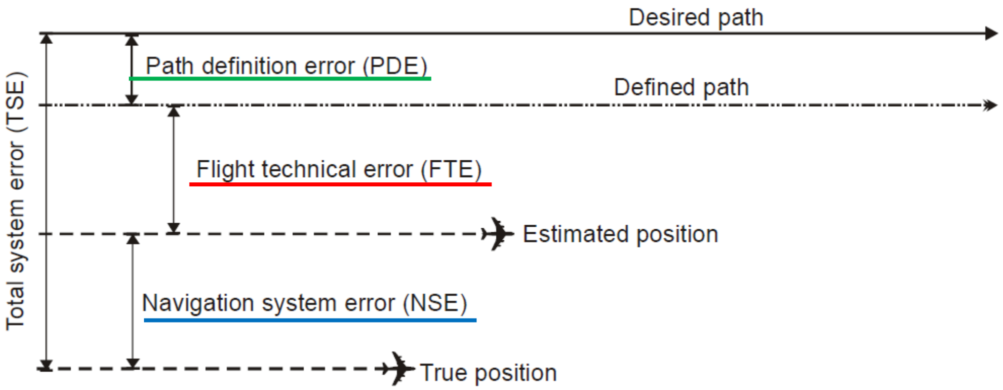
CE

- There are 3 main independent lateral errors in the context of on-board performance monitoring and alerting. Together they account for the **Total System Error (TSE), which forms the basis for performance estimation and monitoring**

(01) ***Path Definition Error (PDE)****: occurs when the path defined in the RNAV system (database) does not correspond to the desired path, i.e. the path expected to be flown over the ground*

(02) ***Flight Technical Error (FTE)****: relates to the air crew or autopilot's ability to follow the prescribed path or track, including any display error (e.g. CDI centering error). Sometimes, if adding display error, referred as PSE (Path Steering Error)*

(03) ***Navigation System Error (NSE)****: refers to the difference between the aircraft's estimated position and actual position. The accuracy of a navigation system may be referred to as NSE. Sometimes referred as* ***EPE (Estimated Position Error)****.*



CE

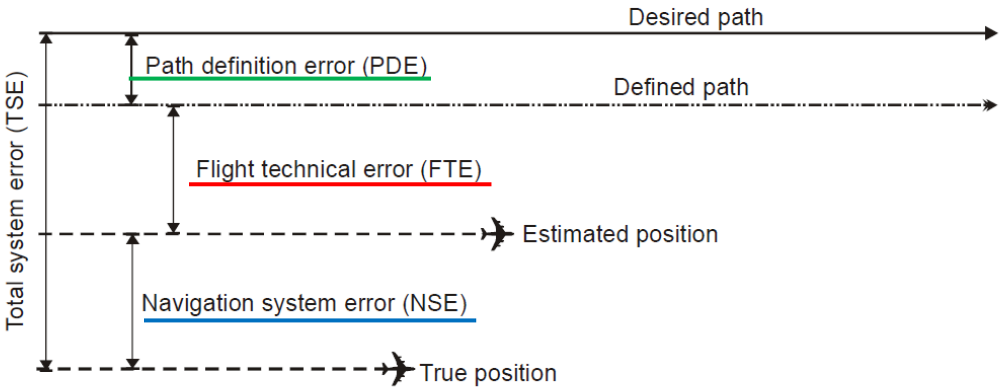
(04) Total System Error (TSE): Root Sum of PDE, FTE and NSE

(05) The navigation accuracy depends on the TSE

With SBAS, expect: NSE << FTE

062 07 04 02– On-board performance monitoring and alerting

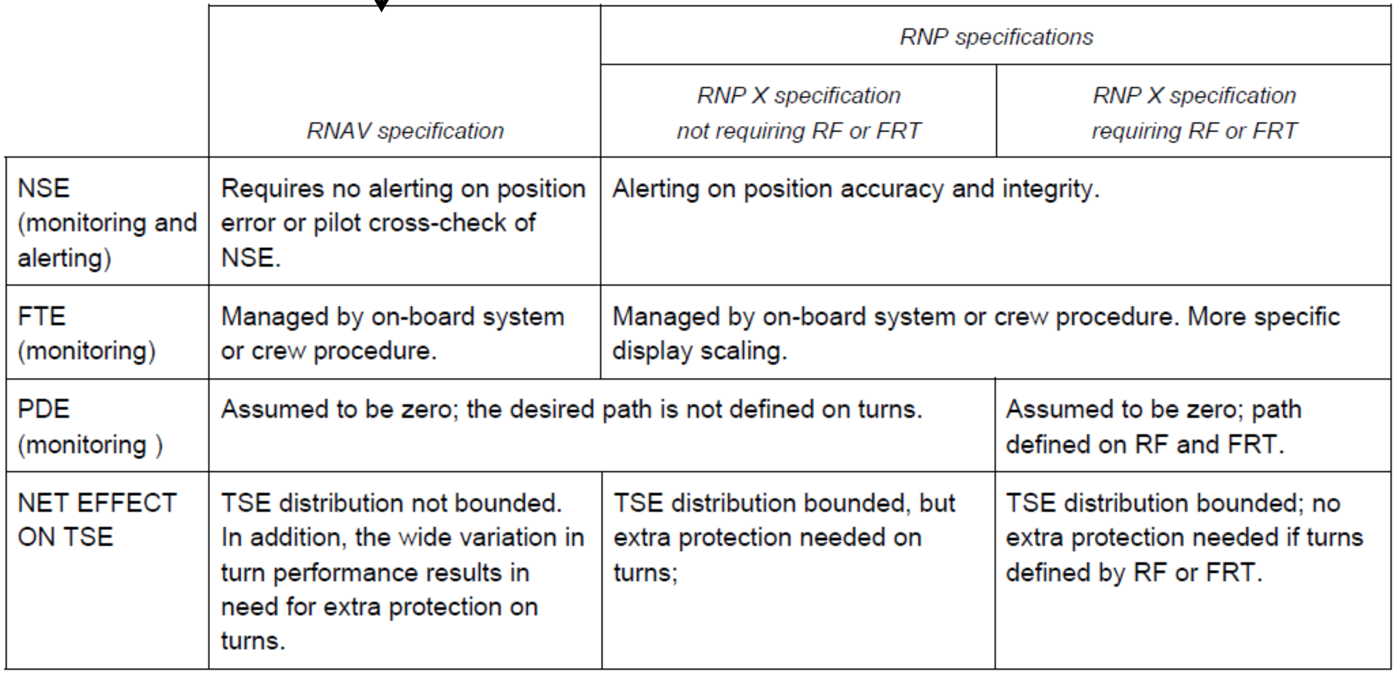
- This function allows the air crew to detect whether or not the RNP system satisfies the navigation performance required (requirements based on TSE) in the navigation specification
  - **On-board** means that the performance monitoring and alerting is effected on board the aircraft and not elsewhere
  - **Monitoring** refers to the monitoring of the aircraft's performance as regards its ability to determine positioning error and/or to follow the desired path
  - **Alerting** relates to monitoring: if the aircraft's navigation system does not perform well enough, this will be alerted to the air crew



- ***Path Definition Error (PDE)**: cannot be monitored or controlled but generally is sufficiently small that it can be ignored.*
- ***Flight Technical Error (FTE)**: FTE can be controlled by the flight crew and should be minimized.*
- ***Navigation System Error (NSE)**: cannot be controlled by the flight crew but should be monitored to ensure that it remains within acceptable limits. **That is why it is characterized by the ANP (Actual Navigation Performance)***

062 07 04 02– On-board performance monitoring and alerting

REMINDER!
RNAV specifications do not require monitoring and alerting functions!



		RNP specifications	
	RNAV specification	*RNP X specification not requiring RF or FRT*	*RNP X specification requiring RF or FRT*
NSE (monitoring and alerting)	Requires no alerting on position error or pilot cross-check of NSE.	Alerting on position accuracy and integrity.	
FTE (monitoring)	Managed by on-board system or crew procedure.	Managed by on-board system or crew procedure. More specific display scaling.	
PDE (monitoring)	Assumed to be zero; the desired path is not defined on turns.		Assumed to be zero; path defined on RF and FRT.
NET EFFECT ON TSE	TSE distribution not bounded. In addition, the wide variation in turn performance results in need for extra protection on turns.	TSE distribution bounded, but extra protection needed on turns;	TSE distribution bounded; no extra protection needed if turns defined by RF or FRT.

CE

(01) *On board performance monitoring and alerting of FTE is managed by on board systems or crew procedures*

Example: RAIM or FDE algorithm + CDI crew monitoring

CE

(02) *On board performance monitoring and alerting of NSE is a requirement of on-board equipment for RNP*

Example: RAIM or FDE algorithm

CE

(06) *On board performance monitoring and alerting of PDE are managed by gross reasonableness of navigation data*

062 07 04 02– On-board performance monitoring and alerting

- On-board performance monitoring **shall not be regarded as error monitoring**
- Alerts are issued when the system cannot guarantee with sufficient integrity that the position meets the accuracy requirement
- When an alert is issued, the probable reason is the loss of capability to validate the position data (insufficient satellites being a potential reason in the case of GNSS)

In other words, even if the position was able to meet the accuracy requirement, since the system is unable to prove it, an alert would be issued.

062 07 04 02– On-board performance monitoring and alerting

(04) **Navigation System Error (NSE)** *(also known as Estimated Position Error -EPE-)*

- **More common terms**, as displayed in the cockpit, are ‘**ANP**’ (Actual Navigation Performance), ‘**EPU**’ (Estimated Position Uncertainty) or ‘**ACTUAL**’
- EPE/ANP is defined as an statistical bound on the NSE and not TSE
- Multiple sources of navigation data may be integrated to determine the ANP. Inertial systems initially are very accurate but may tend to drift if not updated accurately throughout the flight. GNSS units generally provide exceptionally accurate data but must be monitored for undetected failures , etc.
- These sources of data are analyzed continuously to calculate the best estimate of current a/c position and ANP/EPU. If any source is deleted, the confidence in the navigation position will decrease. Thus, the ANP value will increase.

(03) **Depending on the navigation sensor, ANP is compared with the RNP:**

```
          POS REF        2/3
 FMC POS (IRS 3)          GS
N51°29.3 W000°32.6  156KT
 IRS (3)
010°/0.9NM             156KT
 RNP/ACTUAL          NAV STA
2.00/0.06NM          IAA OCK

PURGE ----------   GPS NAV
<CONFIRM           INHIBIT>

<INDEX             LAT/LON>
```

```
       NAV APPR 1/4 M     I
KTUS VOR 11L   TUS 116.00
FR INBOUND             HDG→
123°   2.6NM  -3.04°
TO CALLS       5247FT MNVR→
123°   2.0NM  -3.04°   CNCL
NX POCIB       4600FT APPR→

XTK(A) L0.00  GS        131
WND 044°/  2  ANP      0.03
VDEV      -3  RNP      0.30
```

062 07 04 02– On-board performance monitoring and alerting

Considerations:

- Management of FTE is usually a pilot procedure
- On-board performance monitoring requirement is <u>unique to RNP specifications</u>
- PDE vanishes as the airborne system uses the same coordinate system and computations as the designer to define the path, so monitoring requirement is reduced to FTE and NSE

$$\boxed{TSE^2 = \underset{\searrow\ \mathbf{0}}{PDE^2} + FTE^2 + NSE^2}$$

062 07 04 02– On-board performance monitoring and alerting

Performance assessment

$$TSE^2 = \cancelto{0}{PDE}^2 + FTE^2 + NSE^2$$

- The:
  - aircraft navigation system; or the
  - aircraft navigation system and pilot <u>in combination</u>
- Must <u>monitor the TSE</u> and provide alerts if:
  1. **Accuracy requirement** (i.e. TSE remains equal to or less than 1xRNP for 95 per cent of the flight time) is not met; or
  2. **Integrity requirement** (probability that the lateral TSE is below x2 the accuracy value is higher than 1 x 10-5) is not met. In other words, the lateral TSE should be below 2xRNP for 99.999 percent of the time.
     - Probability calculations (10^{-5} at 2xRNP) based on complex algorithms certified as part of airborne systems
     - The objective of this requirement is to limit the exposure of the aircraft to conditions where the containment limit is exceeded without annunciation

- Various manufacturers of flight management computers (FMC) use different mathematical equations, or algorithms, to calculate actual navigation performance (ANP), depending also on the navigation sensor

RNP NavSpecs

- **PDE assumed to be zero**
- **NSE requires <u>monitoring and alerting</u>**
- **FTE requires <u>monitoring</u>**

e.g. 1: system monitors ANP and alert if ANP > RNP

e.g. 2: RAIM or FDE algorithm

e.g. crew monitors FTE in the CDI so TSE = FTE+ANP < RNP

062 07 04 02– On-board performance monitoring and alerting

(05) Example of how the loss of the ability to operate in RNP airspace may be indicated by the navigation system.

UNABLE REQD NAV PERF-RNP

BOEING

When ANP exceeds RNP, an UNABLE RNP message is displayed to the flight crew. This indicates that the FMS position does not meet the required accuracy, so the procedure (such as an approach) must be aborted.

062 07 04 02– On-board performance monitoring and alerting

EXAMPLE 1: how is this achieved with RNP 1?

The RNP 1 accuracy requirement is (extracted from the ICAO PBN Manual):

> *"During operations in airspace or on routes designated as RNP 1, the* ***lateral TSE must be within ±1 NM for at least 95 per cent of the total flight time****. The* ***along-track error must also be within ±1 NM for at least 95 percent of the total flight time****. To satisfy the accuracy requirement,* ***the 95 per cent FTE should not exceed 0.5 NM****"*

Check of the Accuracy requirement TSE < ± 1NM

- Aircraft navigation system

  "the use of an autopilot or flight director has been found to be an acceptable means of compliance (roll stabilization systems do not qualify)"

- Aircraft navigation system and pilot in combination:

  "the use of a deviation indicator [CDI] with 1 NM full-scale deflection [FSD] has been found to be an acceptable means of compliance"

  The CDI displays the FTE:

  FSD = 2 dots = 1 NM → 1 dot= 0.5 NM i.e. **pilot must fly below 1 dot**.

  If flying at 1 dot, pilot must monitor that ANP < 0.5NM

Check of the integrity requirement TSE < 2NM for 99.999 % of the time

For systems operating in a GNSS mode, some derivative of the GNSS performance could be used: Horizontal Dilution of Precision (HDOP), the Horizontal Protection Level (HPL), etc.

062 07 04 02– On-board performance monitoring and alerting

EXAMPLE 2: how is this achieved with RNP APCH down to LPV?

The ICAO PBN Manual states that:

“NSE requirements are fulfilled (…) if the equipment computes (…) solution in accordance with RTCA DO 229C (or subsequent version) Appendix J”

“FTE performance is considered acceptable if the lateral and vertical display full-scale deflection is compliant with (…) requirements of RTCA DO 229 C (or subsequent version) and if the crew maintains the aircraft within one-third the full scale deflection for the lateral deviation and within one-half the full scale deflection for the vertical deviation”

Check of the Accuracy requirement

- NSE monitoring and alerting

  Equipment compliant with DO-229[x]
- FTE monitoring

  approach guidance must be displayed on a lateral and vertical deviation display (HSI, EHSI, CDI/VDI) including a failure indicator for crew monitoring

Check of the integrity requirement

With **probability of 1-2x10^{-7}**, DO-229[x] equipment checks at all times that:

- Horizontal Protection Level (HPL) < Horizontal Alert Limit (HAL)
- Vertical Protection Level (VPL) < Vertical Alert Limit (VAL)
- and **provide alerts** within 10 seconds before FAP, and 6 seconds after FAP

062 07 04 03– Abnormal situations

Abnormal procedures **Contingency procedures**

CE (01) Abnormal and contingency procedures are to be used in case of the loss of PBN capability

- **Abnormal procedures** should be available to address cautions and warnings resulting from the following conditions:
  - *Failure of the navigation system components including those affecting flight technical error (e.g. failures of the flight director or auto pilot);*
  - *RAIM alert or loss of integrity function;*
  - *Warning flag or equivalent indicator on the lateral and/or vertical navigation display;*
  - *Degradation of the GNSS approach mode during a LPV approach procedure (e.g. downgrade from LPV to LNAV);*
  - *Low altitude alert (if applicable)*

062 07 04 03– Abnormal situations

Abnormal procedures **Contingency procedures**

- LPV to LNAV reversion (adapted from French DGAC/DSAC)
  - *For LPV approaches, some systems allow LPV to LNAV reversion if the vertical signal is lost or degraded*
  - *If LPV to LNAV reversion takes place before the FAF/FAP, the crew can envisage continuing with the approach to the LNAV minima*
  - *If reversion occurs after the FAF/FAP, go-around is required, unless the pilot has in sight the visual references required to continue the approach*

062 07 04 03– Abnormal situations

Abnormal procedures

Contingency procedures

- In case of a complete RNAV guidance loss during the approach, the crew must follow the **operator defined contingency procedure/s**
- In the event of communications failure:
  - *Flight crew should continue with the 2D/3D RNAV(GNSS) procedure in accordance with published lost communication procedures; or*
  - *Follow procedures stated in the chart;*
- The flight crew should react to TAWS warnings in accordance with approved procedures
- The flight crew should notify ATC of any problem with the navigation system that results in the loss of the approach capability

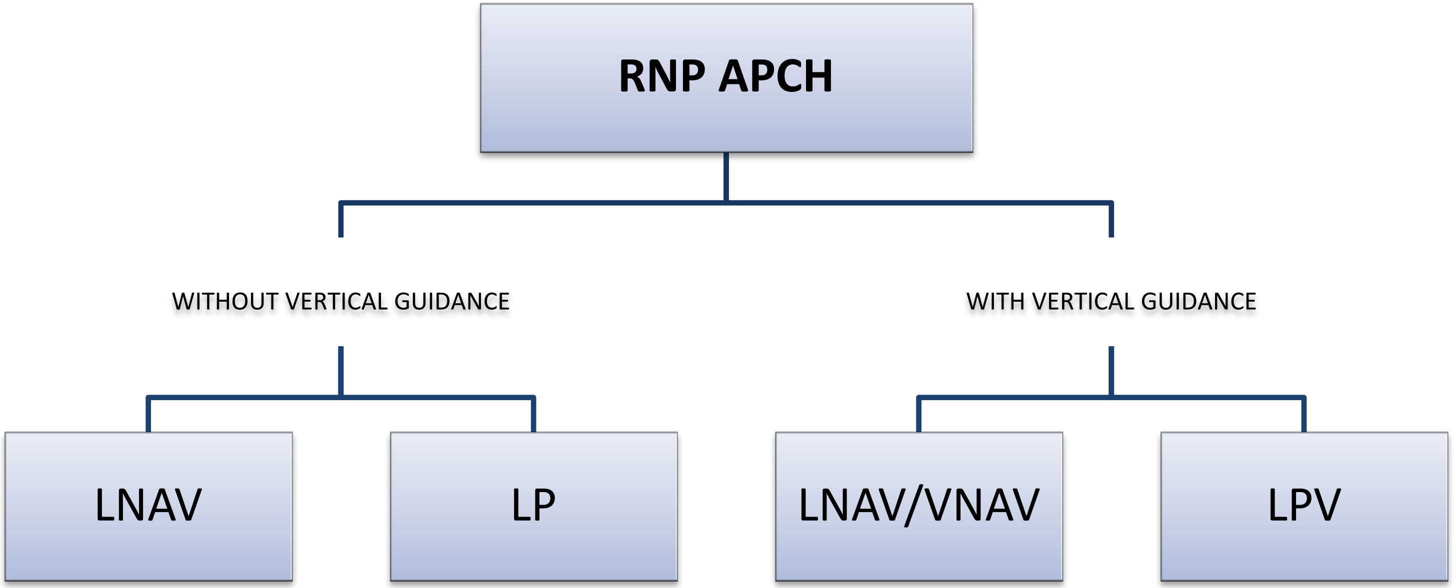
062 07 04 04– Database management

- The navigation database must contain all the necessary data/information to fly the published approach procedure

CE (01) Therefore, the on-board navigation data must be valid for the current AIRAC cycle and must include the appropriate flight procedures, unless otherwise specified in the operations documentation or AMC

- The operator should implement procedures that ensure timely distribution and insertion of current and unaltered electronic navigation data to all aircraft that require it

062 07 05 00– Requirements for specific RNAV and RNP specifications



RNP APCH

WITHOUT VERTICAL GUIDANCE

WITH VERTICAL GUIDANCE

LNAV

LP

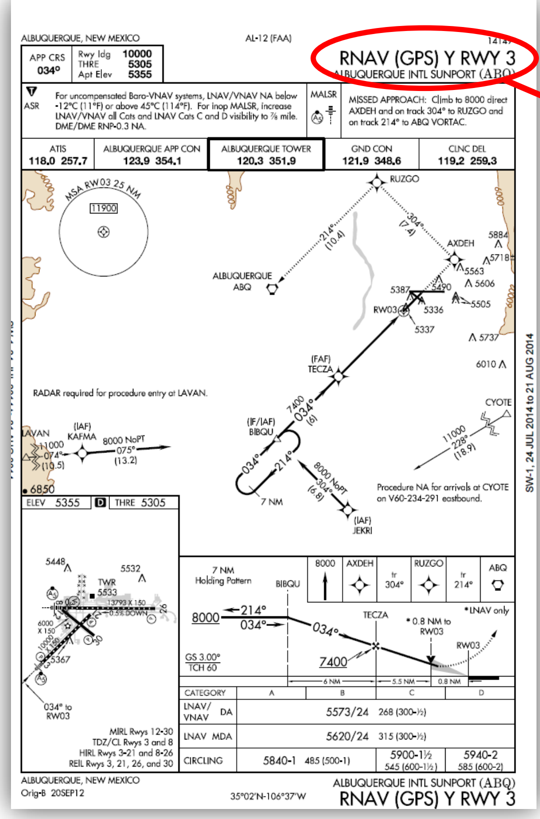
LNAV/VNAV

LPV

LNAV	LP	LNAV/VNAV	LPV
GPS NPA Expected to be flown with CDFA	**NPA SBAS supported** Localiser Performance	APV Baro (can also be supported by SBAS)	**APV SBAS supported** Localiser Performance with Vertical Guidance

062 07 05 05– RNP APCH

CE (01) An RNP APCH shall not be flown unless it is retrievable by procedure name from the on-board navigation database and conforms to the charted procedure

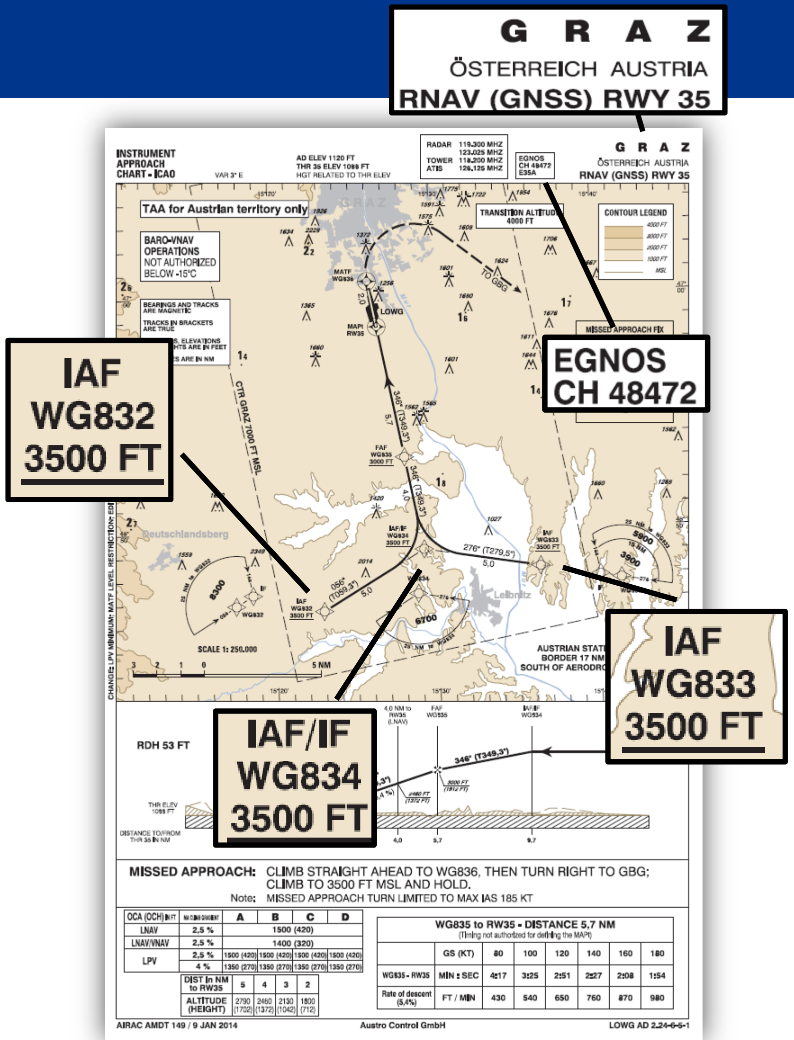


Source: Bendix King by Honeywell

062 07 05 05– RNP APCH

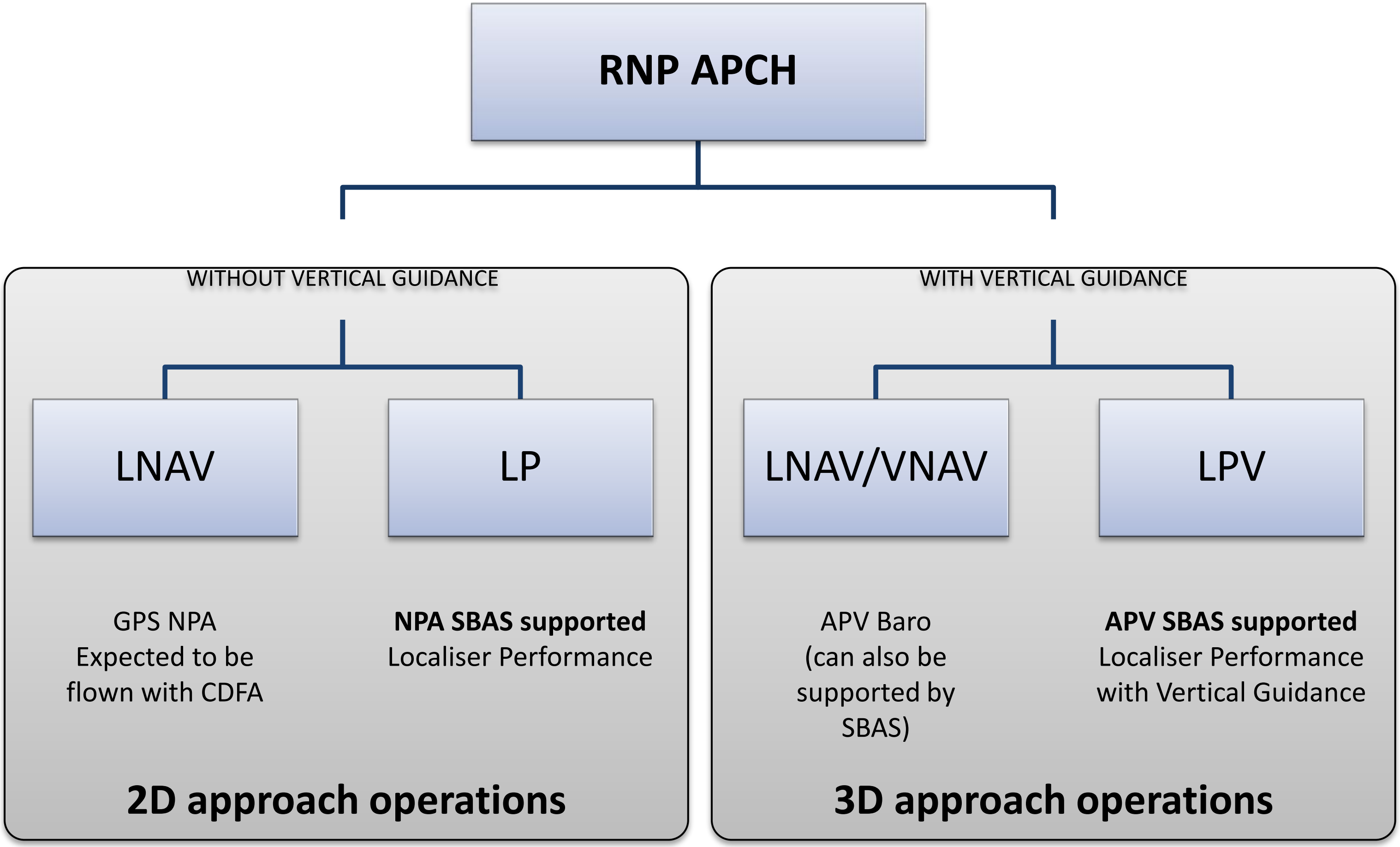
- Retrieving a procedure from the database:
  - *By name: usually IAF*
  - *If LPV is available, also by SBAS Channel Number, which is a unique worldwide identifier composed of 5 numeric characters, in the range of 40000 to 99999*

- Example **GRAZ RNAV (GNSS) RWY 35**
  - 3 IAFs: WG832, WG834 and WG833
  - 1 Channel Number: 48472
  - Pilot can select one of the 4 previous options. Selecting the channel number will load an 'extended' Final Approach Segment, as an ILS. In this later case, pilot is expected to intercept the extended FAS following ATC Vectors To Final
  - 'Direct to' waypoints following ATC clearances are allowed except for FAP



Source: Austrocontrol

062 07 05 05– RNP APCH



RNP APCH

WITHOUT VERTICAL GUIDANCE

LNAV

GPS NPA
Expected to be
flown with CDFA

LP

NPA SBAS supported
Localiser Performance

2D approach operations

WITH VERTICAL GUIDANCE

LNAV/VNAV

APV Baro
(can also be
supported by
SBAS)

LPV

APV SBAS supported
Localiser Performance
with Vertical Guidance

3D approach operations

062 07 05 05– RNP APCH

- In terms of **phraseology**, no distinction is made between the different types of RNAV (GNSS) approaches (no distinction according to LPV, LNAV/VNAV and LNAV minima)
- The minima to which the procedure is flown is unknown to Air Traffic Controllers

(adapted from French DGAC/DSAC)

062 07 05 05– RNP APCH

LNAV LP LNAV/VNAV LPV

CE

- (02) **LNAV minima**
  - *Non Precision Approach*
  - *2D operation*
  - *Linear lateral guidance based on GNSS*
  - *Expected to be flown using CDFA technique*
  - *Integrity provided by RAIM, unless SBAS is available*

- **LP minima**
  - *Non Precision Approach*
  - *2D operation*
  - *SBAS required:*
    - *angular lateral guidance based on GNSS augmented by SBAS*
    - *Integrity provided by SBAS*
  - *Expected to be flown using CDFA technique*
  - ***LP Final Approach Segment specially coded into a Data Block** inside the on-board navigation database.*
  - *Not published at runways with LPV minima*

If SBAS-certified equipment is available on-board, SBAS can provide integrity during LNAV operations.

062 07 05 05– RNP APCH

LNAV LP **LNAV/VNAV** LPV

CE

- (03) **LNAV/VNAV minima**
  - *APproach with Vertical guidance (APV)*

  (07) *3D operation*
  - *Linear lateral guidance based on GNSS*

  (04) *Vertical guidance based on Baro-VNAV or SBAS. In any case, the used angular vertical guidance must be certified for the purpose*
  - *Integrity provided by RAIM, unless SBAS is available*

If SBAS-certified equipment is available on-board, SBAS can provide integrity during LNAV/VNAV operations.

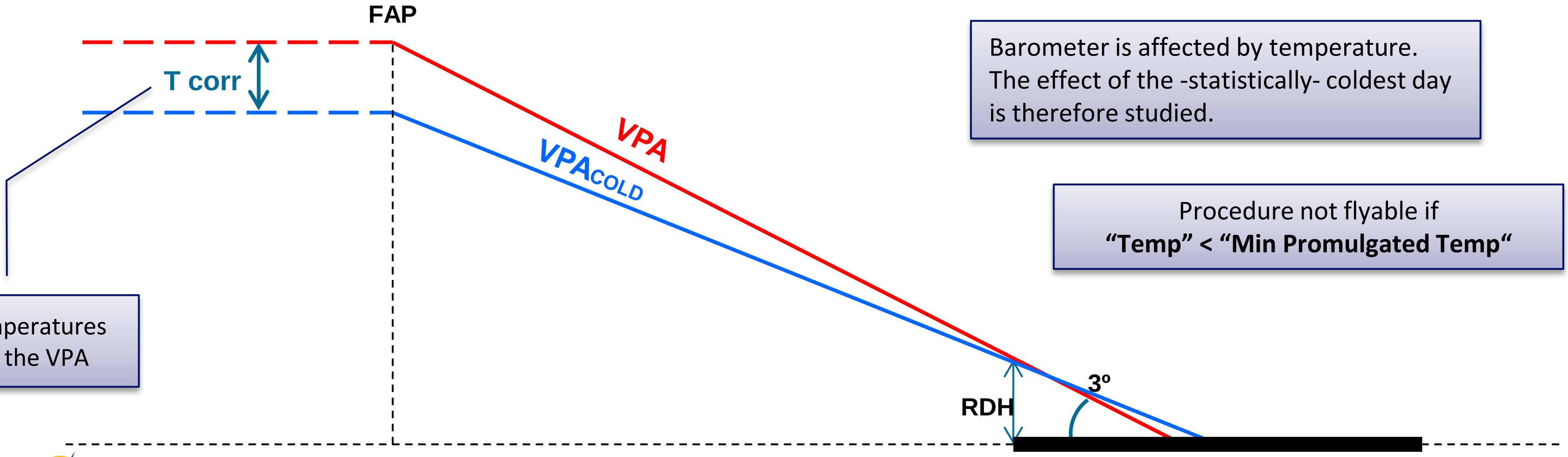
062 07 05 05– RNP APCH

CE (06) **LNAV/VNAV minima**

Considerations about the use of the **Barometric sensor**

- **Affected by temperature variation → LNAV/VNAV based on Baro-VNAV can only be flown when aerodrome temperature is within a promulgated range**, unless a/c has an approved temperature compensation system

- **Altimeter setting is critical →** to safe conduct LNAV/VNAV based on Baro-VNAV, remote altimeter setting is prohibited



Barometer is affected by temperature. The effect of the -statistically- coldest day is therefore studied.

Procedure not flyable if
“Temp” < “Min Promulgated Temp“

Cold temperatures reduce the VPA

062 07 05 05– RNP APCH

LNAV LP LNAV/VNAV **LPV**

CE

- **LPV minima**
  - *Precision Approach CAT-I or APproach with Vertical guidance (APV)*

(08) 3D operation

(10) SBAS required:

- *angular lateral and vertical guidance based on GNSS augmented by SBAS*
- *Integrity provided by SBAS*

(09) ***LPV Final Approach Segment is specially coded into a Data Block*** *inside the on-board navigation database. It is known as the FAS DB*

EGNOS, it's there. Use it.

European Global Navigation Satellite Systems Agency

ESSP

Precise navigation, powered by Europe

062 07 05 05– RNP APCH

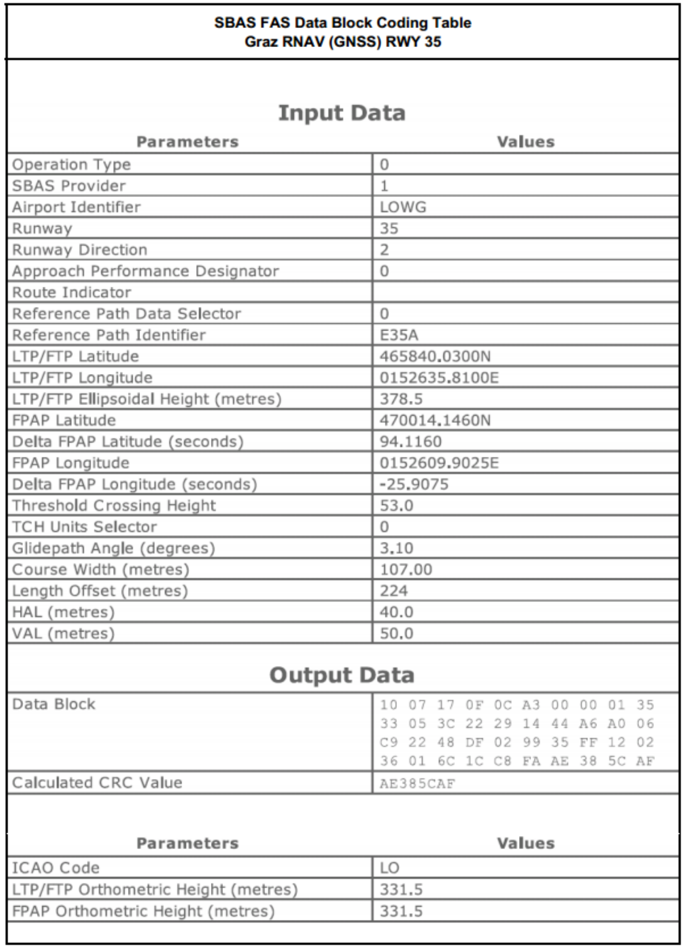
LNAV LP LNAV/VNAV **LPV**

CE (11) **FAS DB**

- *"The set of parameters to identify a single precision approach or APV and define its associated approach path" (ICAO)"*

- *Is part of the data package of an SBAS approach procedure:*
    - *The FAS-DB contain the parameters that define the Final Approach Segment **geometry***
    - *The integrity of the data is ensured by the generation of a **CRC algorithm** (Cyclic redundancy check)*

- *References:*
    - *ICAO Doc 8168: procedure design criteria*
    - *ICAO Annex 10: Aeronautical Telecommunications*
    - *RTCA Do-229: Approval of GPS/SBAS Rx equipment*



SBAS FAS Data Block Coding Table
Graz RNAV (GNSS) RWY 35

Input Data

Parameters	Values
Operation Type	0
SBAS Provider	1
Airport Identifier	LOWG
Runway	35
Runway Direction	2
Approach Performance Designator	0
Route Indicator	
Reference Path Data Selector	0
Reference Path Identifier	E35A
LTP/FTP Latitude	465840.0300N
LTP/FTP Longitude	0152635.8100E
LTP/FTP Ellipsoidal Height (metres)	378.5
FPAP Latitude	470014.1460N
Delta FPAP Latitude (seconds)	94.1160
FPAP Longitude	0152609.9025E
Delta FPAP Longitude (seconds)	-25.9075
Threshold Crossing Height	53.0
TCH Units Selector	0
Glidepath Angle (degrees)	3.10
Course Width (metres)	107.00
Length Offset (metres)	224
HAL (metres)	40.0
VAL (metres)	50.0

Output Data

Data Block	10 07 17 0F 0C A3 00 00 01 35 33 05 3C 22 29 14 44 A6 A0 06 C9 22 48 DF 02 99 35 FF 12 02 36 01 6C 1C C8 FA AE 38 5C AF
Calculated CRC Value	AE385CAF

Parameters	Values
ICAO Code	LO
LTP/FTP Orthometric Height (metres)	331.5
FPAP Orthometric Height (metres)	331.5

Source: Austrocontrol

062 07 05 05– RNP APCH

LNAV LP LNAV/VNAV LPV

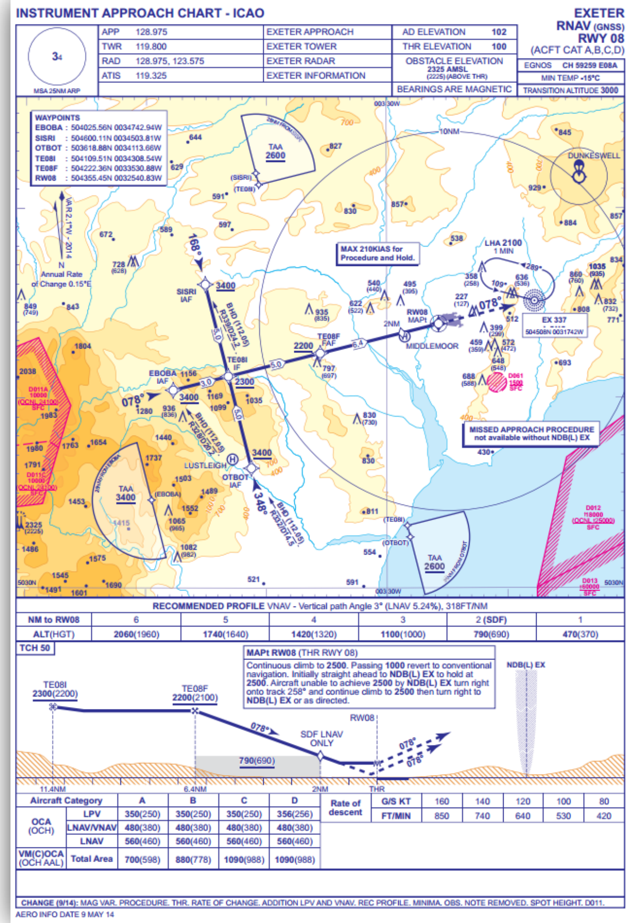
- **FAS DB: why?**
  - *To ensure the integrity of databases*
  - *In ILS/MLS approaches, integrity is ensured by:*
    - *Proper alignment of transmitting antennas*
    - *Flight checks*
    - *Integrity monitors on the transmitted signal*
  - *LPV approaches:*
    - *A kind of approach based on on-board data*
    - *Integrity rests on the data describing the approach path*
    - *Hence the importance of having a **CRC wrapping the FAS DB***

062 07 05 05– RNP APCH

- Most RNAV (GNSS) final approach procedures leading to LNAV, LNAV/VNAV or LPV minima, may be preceded by either an initial and intermediate T-bar or Y-bar approach. In this case all segments are published on the same chart.

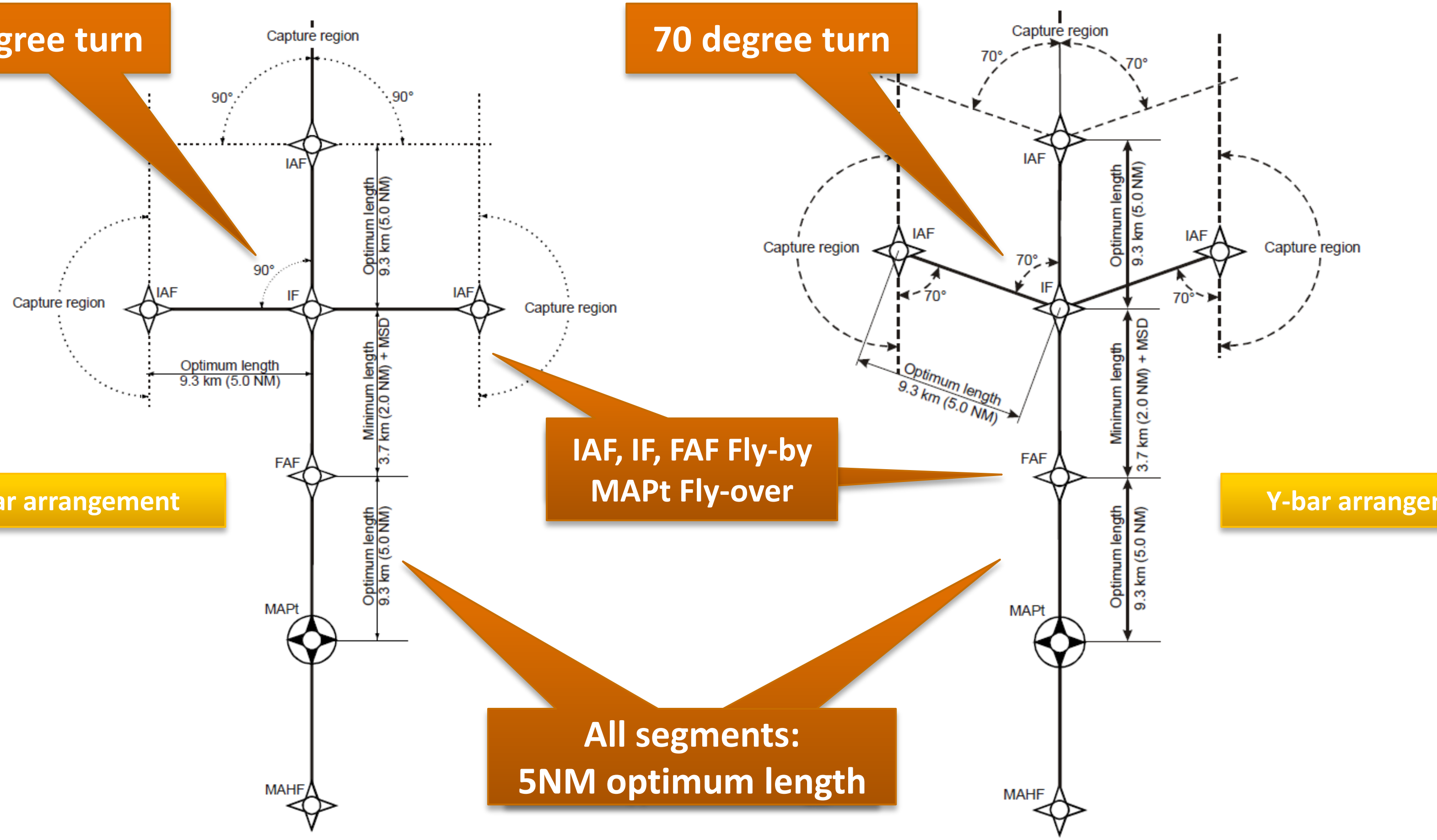
- A T- or Y-bar arrangement permits direct entry to the procedure from any direction, provided entry is made from within the capture region associated with an IAF.

- Where one or both offset IAFs are not provided, a direct entry will not be available from all directions. In such cases a holding pattern may be provided at the IAF to enable entry to the procedure via a procedure turn.



(source: UK CAA)

062 07 05 05– RNP APCH



90 degree turn

70 degree turn

T-bar arrangement

IAF, IF, FAF Fly-by
MAPt Fly-over

Y-bar arrangement

All segments:
5NM optimum length

(source: ICAO)

062 07 05 09– PBN Point in Space (PinS) Approach

(01) The Point-in-Space approach is based on GNSS or SBAS and is an approach procedure designed for helicopters only that includes both a visual and an instrument segment. Therefore, it can be published with LNAV and/or LPV minima

- Obstacle clearance is provided for all IFR segments of the procedure including the missed approach segment

- During an approach to land, the instrument segment ends at the PinS (MAPt). From there, flight continues with a visual segment

- In an approach procedure, the visual segment (VS) is the segment of a helicopter PinS approach between a point (MAPt) and the heliport or the landing location

The flexibility that offers the free positioning of the PinS is the main asset of this concept.

062 07 05 09– PBN Point in Space (PinS) Approach

Visual Segment (VS)

(02) The PinS approach procedure includes either a ***“proceed visually”*** instruction or a ***“proceed VFR”*** instruction from the MAPt to the heliport or landing location

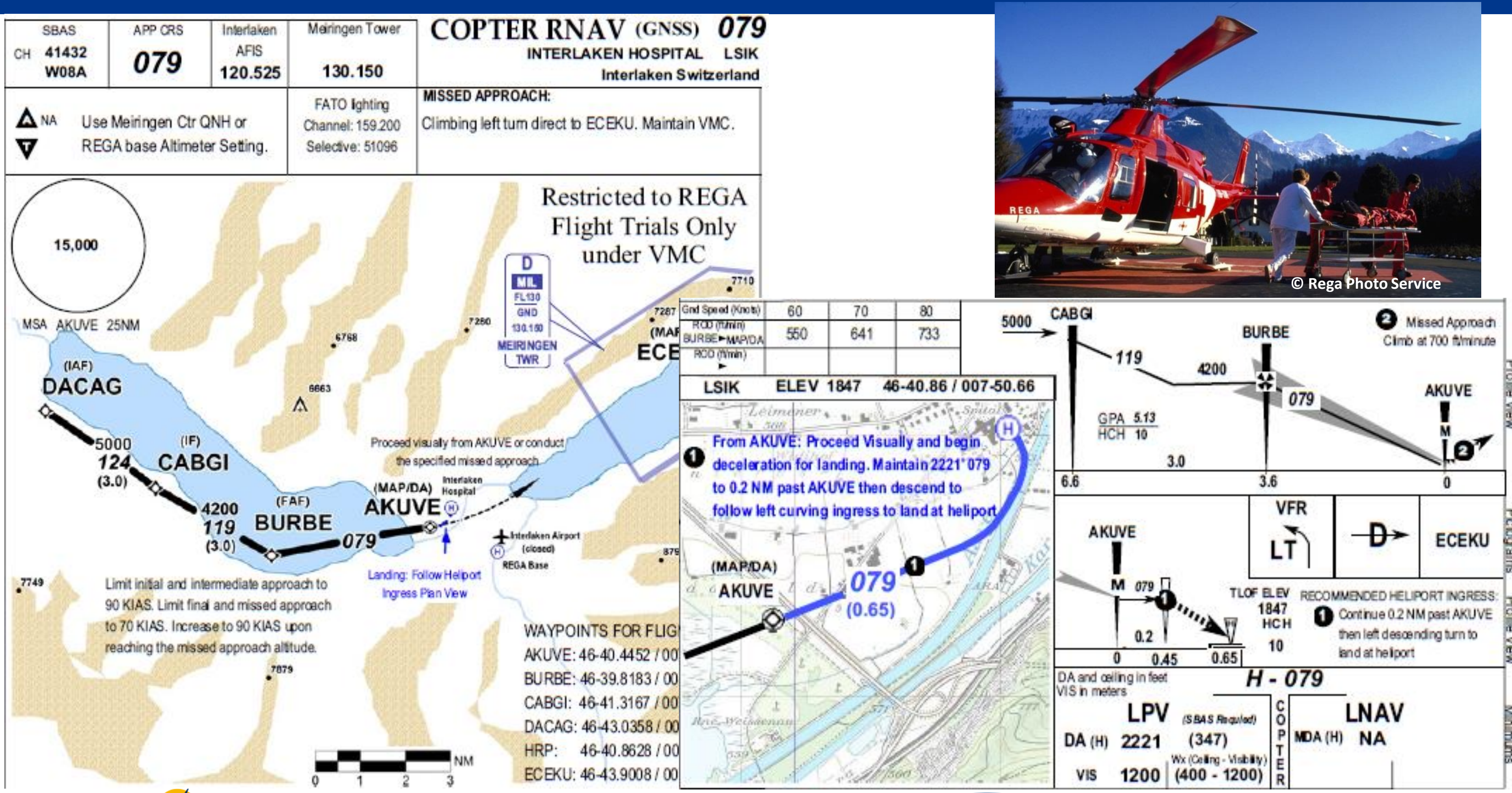
(03) **Proceed VFR**: developed for heliport or landing locations that do not meet the standards for a heliport. The PinS instrument approach delivers the helicopter to a MAPt. Prior to or at the MAPt, the pilot shall decide to proceed VFR or to execute a missed approach, based on visibility

- Pilot determines whether visibility is met based on the published minimum visibility or the visibility required by State regulations (whichever is higher)
- There is no protection after the MAPt if MA is not initiated. The pilot is responsible to see and avoid obstacles

Proceed visually: developed for a heliport or a landing location. The PinS instrument approach segment delivers the helicopter to a MAPt. Prior to or at the MAPt, the pilot shall decide to proceed visually to the heliport or landing location or to execute a missed approach

- A **Direct VS** or a **Manoeuvring VS** connects the MAPt to the heliport or landing location
- The minimum visibility is based on the distance from the MAPt to the heliport or landing location
- IFR obstacle clearance areas are not applied to the visual segment. However the visual segment is protected, by operational limitations in the case of “manoeuvring” VS

062 07 05 09– PBN Point in Space (PinS) Approach



SBAS	APP CRS	Interlaken AFIS	Meiringen Tower	COPTER RNAV (GNSS) 079
CH 41432 W08A	079	120.525	130.150	INTERLAKEN HOSPITAL LSIK Interlaken Switzerland

NA Use Meiringen Ctr QNH or REGA base Altimeter Setting.	FATO lighting Channel: 159.200 Selective: 51096	MISSED APPROACH: Climbing left turn direct to ECEKU. Maintain VMC.

Restricted to REGA Flight Trials Only under VMC

Proceed visually from AKUVE or conduct the specified missed approach.

Limit initial and intermediate approach to 90 KIAS. Limit final and missed approach to 70 KIAS. Increase to 90 KIAS upon reaching the missed approach altitude.

Landing: Follow Heliport Ingress Plan View

WAYPOINTS FOR FLIG
AKUVE: 46-40.4452 / 00
BURBE: 46-39.8183 / 00
CABGI: 46-41.3167 / 00
DACAG: 46-43.0358 / 00
HRP: 46-40.8628 / 00
ECEKU: 46-43.9008 / 00

Gnd Speed (Knots)	60	70	80
ROD (ft/min) BURBE►MAP/DA	550	641	733
ROD (ft/min) ►			

LSIK ELEV 1847 46-40.86 / 007-50.66

❶ From AKUVE: Proceed Visually and begin deceleration for landing. Maintain 2221' 079 to 0.2 NM past AKUVE then descend to follow left curving ingress to land at heliport

❷ Missed Approach Climb at 700 ft/minute

RECOMMENDED HELIPORT INGRESS:
❶ Continue 0.2 NM past AKUVE then left descending turn to land at heliport

H - 079

DA and ceiling in feet
VIS in meters

	LPV	(SBAS Required)	COPTER	LNAV
DA (H)	2221	(347)		MDA (H) NA
VIS	1200	Wx (Ceiling - Visibility) (400 - 1200)		

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