KINGDOM OF BAHRAIN
Ministry of Transportation and Telecommunications

مملكة البحرين
وزارة المواصلات والاتصالات

CIVIL AVIATION PUBLICATION

CAP 11
Volume 1

PBN TECHNOLOGY

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CAP 11

PBN

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VOLUME 1: PBN TECHNOLOGY

Bahrain CAA Publication Revisions Highlight Sheet

☒ CAP: 11 Vol. 1 ☐ TPM: _

The following pages have been revised to Revision 01 dated 09 June 2022.

Item	Paragraph number	Page(s)	Reason
1.	1.2	2	Acceptance criteria clarified
2.	1.4	3	Added clarification to the RNAV & RNP and deletion of irrelevant descriptions
3.	2.1	4	Addition of description of GNSS, GLNASS, EGNOS, WAAS technology
4.	2.5	9	Addition of descriptions and deletion of irrelevant descriptions
5.	2.6	11	Spell correction
6.	3.2	12	Sentence correction and deletion of irrelevant descriptions / references
7.	3.4	16	Minor changes to description
8.	4.1	24	Deletion of irrelevant descriptions
9.	4.10	30	Deletion of irrelevant descriptions
10.	7.1 & 7.2	43	Deletion of irrelevant descriptions
11.	8.1 to 8.3	45-47	Deletion of irrelevant descriptions

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I. INTRODUCTION

Bahrain CAA CAP 11 is divided into three volumes.

Volume 1 PBN Technology provides a summary of the enabling area navigation technology in order to provide operational approval inspectors with the technical background necessary for an informed and consistent management of PBN operational approvals. Additional study may be required depending upon the complexity of the operation and other factors, and reference is made to CAP 11 as a suitable source of information.

The operational approval process for established navigation technologies is well known and understood by inspectors and there is general consistency amongst regulators worldwide on the issue of operational approvals. As Performance Based Navigation isa relatively recent development, regulatory authorities, inspectors and applicants require some time and experience to develop a thorough understanding of PBN operations, the associated technology and the approval process. In addition, it is necessary that inspectors have a good knowledge of PBN principles, the associated technology and operating practices in order to accommodate any perceived limitations in the available documentation.

CAP 11 Volume 2 PBN Operational Approval discusses the approval of operations for each of the navigation specifications. Where appropriate, additional guidance material is provided to explain the context or intent of the navigation specification.

CAP 11 Volume 3 Job Aids provide inspectors and operators with guidance on the process to be followed in order to obtain a PBN operational approval.

It is intended that this CAP is supplemented by a formal course of training for inspectors.

II. STATUS OF CAP 11

This is the first issue of CAP 11 volumes 1, 2 and 3, and will remain current until withdrawn or superseded.

CAP 11 Volumes 1, 2 and 3 cancel CAP 11 RNAV, CAP 12 BRNAV, CAP 13 PRNAV, CAP 14 RNP AR and CAP 15 RNP APCH.

III. DEFINITIONS & ACRONYMS

See CAP 11, Volume 2 PBN Operational Approval, Chapter 1.

VOLUME 1: PBN TECHNOLOGY

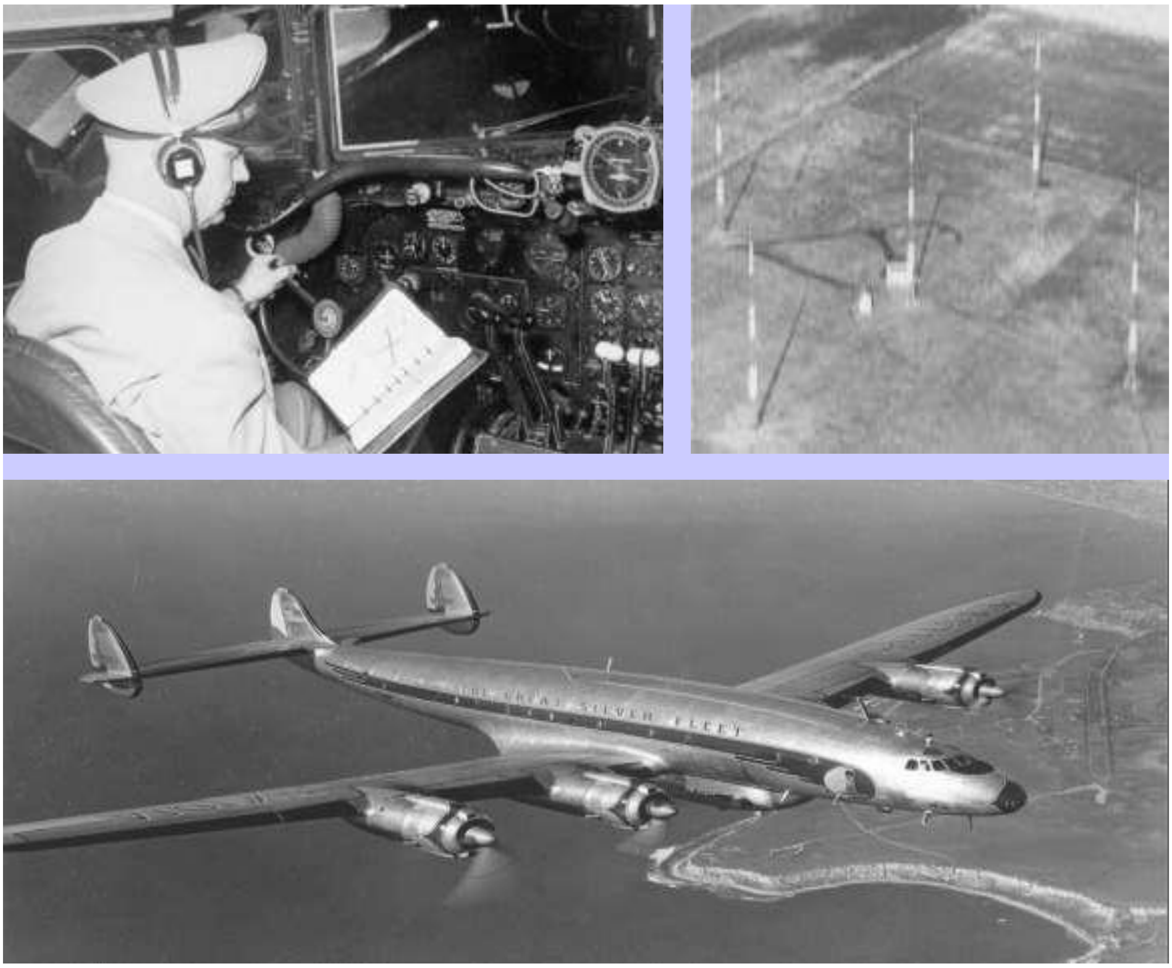
Chapter 1 OVERVIEW

1.1 Introduction

The information in this volume is intended to provide inspectors with the necessary technical knowledge necessary to manage an application for operational approval in accordance with a navigation specification contained in CAP 11, Vol. 2 and 3. This volume contains information relative to the full complement of PBN navigation specifications and, in general, individual PBN operations are not discussed in detail.

1.2 Transition from Conventional Navigation to PBN

Conventional navigation, that is navigation dependent upon ground-based radio navigation aids, has long been the mainstay of aviation. Pilots, operators, manufacturers and ANSPs are all familiar with the technology; the avionics, instrumentation, operations, training and performance are very much standard throughout the world. Consequently, apart from some more demanding operations such as Cat II/III ILS, specific operational approval is not necessary.



Performance Based Navigation is dependent on area navigation. While various methods of RNAV have been in existence for many years, the use of RNAV has not yet reached the same level of common use as conventional navigation. The Performance Based

Navigation concept is intended to better define the use of RNAV systems and provide a means to eventually reach a similar level of common use. The approval process shall be precise and only aircraft with approved AFM documentation will be accepted.

The approval process shall be precise. the fundamentals of PBN operations are relatively straightforward and, therefore, operational approval need not be a complicated process for either applicant or regulator. Even the highest performing type of operation (RNP AR APCH), once implemented, is a simple and safe operation when conducted in an appropriately equipped aircraft operated by a properly trained crew, due the capability of modern avionics and auto-flight systems.

However, the transition to new technology, new navigation and operational concepts and the dependence on data-driven operations requires careful management. The purpose of the operational approval process to ensure that, for all PBN operations, the appropriate level of oversight is provided to ensure that, in the current environment where there are many variables in terms of equipment and experience, the benefits of PBN can be achieved consistently and safely.

The key to successful PBN implementation is knowledge and experience. This CAP is intended to assist in improving that level of knowledge. Experience can only be gained by doing, and an operational approval will commonly be required before relevant experience is gained. In this CAP, guidance is also provided on strategies for implementation which allow experience to be gained (by all parties) in a controlled environment, allowing progression to full capability in stages as experience is gained.

1.3 Performance Based Navigation

Performance Based Navigation encompasses a range of operations which are all based upon Area Navigation. Area navigation, commonly abbreviated as RNAV, has been available for around 30 years using a variety of technology. However, some difficulties arise from the dual application of the term „RNAV" as a fundamental method of navigation (area navigation) and also as a particular type of operation (e.g. RNAV 5). Further complications arise with the implementation of Required Navigation Performance (RNP) operations which, by definition, are also area navigation operations.

There has been both difficulty in identifying the differences between RNAV operations and RNP operations and a lack of definition in the requirements for both RNAV and RNP operations. A number of regions established local RNAV and RNP standards which led to complexity in international operations and operational approvals.

ICAO established the Required Navigation and Special Operational Requirements Study Group (RNPSORSG) to resolve these issues. The RNPSORSG (now called the PBN Study Group) developed the concept of Performance Based Navigation to encompass both RNAV and RNP operations.

1.4 RNAV vs. RNP

One of the issues that the RNPSORSG had to deal with was to differentiate between area navigation operations which are described as either RNAV or RNP. While both RNAV and RNP operations could be described in terms of navigation performance (e.g. accuracy), RNP operations can be identified by the capability of the on-board navigation system to monitor, in real time, the achieved navigation performance and to alert the operating crew when the specified minimum performance, appropriate to a particular operation, could not be met. This additional functionality provided by RNP allows the flight crew to intervene and to take appropriate mitigating action (e.g. a go-round), thereby allowing RNP operations to provide an additional level of safety and capability over RNAV operations.

As GNSS systems incorporate performance monitoring and alerting, the distinction between RNAV and RNP operations, in practice, is the requirement for GNSS. While there are exceptions to this rule, RNP operations are based on a variety of technologies whereas RNAV operations are based on older technology.

RNAV navigation specifications have been developed to support existing capability in aircraft equipped with systems which, in general, were not designed to provide on-board performance monitoring and alerting. RNP navigation specifications can be achieved by any number of technologies. It is dependant on performance, not a single technology.

Chapter 2 AREA NAVIGATION

2.1 Area Navigation Principles

Area navigation (RNAV) is a term applied to navigation between any two selected points on the earth's surface. RNAV has been around since the 1960s and the earliest avionics used triangulation measurements from ground-based navigation aids to compute an RNAV flight path between waypoints.

A number of self-contained navigation systems which are independent of any ground- based navigation systems have also been developed, including OMEGA (now obsolete) LORAN C, GPS, Glonass, Inertial Navigation Systems (INS) and Inertial Reference Systems (IRS).

Perhaps the most common type of RNAV system in use in commercial aviation today involves the use of IRS positioning, updated by reference to ground-based radio navigation aids (DME and VOR) or GPS. Updating by reference to ground-based aids is limited by the availability of sufficient navigation aids and, in many parts of the world, including oceanic and remote areas, position updating is unavailable.

Commonly referred to by the generic term GNSS (Global Navigation Satellite System), satellite navigation has revolutionised area navigation by providing highly accurate and reliable positioning. For modern air transport operations, area navigation is managed by a Flight Management System using a combination of technologies. GNSS now includes four constellations for satellites: China (BeiDou), Russia (GLONASS), Europe (Magellan) and the United States (GPS). Modern aircraft use these space based systems, in conjunction with IRU and ground-based navigation aids to produce a composite system. In addition Europe as EGNOS and the United States have WAAS that use low orbit satellites to add additional accuracy to the navigational signals.

There are many various area navigation systems in use throughout the world, CAP 11 Vol. 2 provides a number of navigation specifications to accommodate a range of RNAV and RNP performance levels. One of the tasks of the operations approval inspector is to ensure that the equipment available meets the requirements of the relevant PBN operation.

2.2 Geodetic Reference

An area navigation system-computed position must be translated to provide a position relative to the real position on the earth‟s surface. Horizontal data are used for describing a point on the earth's surface, in latitude and longitude.

A specific point on the earth‟s surface can have substantially different coordinates, depending on the data used to make the measurement. There are hundreds of locally-developed horizontal data around the world, usually referenced to some convenient local reference point. The WGS 84 datum is the common standard datum now used in aviation.

2.3 Path Terminators

In its simplest form, an area navigation system computes a track between two selected waypoints. However, the demands on aircraft navigation require the definition of complex flight paths, both lateral and vertical. The international standard for definition of path and terminator is ARINC 424. A flight path is described in coded ARINC 424 language which is interpreted by the RNAV system to provide the desired navigation function and inputs to flight guidance systems.

The path between any two waypoints can be specified, depending upon the coding. Each segment is also defined by a terminator or end statement which provides information to the navigation system on the intended method of connection of one segment (path) with the next.

For example, two waypoints could be connected by a great circle track between the two waypoints (TF) or by the arc of a circle of defined radius (RF). Other options include a path defined from the current position to a waypoint (DF) or a path defining a holding pattern (HF). In general usage, path and terminator are commonly abbreviated to path terminator or sometimes leg type. A complex series of ARINC 424 rules govern the definition of leg types and their interaction with each other.

One example of a common sequence of leg types is TF to TF. Effectively, this is a series of "straight lines" as in the diagram below. In the normal case, the aircraft avionics interprets the ARINC 424 coding as two legs joined by a curved flight path. The aircraft will therefore "fly by" the intermediate waypoint.

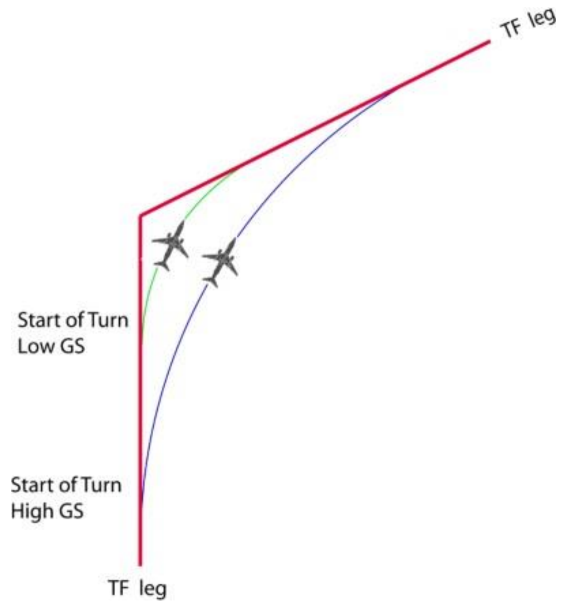


Figure 2.1: TF to TF Transition

The aircraft navigation system is programmed to provide a start of turn prompt (turn anticipation) based the current groundspeed and a programmed bank angle, which will normally provide a turn of sufficient radius to allow the subsequent segment to be intercepted. As each aircraft will compute a different start of turn point, the result is a spread of turns between the tracks of faster aircraft using lower bank angles and slower aircraft with larger bank angles.

Turn anticipation does not provide track guidance during the turn so, until the aircraft is established on the subsequent leg, cross-track error cannot be monitored. The effectiveness of the turn anticipation algorithm is limited by variation in groundspeed during the turn (e.g. headwind to tailwind) and the achieved bank angle. Undershooting or overshooting of the turn can occur and crew intervention may be required.

Using a range of leg types available with ARINC 424 coding (approx. 18), complex fight paths can be designed. However, it must be noted that not all navigation systems are capable of accommodating all leg types. Two common examples of leg types that may not be supported are RF and CA legs.

An RF or Radius-to-Fix leg defines a circle of specified radius, enabling an aircraft to fly a precise curved flight path relative to the surface of the earth, rather than an undefined path as in the previous example of a TF/TF.

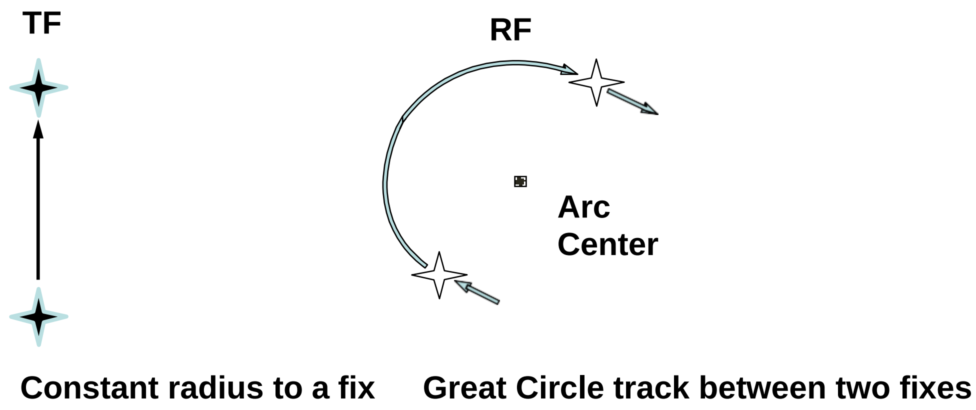


Figure 2.2: Common Path Terminators

A CA or Course-to-Altitude leg defines a nominated course until a specified altitude is reached. On reaching the altitude, the path is "terminated" and the avionics will follow the path defined by the next leg or path and terminator. The CA leg which is commonly used to specify the initial leg of a departure is not normally supported by general aviation GPS receivers, which are not usually integrated with the aircraft"s vertical navigation system. Consequently, the flight planned departure route may not be followed and pilot intervention (manual selection of next leg) is required.

In the example below (Figure 2.3), two aircraft are cleared on a departure with the same instruction. Depending on the climb performance, the position at which the aircraft reaches 3000ft and the CA leg terminated will vary. If the aircraft is equipped with an integrated vertical navigation system, the termination will be automatic, and the active route will sequence to the next leg which may be (for example) a Direct to Fix (DF) leg.

If vertical navigation capability is not available, the termination must be initiated by the flight crew. For manually sequenced navigation systems, the track to the next fix will depend on the point at which the Direct To function is selected. In the example, the pilot has selected Direct To immediately on reaching 3000ft and the track is generated from that position. If Direct To is selected after the turn, a different track will be displayed. In this and similar examples, the actual flight path is variable and may not meet operational requirements. A different sequence of Path Terminators may be needed to better define the flight path but may result in the inability to place a minimum altitude requirement on the turn initiation.

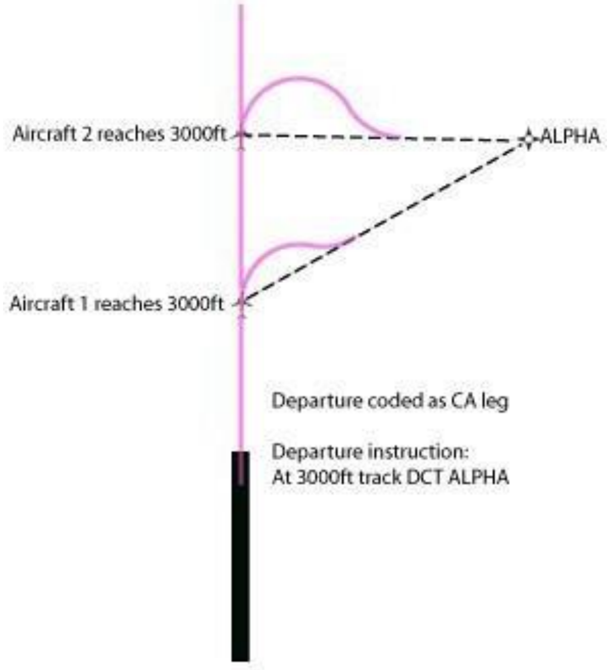


Figure 2.3: CA Path Terminator Example

It is essential that operational approval inspectors gain a working knowledge of common path terminators, the basics of flight path design and the functionality of aircraft avionics and flight control systems in order to properly manage operational approvals. For example, while an operation might meet the requirements of a specific CAP 11 Vol. 2 navigation specification, the operational approval may need to ensure that crew procedures are defined in order to fly a certain type of procedure, as in the case of the CA example described above.

2.4 Radius to Fix segments

The use of an RF segment or multiple segments, including TF and RF legs, provides great flexibility in route design, enabling flight paths to be designed to avoid terrain, manage noise footprint and better utilise airspace.

RF leg capability is available on most late model FMS-equipped aircraft, but the lack of general availability can limit its broader use. Currently only the RNP AR APCH navigation specification supports the use of RF legs. However, it is expected that application will be extended in due course.

Capability for RF legs, while extremely useful, is not without limitation. It is important that the FMS functionality, aircraft flight control logic and the application of RF legsto flight procedure design are properly understood.

A segment, coded as an RF leg, creates a circular flight path over the surface of the earth, defined by a start and end point, a turn radius and an origin. ARINC 424 coded segments, before and after the RF legs, must join at a tangent to the circle defined by the RF leg. Consequently, the sequence of legs used can be TF/RF or RF/TF and RF/RF. Joining of RF legs to other RF legs is acceptable and turn reversal and change of radius may occur. This capability allows great flexibility in design.

While complex flight paths can now be designed and displayed as the active route, the aircraft must have the capability to accurately follow the defined flight path. Pilots are familiar with flying turns at a constant airspeed and angle of bank which enables a circular flight path to be flown *with reference to the air mass* and they are trained to manually compensate for the presence of wind, if necessary. Pilots now need to understand that the FMS will fly an exact circular flight path *over the ground* and the angle of bankwill be adjusted by the flight control system to maintain that circular flight path.

The physics of flight are such that the radius of a circle (over the ground) is limited by groundspeed and angle of bank. The minimum radius that can be flown is thereforelimited by the maximum available bank angle and the groundspeed.

Bank angle limits are determined by the aircraft manufacturer. They are also limited by crew selection, aircraft configuration and phase of flight. In normal approach/departure configuration, a typical bank angle capability for modern jet transport aircraft is 30° but may be as low as 20°. The bank angle limit can be 8° or less at low altitude, and, similarly, bank angle limits are also applied at high altitude. The RNP AR APCH navigation specification requires aircraft to be capable of 25° angle of bank in normal circumstances and 8° below 400ft. As the procedure designer uses these limits in the design of RF turns, pilots need to be aware of the aircraft capability in all flight phases. For aircraft that will utilise RF leg capability, inspectors should familiarise themselves withaircraft capability documentation during the operational approval process.

Groundspeed is a function of TAS, and, consequently, IAS, plus or minus the ambient tailwind or headwind component. In order to ensure that the flight path during an RF turn can be maintained under all normal weather conditions, the procedure designer allowsfor a maximum tailwind component or “rare-normal” wind. The maximum tailwind component is selected from a wind model which is intended to represent the maximum winds likely to be encountered at various altitudes, generally increasing with altitude. A tailwind component of up to 100KT may be applied in some cases.

As groundspeed is also affected by TAS, the flight crew needs to manage the IAS within acceptable limits to ensure that the bank angle limits, and, hence, the ability to maintain the flight path, are not exceeded in circumstances where high winds exist. In normal routine operations, where ambient winds are generally light, quite low bank angles are sufficient to maintain RF turns of average radius. However, if the IAS is allowed to exceed normal limits, the limiting bank angle may be reached at less than the maximum design tailwind component, leading to a potential loss of track adherence.

Generally, applicable maximum indicated airspeeds are specified in the RNP AR APCH navigation specification. However, the designer may impose specific limiting speeds in some cases.

Flight crews needs to be thoroughly conversant with the principles and practice of RF turns, limiting airspeeds, bank angle/aircraft configuration, the effect of high winds and contingency procedures for manual intervention which, although rare, may be required.

2.5 Area Navigation Systems

Although there are many different types of area navigation systems, the most common systems are:

Legacy systems. Self-contained DME/DME and VOR/DME navigation systems.

Stand-alone GNSS systems comprising of a receiver and a pilot interface which may be combined with the receiver unit, or installed as a separate control and display unit.

(Note: A control and display unit (CDU) should not be confused with a Flight Management System, as the interface units are similar in appearance.)

Figure 2.4: Typical Stand-alone GNSS Receiver

This type of GNSS installation should provide steering commands to HSI or CDI displays in the pilot‟s primary field of view. Many GNSS units provide an integrated navigation display and/or map display as part of the receiver unit. However, in many cases, the size, resolution and location of the display may neither be suitable nor be in the pilot‟s primary field of view.

Flight Management System There are many types of flight management systems with varying complexity, so care should be taken in determining the capability of each particular installation. In modern transport operations, the FMS usually incorporates two Flight Management Computers which are provided with position updating from a number of sensors. These sensors will normally be inertial, radio and GNSS (as installed). The inertial information is normally provided by two or more Inertial Reference Systems (IRS), with radio and GNSS information provided by two or more Multi Mode Receivers (MMR). Prior to the FMC accepting a sensors positional update, a gross error check is performed to ensure that the sensor position falls within the ANP or EPE value.

The computed aircraft position is commonly a composite position based on the IRS position corrected by inputs from the navigation information received from the MMR. Recently manufactured aircraft will usually be equipped with GNSS, so the computed position will be based on a variety of technologies.

Figure 2.5: FMS Equipped Aircraft with Large Screen Multifunction Displays

2.6 Data Management

In all but the simplest area navigation systems, navigation data is contained in an airborne database. From a Human Factors standpoint, navigation data should only be extracted from a valid database, although some navigation specifications permit pilot entry of waypoint information. Where pilot entry of co-ordinates is permitted, it should be limitedto en-route operations only and above the minimum obstacle clearance altitude. For allother operations, pilot entry or modification of waypoint data should be prohibited.

Arrival, approach and departure operations should be extracted from the database by the selection of a named flight procedure (Figure 2.6). User construction of procedures, even if waypoints are extracted from an airborne database, should be prohibited.

PBN operations are dependent upon valid navigation data. Unlike conventional navigation, where the basic navigation guidance is originated from a physical point (e.g. a VOR transmitter), area navigation is totally dependent on electronic data. Therefore, gross errors can occur due to erroneous data or mismanagement of valid data. In general, navigation specifications require or recommend that data is obtained from an approved supplier who has implemented appropriate quality control procedures. Despite a data supplier meeting such quality control standards, there still remains a risk that invalid data may be contained in the airborne database and caution should be exercised. In the case of operations, conducted where collision with terrain is a risk (approach/departure), additional checks at each data update cycle are required. Electronic comparison of data against a controlled source is preferred, but manual or simulator checks may be used where this method is not available.

It should also be noted that whilst every precaution may be taken to ensure the validity of the airborne database, valid data can, in some circumstances, be incorrectly interpreted and managed by the airborne navigation system. It is extremely difficult to protect againstthis type of problem. However, in evaluating PBN operating procedures, due attention should be made to ensure that crew review procedures are appropriate and sufficient to constitute a last line of defence.

Chapter 3 NAVIGATION PERFORMANCE

3.1 General

All navigation systems can be described in terms of performance. For example, a ground-based navigation aid, such as VOR, delivers a measurable level of performance which is applied in terms of accepted navigational tolerances.

PBN operations are similarly based on navigation performance, but the concept of performance is fundamentally different. Whereas an operation based on a ground-based navigation aid is dependent upon the performance of the radiated signal and the ability of an aircraft to accurately utilise that signal, in Performance Based Navigation, the performance itself is specified and the navigation system is required to meet the minimum level of performance. In principle, any method of navigation that achieves the specified level of navigation performance is acceptable. However, in practice, a particular navigation system is required in some cases in order to meet the requirements of a particular navigation specification. For example, RNP 4 requires the mandatory carriage of GNSS, as no other current navigation system is available to meet the requirements of the navigation specification. In theory, at least, if another means of navigation became available which met the performance requirements for RNP 4 without GNSS, the requirement for GNSS could be removed from the navigation specification.

3.2 Performance Evaluation

A navigation specification requires performance which is defined by a number representing the accuracy of the navigation system, measured in nautical miles. Accuracyis specified as the probability that the computed position will be within the specifiedradius of the actual position 95% of the time. While this is the basis for the specification of the accuracy requirement, the achieved accuracy may be many times much better and this can be somewhat misleading.

Figure 3.1 is an example of in-service data collected for RNP AR APCH operations at Brisbane Australia. The observed standard deviation of TSE is typically of the order of 18m or less, or less than 36m 95% of the time. In this example, where the navigation accuracy for the approach is RNP 0.3, the navigation specification requirement is 95% of 0.3NM or 528m, the observed accuracy is over 15 times better than the minimum.

Navigation systems that utilise GNSS can provide very high levels of accuracy with a probability far exceeding 95% of the navigation accuracy. Consequently, it can beconfusing and even misleading to quote a 95% probability of accuracy for GNSS navigation when the actual positioning can be measured in metres, irrespective of any particular navigation specification performance requirement. In general, when considering performance for GNSS based applications, reference to a 95% probability should be avoided as it suggests a level of accuracy far below that which provides sufficient confidence to flight crews and, indeed, far less than that observed in actual operations.

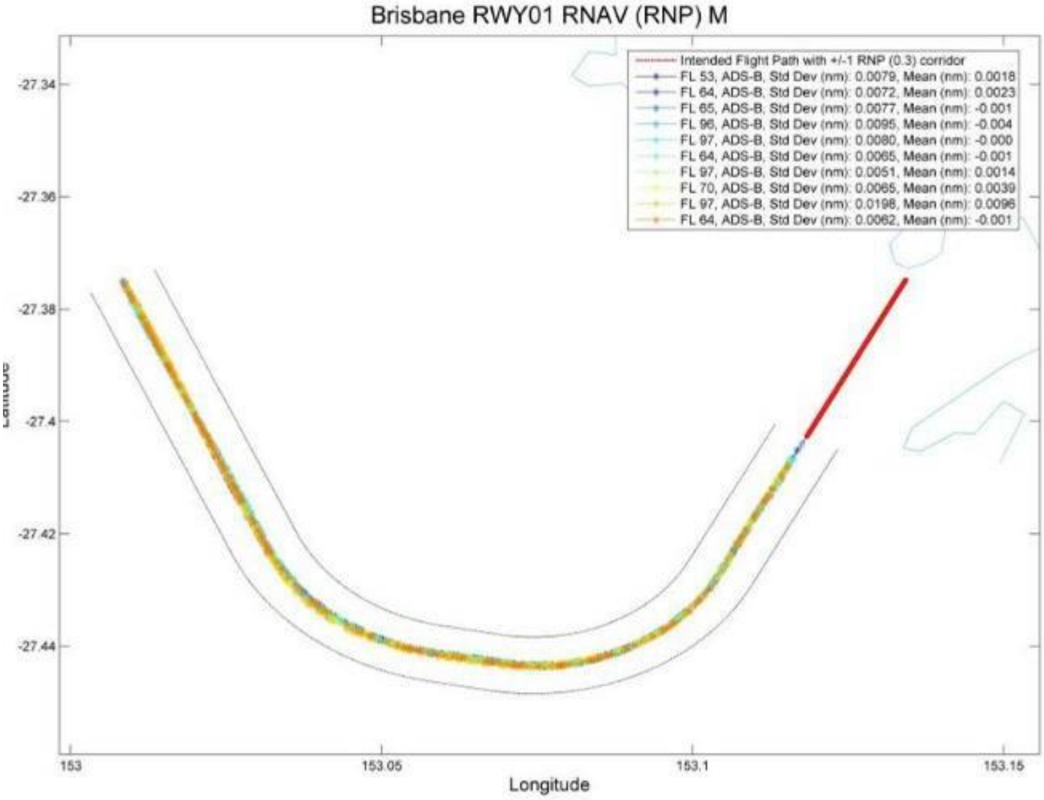


Fig 3.1: In-service tracking data showing TSE in relation to 0.3 NM (1 x RNP) tolerance

Accuracy is only one of a number of considerations when evaluating performance and the overall capability of the navigation system. Cockpit displays, flight control systems and other factors are also considered in determining the aircraft‟s navigation performance capability.

The computation of navigation performance is normally carried out by the aircraft manufacturer, and, in many cases, the manufacturer will provide a statement in the AFM giving the computed capability. However, the basis upon which performance is computed varies between manufacturers and, in some cases, the methodology differs between aircraft types from the same manufacturer.

3.3 Performance Components

Navigation performance is computed by considering the following components:

Navigation System Error (NSE). Sometimes called PEE or Position Estimation Error, this value represents the capability of the navigation avionics to determine position, relative to the aircraft‟s actual position. NSE is dependent on the accuracy of the inputs to the position solution, such as the accepted accuracy of DME or GNSS measurements.

Flight Technical Error (FTE). Also referred to as Path Steering Error, this value represents the ability of the aircraft guidance system to follow the computed flight path. FTE is normally evaluated by the aircraft manufacturer based on flight trials, although, in cases where the manufacturer is not able to provide adequate data, the operator may needto collect in-service data. FTE values will usually vary for a particular aircraft dependingon the flight control method, and, for example, a lower FTE may be applicable to operations where the autopilot is coupled compared to the FTE for manual flight using flight director. This variation may, in turn, lead to different overall performance values, depending on the method of control.

Path Definition Error (PDE). An area navigation route is defined by segments between waypoints. The definition of the path therefore is dependent on the resolution of the waypoint and the ability of the navigation system to manage the waypoint data. However, as waypoints can be defined very accurately and a high level of accuracy is able to be managed by most navigation systems, this error is minimal and is generally considered tobe zero.

Total System Error (TSE) is computed as the statistical sum of the component errors. An accepted method of computing the sum of a number of independent statisticalmeasurements is to compute the square root of the sum of the squares of the component values - the Root Sum Square (RSS) method.

The computation for accuracy is:

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

As discussed, PDE is normally considered to be zero and can be ignored.

No measurement can be absolute and some error or variation will always occur. Therefore, errors are normally stated in terms of the probability of the specified accuracy achieved. For example, the FTE might be described as +/- (X) NM / 95%.

Where accuracy is specified at 95%, the 95% TSE is calculated for the 95% values forNSE and TSE.

The risk that an aircraft capable of a particular navigation performance (95%) will exceed a specified navigation tolerance can then be estimated for any desired probability. It is convenient and reasonably reliable to consider that navigation errors are “normally distributed” and represented by a Gaussian distribution. A Gaussian or normal distribution is a representation of the probable errors that may be expected for many common random events. If the probability of a particular event is known, (e.g. 95% TSE) then, using a Gaussian distribution, the estimated error for another probability can also be calculated.

Standard deviation is a widely used measure of variability or dispersion. In simple terms, it shows how much variation there is from the "average" (mean). It may be thought of as the average difference of the scores from the mean of distribution, how far they are away from the mean. A low standard deviation indicates that the data points tend to be very close to the mean, whereas high standard deviation indicates that the data are spread out over a large range of values.

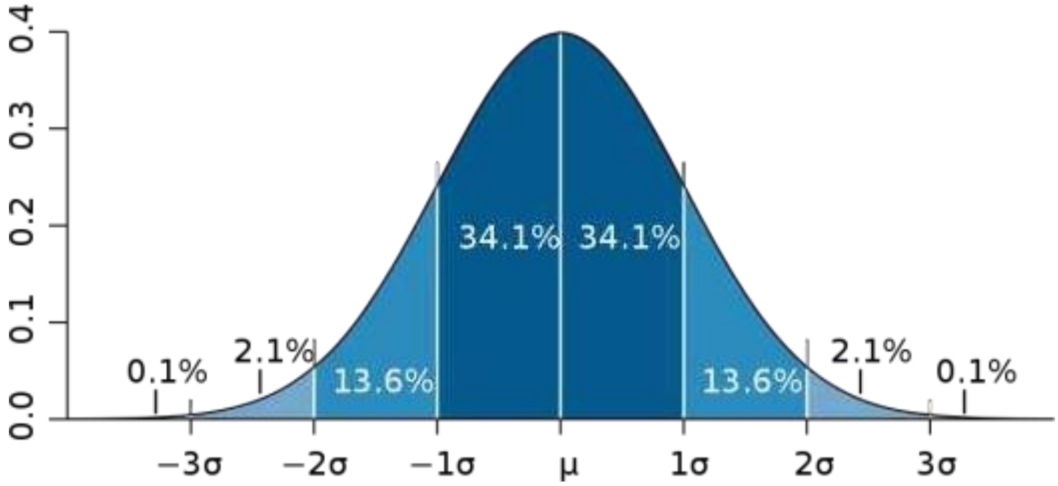


Figure 3.2: A plot of a Gaussian or Normal distribution curve.

In Figure 3.2, each colored band has a width of one standard deviation. The percentage of results within 2 standard deviations of the mean is: 2 x (34.1% + 13.6%) = 95.4%. (A probability of 95% is equivalent to 1.96 standard deviations.)

In the table below, probabilities for various standard deviations are shown.

Standard Deviation	Probability	Fraction
1σ	68.2689492%	1 / 3.1514871
1.960σ	95%	1 / 20
2σ	95.4499736%	1 / 21.977894
3σ	99.7300204%	1 / 370.398
4σ	99.993666%	1 / 15,788

For example, if the demonstrated performance (TSE) is 0.3 NM/95% then the probability that the aircraft will be within 0.6 NM of the computed position can be calculated.

For simplicity, we will assume that the 95% value is equal to 2 standard deviations rather than the actual value of 1.96. Therefore 0.6 NM is equal to twice the 95% value or 4 standard deviations which is equivalent to 99.993666%. This, in turn, can be approximated as 99.99%, which indicates that only .01% of all computed positions will be greater than 0.6NM. For convenience, .01% can be described as 1 in 10,000 or 1 x 10^{-4}.

3.4 Required Navigation Performance

RNP is a means of specifying the performance for a particular type of operation. In order to meet a particular performance level, a number of requirements must be met:

Accuracy. Position accuracy can be defined as the probability that the computed position will be within a specified distance of the actual position. This performance measure assumes the reliability of the computation (i.e. the system is operating within its specification without fault). We have seen in the previous section how this can be computed.

Integrity. For aviation purposes which are safety critical, we must be assured that the navigation system can be trusted. Even though we may be satisfied as to the accuracy of the determination of position, we must also ensure that the computation is based on validor "trusted" information. Various methods (e.g. RAIM) are used to protect the position solution against the possibility of invalid position measurements.

Availability means that the system is usable when required. For GNSS operations, unless augmented, availability is high but normally less than 100%. Operational means are commonly needed to manage this limitation.

Continuity refers to the probability that a loss of service will occur whilst in use.

For RNP operations, the navigation system must meet accuracy and integrity requirements, but operational procedures may be used to overcome limitations in availability and continuity. In addition to the four performance parameters, RNP also requires on-board performance monitoring and alerting.

In practice, RNP capability is determined by the most limiting of the characteristics listed above.

As discussed, in general, RNP is based on a variety of technologies. The position accuracy for GNSS is excellent and can support operations with low RNP. The lowest current RNP in use isRNP 0.10, although considering position accuracy alone, GNSS would be able to support lower RNP.

However, it will be recalled that accuracy is also dependent on FTE and this component is, by far, the dominant factor. Consequently, the RNP capability of GNSS equipped aircraft is dependent not on navigation system accuracy, but on the ability for the aircraft to follow the defined path. FTE is commonly determined by the ability of the aircraft flight control system. The lowest FTE values are commonly achieved with auto-pilot coupled.

A further consideration is the requirement for on-board performance monitoring and alerting. For GNSS systems, navigation system performance monitoring and alerting is automatic. Except in some specific installations, FTE monitoring and alerting is a crew responsibility, and the ability of the crew to perform this function depends on the qualityof information displayed to the crew.

While an aircraft may be capable of a particular RNP capability, it is not always necessary or desirable that the full capability is applied. In addition to the consideration of accuracy and performance monitoring, the operation must always be protected against invalid positioning information, i.e. integrity is required.

In order to support low RNP operations, an appropriate level of integrity protection is necessary. The lower the RNP type, the greater level of integrity protection required, which, in turn, reduces the availability and continuity of the service. Consequently, a trade-off needs to be made between the RNP selected and availability.

CAP 11 Vol. 2 Navigation specifications are based on a level of navigation performance appropriate to the intended purpose, rather than the inherent capability of the navigation system. For example, a GNSS equipped aircraft has very high positioning accuracy, and, if flown using autopilot, exhibits low FTE. However, for terminal SID/STAR operations, RNP 1 is adequate for the intended purpose, resulting in virtually 100% availability and reduced crew workload in FTE performance monitoring.

3.5 Performance Limitations

The overall system performance is limited by the most constraining case. For DME/DME systems, the most constraining condition is likely to be accuracy. The positioning is dependent upon measurements which are limited by the accuracy of DME.

Systems which use GNSS as the primary means of position fixing are, inherently, extremely accurate. The navigation system accuracy is independent of the navigation application i.e. the underlying positioning accuracy is the same for RNP 10 as it is for RNP 0.10.

GNSS system performance is normally dependent on FTE and, in particular, the capability for monitoring and alerting of FTE. In the performance formula $TSE = NSE^2 + FTE^2 + PDE^2$, NSE is small, PDE is considered negligible and FTE becomes the dominant contributor.

FTE is normally dependent upon the capability of the flight control system (A/P or FD) to maintain the desired flight path. This commonly varies with phase of flight. In climb, decent and cruise, the sensitivity of the flight control system is normally less than in the approach phase, for obvious reasons.

Despite the capability of the flight control system to achieve low FTE values, RNP also requires the flight crew to be able to monitor cross-track error and provide an alert if deviation limits are exceeded (normally achieved by flight crew procedures). In many cases, the cockpit display of cross-track error limits the crew‟s ability to monitor cross- track error, irrespective of the demonstrated FTE. This may limit the RNP performance. Some aircraft AFMs contain statements of RNP performance which are valid when the accuracy of the flight control system alone is considered. However, it may be difficult to justify the same performance when the display of cross-track deviation is taken intoconsideration.

GNSS integrity monitoring, consistent with the manufacturer‟s stated RNP performance, is normally provided and is seldom a limitation on overall RNP capability. In practice, however, the satellite system may not be capable of supporting the full aircraft RNP capability, and the available RNP capability can be limited by the satellite constellation.

In Europe, for RNP AR APCH, RNP performance also considers the effect of non-normal events. Different RNP performance may be stated depending on the operational circumstances. Typically, differing RNP values will be published for all-engines operating and one engine inoperative cases. ICAO approach procedure design does not consider non-normal conditions and the all-engines operating RNP is applicable. However, the manufacturer‟s stated limitations should be considered during the FOSA.

Figure 3.3: Difference between FAA and EASA OPS Approval philosophy

3.6 Flight Technical Error Management

FTE is a term that is generally unfamiliar to pilots and operators, although the notion of expected standards of track-keeping is well established. However, as pilots, we have traditionally associated the management of cross-track tolerances with pilot skill levels and flight crew proficiency. This limited concept is no longer adequate, and, for PBN operations, it is somewhat irrelevant, as cross-track error is more commonly managed bythe aircraft system rather than the pilot manipulating the controls. In the PBN context, we need to expand the concept of FTE and therefore there are a number of measuresthat we need to apply.

Demonstrated FTE: As noted previously, the aircraft performance can be determined on the basis of flight trials, depending on the method of control. Pilot skill is less important and, more commonly, FTE is a measure of autopilot performance.

FTE tolerance: The normal cross-track FTE limit for each navigation specification(½ navigating accuracy.)

Procedure Design FTE value: The procedure designer uses a value of FTE in the assessment of lateral flight tolerance computation.

Limiting FTE: An operational limitation is placed on the value of FTE acceptable in flight. Beyond this value the procedure must be discontinued.

In general, accurate adherence to track is expected for all operations. For all normal operations, a deviation of up to ½ the navigation accuracy is considered acceptable. However, it is assumed that any deviation will be corrected and accurate tracking regained. Brief deviations up to 1 x navigation accuracy, during and immediately after turns, are allowable but in practice such deviations should be considered poor technique and action taken to limit such excursions.

However, for most PBN applications, an accuracy of ½ navigation accuracy is not observed in normal operations and a cross-track error of this order would be considered excessive by most pilots and operators.

Figure 3.4: Typical FTE values (NM)

Navspec	Nav Accuracy	Design FTE 95%	PBN Max FTE	Lateral Protection (either side of track)
RNAV 5[1] >30NM ARP	5	2.5	2.5	5.77
RNP 4	4	2	2	8
RNAV 1 (<15NM ARP)	1	0.5	0.5	2
RNP 1 (<15NM ARP)	1	0.5	0.5	2

RNP APCH (MAPt)	0.30	0.25	0.15	0.95
RNP AR APCH (min)	0.10	N/A[1]	0.05[2]	0.20

[1] FTE for RNP AR APCH must be consistent with the RNP capability. Design is based on 2 x RNP obstacle evaluation area either side of track.

[2] A missed approach must be conducted if the FTE exceeds 1 x RNP.
Some inconsistencies may be noted where values have been adopted prior to the development of CAP 11 and ICAO requirements.

Although navigation performance is determined by a statistical calculation, in practice, a limit is placed on cross-track deviations. This effectively cuts off the "tails" of the probability distribution, avoiding the statistically rare but nevertheless real possibility of large cross-track errors. The selection of a point at which the FTE is limited and the flight crew intervenes, (e.g. a go-round), is arbitrary and a matter of judgment rather than mathematics. For RNP AR APCH, mandatory discontinuation of an approach is required if the cross-track tolerance exceeds 1 x RNP.

Note: It can be demonstrated mathematically that for the lowest available RNP (0.10), RNP performance is maintained for cross-track deviations of up to 1 x RNP. As GNSS accuracy does not decrease with increasing RNP, for values of RNP in excess of RNP 0.10, application of a 1 x RNP FTE limit becomes conservative.

However, for RNP APCH, the CAP 11 Vol. 2 requirement implies a mandatory go-round at ½ navigation accuracy. The design FTE for RNP APCH (0.25NM on final) is the value used in the development of RNAV (GNSS) design criteria, prior to the development of ICAO PBN requirements. This value was based on manual piloting tolerances using stand-alone GNSS equipment and a 0.3NM CDI scaling. For FMS equipped aircraft, a go-round requirement of ½ navigation accuracy limit may be impractical in many aircraft. A more general view exists that immediate recovery action should be taken whena deviation exceeds ½ navigation accuracy and a go-round conducted if the deviation exceeds 1 x RNP (0.3).

The validity of the performance capability calculation or the design of the procedures is not in question, as the normal achieved FTE is likely to be extremely small. The issue is merely what indication of a cross-track error, as a trigger for discontinuation, is acceptable. In some cases, this may be higher than preferred. The safety of the operation and the confidence in the navigating accuracy is, in no way, compromised, but the operating procedures may need to recognise the limitations of the display of cross-track information. Reasonable instructions should be provided to the crew regarding the point at which action should be taken.

Training should emphasise that for all PBN operations, accurate adherence to track is required. A misconception exists that for en-route operations, where the navigation accuracy is relatively large (RNP 10, RNP 4, RNAV 5), unauthorised off-track deviations, up to the navigation accuracy, are acceptable without ATC approval. Pilots need to understand that aircraft separation standards are based on the statistical FTE probability assuming that the aircraft follows the defined track as closely as possible. Inspectors should take care to ensure that training programs provide proper guidance on the management of FTE.

3.7 Lateral Deviation Monitoring

The monitoring of FTE requires that suitable information is displayed to the flight crew, indicating any deviation from the lateral or (for VNAV) vertical path. CAP 11 includes some guidance on the use of a "lateral deviation indicator", or as other means, a flight director or an autopilot, to manage FTE. However, in practice, some judgment, on the part of inspectors, is required in order to assess that the information displayed to the flight crew is adequate for a particular application.

No difficulty should be experienced with aircraft equipped with stand-alone GNSS receivers which should be installed to provide a display of cross-track information on aCDI or HSI. Normal TSO C129a and TSO C146a functionality provides automatic full- scale deflection scaling appropriate to the phase of flight and, provided the flight crew is properly trained in the operation of the receiver, suitable indications of cross-track deviations will be available.

Unfortunately, FMS-equipped aircraft are generally not equipped with a course deviation indicator when operated in an NAV mode. This type of installation will therefore require evaluation during the approval process.

Although it is not possible to generalize given the variation between manufacturers of FMS-equipped aircraft, the Navigation Display (ND) is commonly used to indicate the aircraft position relative to the flight planned path. As it is common practice to operate withthe autopilot engaged, track adherence is generally good. Manufacturers have therefore historically not taken the view that the indication of cross-track error, either by the use of a CDI-type graphical indicator or a numerical indication on the ND, is of importance.

With the development of RNAV approach operations, where accurate track adherence is of significance, the suitability of displays has become a topic of interest.

Typical sources of cross-track information in production aircraft include:

Navigation (MAP) Display - Graphical indications: Graphical indication of track deviation relative to the flight planned track. Depending on the selected map scale, the size of the aircraft symbol can be used to estimate the cross-track deviation. For deviations as small as 0.1NM, this type of indication is sufficient to allow for reasonable estimation, depending on the map scale selected and the aircraft symbol. For operations where the cross-track tolerance is relatively large, (RNAV 10, RNAV, RNP 4, and RNAV1 or RNP 1), this may be considered adequate. This type of indication, although limited, is available in the pilot"s forward field of view and, in this regard, satisfies some of the basic requirements for track monitoring.

Navigation (MAP) Display - Numeric indications: In addition to a graphical display of position relative to flight planned track, many manufacturers also provide a digital indication of cross-track deviation on the ND. Commonly, this is limited to one decimal place e.g. 0.1, 0.2, 0.3 NM. Some aircraft apply a rounding to the display of digital cross-track deviation. For example, in at least one case, the display of deviation is not indicated until the deviation reaches 0.15NM, and then a rounded value of 0.2NM is displayed. In this case, the initial digital indication to the crew is 0.2NM which is displayed when the actual deviation is 0.15NM. Similarly, as the XTK deviation reduces, the last digital indication shown is 0.10NM, which occurs when the actual deviation is 0.15NM. Increasingly, manufacturers are offering, as either standard or as a customer option, digital indications to 2 decimal places e.g. .01, .02, .03 NM. Two digital place cross-track deviation indication is becoming the industry standard and operators should be encouraged to select this option, if available. Unfortunately, on older aircraft, this is often not available due to software or display limitations.

Control and Display Unit Numeric Display: Many systems display a numeric indication of cross-track and/or vertical deviation on the CDU (MCDU). In cases where the ND does not provide a numeric display, an initial graphical indication of deviation may be supplemented by a cross-reference to the appropriate CDU page to obtain a numeric indication. Numeric indications may be one or two decimal places. The disadvantage of this indication is that it is not in the primary field of view. When CDU indications are taken into account in the evaluation of the adequacy of cockpit track monitoring, the crew procedures need also to be evaluated. A procedure needs to be in place such that at least one member of the crew (normally the PNF/PM) has the appropriate CDU page displayed during the operation and there is a system of cross-checking and crew callouts in place.

Primary Flight Display (PFD) CDI displays: A number of manufacturers are now offering, either as standard or as a customer option, the display of cross-track deviation on the PFD, in a manner similar to the display used for ILS. A different symbol is used to identify that the information is RNAV rather than LOC. Implementation varies from relatively simple fixed scale displays to more sophisticated displays which provide an estimate of “available” cross- track tolerance based on the current estimate of navigation performance.

3.8 Vertical Deviation Monitoring

Many VNAV indicators have been installed to provide relatively coarse indications of vertical path adherence, intended to provide adequate monitoring for en-route climb/descent and cruise operations. Commonly, this type of display was not intended for use on approach operations where a resolution of as low as 10ft is expected. The size of the display may be quite small and the full scale indication can be a much as +/-400ft.More commonly, a vertical deviation indicator, similar to an ILS glide slope indicator, is provided on the PFD. Numeric indications of vertical deviation may also be available on the CDU.

3.9 Evaluation of Deviation Displays

While each case must be evaluated, some broad guidelines can be applied.

Consideration must be given to the means of flight control. Where AP or FD is the means of flight control, lateral and vertical deviations can be expected to be small. Therefore, displays sufficient only for adequate monitoring of performance are necessary.

1. The display of information is be related to the required navigation tolerance. For en- route and terminal operations, a lesser standard, such as a graphical or basic numeric XTK indication is normally adequate.

2. For RNP APCH operations, the final approach tolerance is half (½) the navigation tolerance i.e. 0.15NM. Consequently, indication of small XTK deviations is necessary. The use of a graphical (MAP) display and a digital XTK indication, either on the ND or CDU, is generally adequate, provided the flight control method (AP or FD) and crew monitoring procedures are appropriate.

3. For VNAV approach operations, a PFD indicator is normally the minimum requirement, although an alternative means might be assessed as adequate provided the crew can readily identify vertical track deviations sufficient to limit the flight path within the required tolerances (- 50ft or 75ft and +100ft).

4. For RNP AR APCH operations not less than RNP 0.3, the same tracking accuracy as for RNP APCH applies. Therefore, a similar standard of display is generally adequate. A CDI indication on the PFD, while preferred, is not essential, as is the display of 2 digit numerical XTK deviation on the ND. As flight control using AP or FD is normally used, adequate procedures should be in place for the crew to manage cross- track error.

5. For RNP AR APCH operations less than RNP 0.3, the generally accepted standard is a graphical display of XTK on the PFD and a numeric display to two decimal places on the ND.

In assessing the displays and procedures for monitoring of XTE, consideration should also be given to functions such as flight path prediction, vertical situation displays, HUGS, etc. It should also be noted that the manufacturer‟s statement of RNP capability is dependent on the method of flight control, which determines the statistical value of FTE used in the demonstration of RNP capability. Some manufacturers and/or regulatory authorities require a minimum standard of cockpit displays for RNP AR APCH operations.

Chapter 4 GNSS

4.1 General

The advent of satellite-based navigation provides significant improvement in navigation performance and it is available to aircraft of all types. Performance Based Navigation is not dependent upon satellite navigation.

It is not within the scope of this volume to cover the basics of GNSS navigation as it is assumed that readers have or will obtain knowledge and training in satellite-based navigation principles and practice.

The discussion of satellite navigation will be related to specific elements of satellite-based navigation that are relevant to PBN operational approvals.

GNSS systems range from stand-alone receivers, now in use in general aviation and commuter airline applications, to Flight Management Systems incorporating composite position. Whatever the installation, the navigation capability of GNSS is excellent, as there is little variation in the positioning accuracy across the various types of installation. However, there are considerable differences in functionality, cockpit displays, integrity monitoring, alerting and other characteristics that must be considered in the operational approval, depending upon the particular navigation specification.

4.2 Monitoring and alerting

An IFR GNSS navigation receiver incorporates, by design, a system to monitor the positioning performance and to provide an alert to the operating crew when the minimum requirements, appropriate to the desired navigation performance, are not available. Consequently, a GNSS navigation system qualifies as an RNP navigation system as it is able to provide the necessary on-board performance monitoring and alerting functions. However, the monitoring and alerting function of the navigation system alone are insufficient for RNP applications; FTE must also be monitored. A number of aircraft equipped with GNSS fail to meet the monitoring requirements for RNP because of a lack of capability for the crew to monitor cross-track deviation.

Previously, many operations utilising GNSS were classified as RNAV operations, such as RNAV (GNSS) approach procedures. In order to be consistent with current I C A O definitions of RNP, RNAV (GNSS), procedures are now classified as RNP APCH procedures, as they fulfil the on-board performance monitoring and alerting requirements associated with RNP systems.

4.3 GNSS Accuracy

The positioning accuracy of GNSS signal in space is dependent upon the satellite constellation and is generally independent of the aircraft systems. Positioning accuracy is excellent and a significant amount of data has now been accumulated which demonstrates that unaugmented GNSS is able to provide accuracy measured in metreswith a high degree of availability over much of the earth's surface.

Whilst navigation specifications may contain an accuracy requirement specified as a 95% probability, when GNSS is used, the underlying accuracy is independent of the navigation specification requirement. An aircraft equipped with GNSS and approved for operations at a particular RNP level e.g. RNP 0.3 is capable of no less accurate navigation whenoperating to another navigation specification such as RNP 1.

It should be recognised that when GNSS is available, navigation position accuracy remains high, irrespective of the particular operation. However, it should also be noted that accuracy is only one consideration in regard to a PBN operation and other factors may limit the approved operational capability.

4.4 Integrity Monitoring

All IFR lateral navigation systems, both conventional and performance based, are required to meet standards for integrity. Integrity represents the trust that we place in the ability of the system to provide navigation information that is not misleading. Whilst a navigation system may provide accurate guidance, in aviation we require assurance that the guidanceis valid under all reasonable circumstances. Various means have therefore been implemented to provide that assurance.

Integrity for conventional navigation aids is indicated either by the absence of a warning flag on a VOR or ILS indicator or the presence of the Morse ident when using an ADF. ForGNSS systems, a loss of integrity availability is indicated by an annunciation (in various forms) displayed to the flight crew.

GNSS systems employ a variety of methods to monitor the integrity of the navigation solution, the most basic being Receiver Autonomous Integrity Monitoring or RAIM.

This type of monitoring system is generally associated with (but not limited to) stand- alone general aviation receivers. Other types of integrity monitoring include proprietary hybrid systems which integrate inertial navigation with GNSS positioning to provide high levels of availability of navigation with integrity.

Unfortunately, the term RAIM is erroneously used to describe integrity systems in general. This can therefore lead to some misconceptions of the role and application of integrity monitoring to performance based navigation.

4.5 Fault Detection

Integrity and accuracy are both required for valid GNSS navigation. However, although in some ways related, they are entirely different parameters and should not be confused.

The GNSS receiver, GNSS satellites, ground monitoring and control stations all contribute to providing a valid navigation system, each element incorporating fault detection protection. A GNSS receiver continuously monitors the computed position and it will detect and annunciate a fault if the position solution is not within defined limits.

However, the ability of a GNSS receiver to detect a fault is limited by the extremely low GNSS signal strength. GNSS satellites radiate a low power signal from some 20,000 km in space which reduces in inverse proportion to the square of the distance. The usable signal is therefore very weak and below the general ambient signal noise level. Normally, a fault will be detected despite the low signal strength; however in rare circumstances the ability to detect a fault can be limited by the noise level, constellation geometry and other factors. Therefore, for commercial aviation applications, a means is necessary to protect the user against the unlikely but nevertheless real possibility that a fault might not be detected.

RAIM uses a mathematical solution to protect against this rare condition. The receiver calculates in real time a parameter called Horizontal Protection Level (HPL) in order to protect the navigation solution against a *potential* navigation fault.

4.6 Horizontal Protection Level

HPL is the radius of a circle in the horizontal plane with its centre being at the true position, such that the probability that an indicated position being outside the circle, but not detected, is less than 1 in 1000. That is, the receiver calculates a level of protection currently available based on the geometry of the satellite constellation. As the position of the satellites in view is constantly changing, HPL also continually changes.

HPL is a parameter, as the name suggests, designed to provide integrity *protection* rather than error *detection*. Unfortunately, it is a common misconception that the actual position "floats" anywhere within the HPL radius. The actual navigation solution, as evidenced by a substantial body of observations over many years, remains very accurate. The function of HPL is to *protect* the navigation solution against the possibility that, in the unlikely event that a satellite ranging error should occur, the risk of a missed detection is reduced to an acceptable probability.

In normal circumstances, should a satellite ranging error occur which results in an out-of tolerance solution, the GNSS system will detect the fault and provide an alert. The problem is that we cannot be certain that the fault detection system will always work, so, as discussed, due the ambient noise level, under certain circumstances, a fault could bemissed. So if we cannot be 100% sure about the detection system, something else must be done. That is where RAIM and HPL (or an equivalent protection system) come in.

The way this is done is to program the receiver to calculate, in real time, based on the actual satellite geometry, a worst case scenario which provides an acceptable level of confidence that should a real fault occur, it would be detected. Note that we are not talking about detecting a fault right now, but rather that we are protecting a region around the indicated position, just in case a fault should happen at any time in the future. That potential fault may never occur, but we can be confident that, if it did, we are protected.

HPL provides for a number of “worst case” circumstances. As GPS position is a triangulation of pseudo-range measurements from satellites, any ranging error from one of those satellites has the potential to result in an inaccurate solution. A failure in the US GPS satellite system is any ranging error greater than 150m. However, as any position solutionis a computation dependent on a number of range measurements, the ranging error would need to be significantly greater to be a problem. In addition, the HPL computation assumes that only the “worst” satellite fails, when, in reality, any one of the satellites used in the position solution has equal probability of failure. The “worst” satellite wouldbe one lower to the horizon, as any ranging error will bias the lateral position more than a satellite which is closer to overhead.

Depending on the date when the receiver was manufactured, the HPL calculation may also assume that Selective Availability is still active. Consequently, when conducting RNP operations, observers may note differing “performance” displayed in the cockpit between aircraft operating in the same position and time, where SA is assumed active in the HPL calculated by one aircraft and not active in another. This effect also has a bearing on RNP availability prediction results.

Consequently, there is some in-built conservatism in the computation of HPL.

For each phase of flight, the maximum acceptable HPL is limited by a Horizontal Alarm Limit (HAL). For stand-alone GPS receivers, the HAL for each phase of flight is fixed (0.3 approach, 1.0 terminal. 2.0 en-route). For other navigation systems, the limit can be selected by database or crew input. For example, in an aircraft where the RNP is selectable, changing the RNP (in general) has the effect of changing the limiting HPL. However, this selection has no effect on the accuracy of the position.

From an operational approval perspective, it important to understand that the GNSS position solution is very accurate and that the aircraft position is reliably defined by the very small navigation system error and the relatively large flight technical error. Consequently, operational considerations should be based on the acknowledged and reliable guidance available, rather than the misconception that the actual position is randomly located within the area that is defined about the intended flight path that we protect.

For example, when operating procedures rely on the alignment of an RNP approach with the landing runway, we can be confident that the aircraft will reliably be on track.

At the same time, we must also understand that, despite the observed accuracy, it isnecessary to provide an area of "protection" around the aircraft flight path, so that if at some time, whether in the next 30 seconds or 30 years, a satellite ranging fault of sufficient magnitude were to occur, the aircraft will either be within the protected area or a fault annunciated.

Integrity is our insurance policy and we do not operate without it in IFR aviation. But just as in day-to-day life, although we make sure our policy is paid up, we do not run our lives based on our insurance policies.

4.7 Integrity Alerting

For aviation applications, it is accepted that integrity is essential and therefore operations are predicated on the availability of an integrity monitoring system, and the absence of an alert. However, as discussed above, the computed HPL will vary depending upon the geometry of the constellation, and the maximum value of HPL is determined by the HAL appropriate to the particular operation. If the number of satellites in view is reduced, or the position of satellites is poor, then the ability to detect a potential fault reduces and the computed HPL consequently increases. If, for example, for the particular phase of flight, the computed HPL exceeds the HAL, then the required level integrity is determined to be not available, and an alert is generated.

Note: The condition HPL <HAL is only one example of a limiting integrity condition. There are a number of systems which provide equal or better integrity monitoring which may not depend on HPL.

Alerts vary depending upon the type of system, aircraft and avionics manufacturer, but typical alerts are:

- RAIM NOT AVBL
- LOSS OF INTEGRITY
- UNABLE REQD NAV PERFORMANCE RNP
- GPS PRIMARY LOST

Fig 4.1: Alert annunciated on Boeing 737NG navigation display

4.8 Loss of Integrity Monitoring Function

Whilst it is accepted that integrity is fundamental to safe aviation operations, the unavailability of the integrity monitoring function is not, in itself, an indication of a degradation of navigation accuracy. Although both HPL and the computed position accuracy are both a function of satellite geometry, a loss of integrity monitoring is not normally accompanied by an observed degradation in accuracy. Integrity monitoring protects against a potential failure so a loss of the integrity function means that that protection is no longer available, not that a failure has necessarily occurred. The number of actual satellite failures in the US GPS system is small given the number of years since commissioning.

In normal operations, where the safety of flight is affected (e.g. approach operations), a loss of integrity protection is reason for discontinuation of a GNSS operation. However, in an emergency situation, a loss of integrity monitoring is unlikely to be accompanied by a loss of navigation accuracy and flight crews should exercise good judgment in selecting the best course of action, given the circumstances of the emergency.

4.9 Availability Prediction

Commonly, receivers include a prediction function. However, their use is limited as information on known or planned satellite outages is not included. More accurate predictions are available from commercial and State sources which include up-to-date information on the health of the constellation.

Any prediction of availability needs to provide the operating crew and dispatchers with an accurate indication that the aircraft can conduct a particular operation without an alert being generated. Irrespective of the method used to predict availability, it is the generation of a cockpit warning that precludes the successful completion of an operation. Therefore, it is advantageous to ensure that the prediction method represents the aircraft alerting system as closely as possible.

The computation of availability is complicated by the variations in the methods used to provide integrity protection. For basic stand-alone GNSS receivers, alerting limits are fixed (e.g. HPL < 0.3 in approach mode), but for other installations, integrity alerting is based on more complex analysis and/or more sophisticated integrity monitoring systems. Consequently, for accurate integrity protection, the actual technique applicable to the particular aircraft and navigation equipment must be applied. For RNP AR APCH operations, where a number of lines of RNP minima may be available, availability prediction needs to be related to the various levels of RNP.

The prediction of the availability of a navigation service with integrity is useful as it permits the flight crew or dispatcher to take into account the probability of a loss of serviceand plan an alternative course of action such as delay, rescheduling or selection of an alternative means of navigation.

In some RNP systems, the required level of performance is able to be maintained for some time after the loss of the GNSS signal, (normally with IRS coasting) and an alert is not annunciated until the performance is computed to have reached the relevant limit. Advanced hybrid (IRS/GNSS) integrity monitoring systems are able to provide GNSS position with integrity for long periods (e.g. 45 minutes) after a loss of the GNSS signal.

4.10 Augmentation systems

The majority of Performance Based Navigation operations are able to be conducted using an unaugmented GNSS signal in space. The general GNSS signal is sometimes referred to as an Aircraft Based Augmentation System (ABAS), although this may lead to the misconception that some correction is made to the basic GNSS signal.

The currently available augmentation systems rely on either Ground-Based augmentation (GBAS) or Satellite Based augmentation (SBAS). GBAS relies on an array of receivers located close to the area of operations and supports operations such as GLS (GBASLanding System). In the United States, GBAS is referred to as the Local Area Augmentation system or LAAS. Europe has a similar system called EGNOS.

SBAS, which is represented in the United States by the Wide Area Augmentation System, employs additional geo-stationary satellites and a network of ground-based reference stations, in North America and Hawaii, to measure small variations in the GPS satellites' signals in the western hemisphere. Measurements from the reference stations are routed to master stations, which queue the received Deviation Correction (DC) and send the correction messages to geostationary WAAS satellites in a timely manner (every 5 seconds or better). Those satellites broadcast the correction messages back to earth, where WAAS- enabled GPS receivers use the corrections, while computing their positions, to improve accuracy and integrity.

An SBAS system is capable of supporting all navigation specifications requiring GNSS. In addition, an SBAS system provides capability for Satellite based APV approach procedures which are classified, in terms of ICAO requirements, as a type of RNP APCH operations. This type of approach operation is referred to as Localiser Performance with Vertical guidance or LPV and provided ILS-like guidance to a DA of not lower than 200ft.

LPV operations are designed to be compatible with existing flight guidance installations and provide lateral and vertical course guidance which varies in sensitivity with distance from the runway, much like an ILS.

Chapter 5 ROUTE DESIGN

5.1 Protected Area

PBN flight paths are protected by an area surrounding the intended flight path based upon the navigation system performance and other factors.

The protected area is used to assess clearance from terrain and obstacles and may also be used to establish lateral separation between routes. Details on the computation ofprotected areas are contained in ICAO Doc 8168 PANS OPS Volume II and ICAO Doc 9905 RNP AR Procedure Design Manual.

5.2 RNP AR APCH

RNP AR APCH route segments are protected by rectangular volume defined by a minimum obstacle clearance (MOC) applied to distance 2 x RNP either side of track.

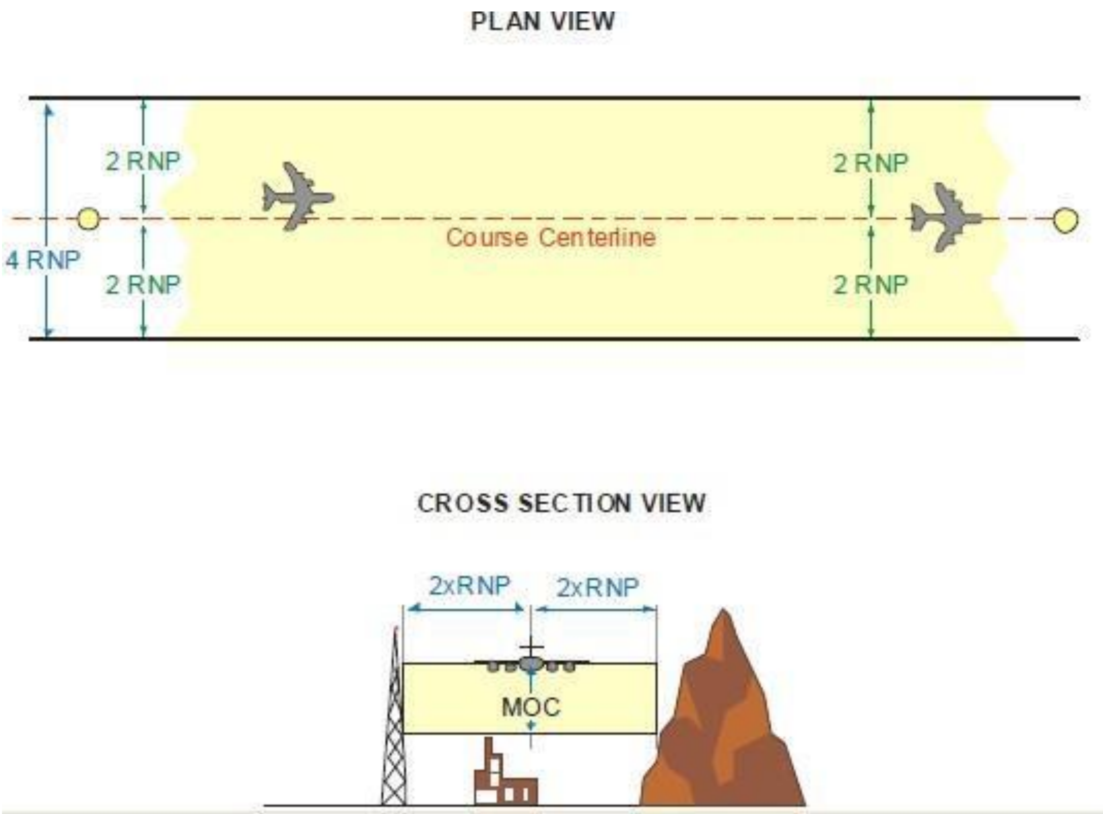


Figure 5.1 RNP AR APCH Obstacle Clearance

5.3 RNP APCH

RNP APCH route segments are protected by variable lateral areas and a minimum obstacle clearance (MOC) applied to primary and secondary areas. The lateral dimensions of the protected area are based on 1.5 x the navigation tolerance associated with the segment plus a buffer value.

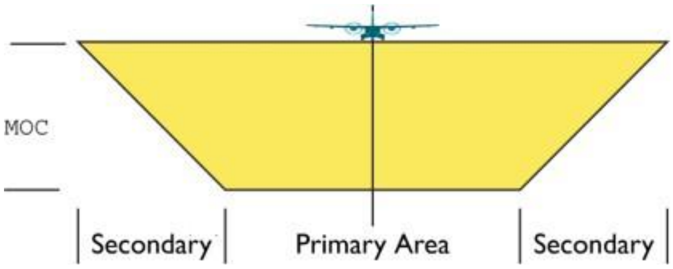


Figure 5.2: Primary and Secondary Areas

Segment	Navigation Tolerance	Buffer Value	Lateral Protection (either side of track)
Initial/intermediate	1.0	1.0	2.5
FAF	0.3	1.0	1.45
Final (MAPt)	0.3	0.5	0.95
Missed approach	1.0	0.5	2.0

Figure 5.3: Typical lateral protection values for RNP APCH (NM)

5.4 En-route and Terminal

RNAV and RNP terminal and en-route segments are protected in a similar manner to RNP APCH. Lateral protection areas are defined by 1.5x the navigation accuracy plus a buffer value. Obstacle clearance protection is not included in PANS-OPS for RNAV 10.

Figure 5.4: Typical lateral protection values for En-route & Terminal Navspecs (NM)

Navspec	Navigation Tolerance	Buffer Value	Lateral Protection (either side of track)
RNAV 5[1] >30NM ARP	2.51	2	5.77
RNP 4	4	2	8
RNAV 1 (<15NM ARP)	1.0	0.5	2
RNP 1 (<15NM ARP)	1.0	0.5	2

[1] Based on GNSS. Different values apply to DME/DME routes.

Chapter 6 BAROMETRIC VERTICAL NAVIGATION

6.1 General

CAP 11 Volumes 2 and 3 do not include a navigation specification for Barometric Vertical Navigation. (For guidance on the application of Baro-VNAV (see ICAO Doc. 9613, Vol. 2, Attachment A).

Baro-VNAV has application in PBN operations for RNP AR APCH and RNP APCH. For RNP AR APCH operations, vertical guidance is currently dependent upon Baro-VNAV and is integral to this type of 3D or APV operation. For RNP APCH operations, vertical guidance is not mandated but may be achieved by the use of Baro-VNAV. Other forms of vertical guidance for both RNP AR APCH and RNP APCH operations (e.g. SBAS) are expected to become available.

6.2 Baro-VNAV Principles

Barometric VNAV has been available for many years on a wide range of aircraft and was developed essentially to permit management of climb, cruise and descent in the en-route and arrival/departure phases of flight. More recently, Baro-VNAV systems have been adapted to provide vertical guidance in the approach phase and, specifically, in the final approach segment, permitting vertically guided approach procedures, typically to a Decision Altitude as low as 75m (250ft).

There are a number of vertical navigation systems in use which provide some means of managing the flight path in the vertical plane. However, many such systems are not able to provide guidance along a specific vertical flight path to a fixed point, for example, the runway threshold.

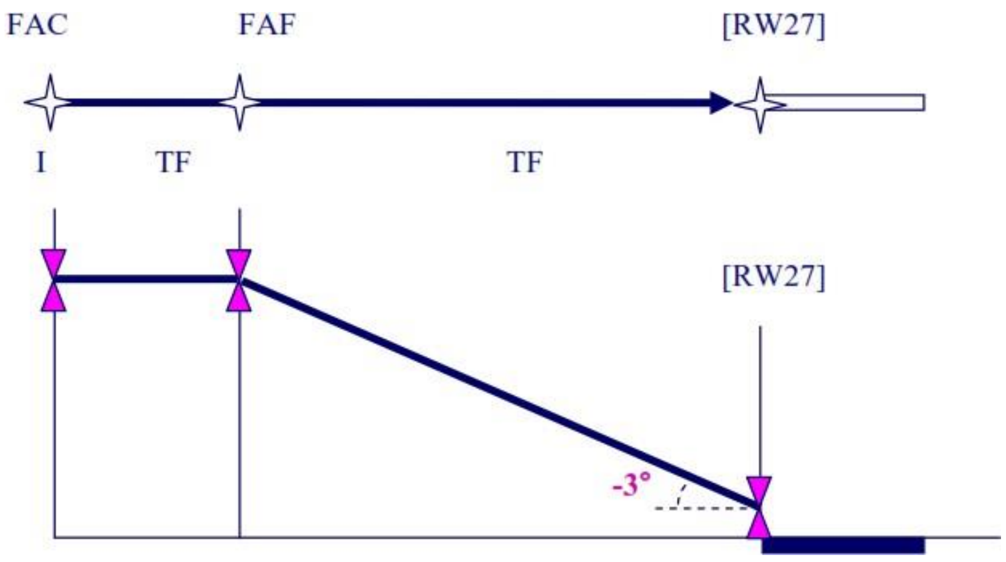


Figure 6.1: Construction of Vertical Flight Path

For Baro-VNAV approach operations, the following elements are required:

(a) an area navigation system to enable distance to be determined to a waypoint that is the origin of the vertical flight path;

(b) the vertical flight path angle from the origin waypoint (normally the runway threshold) coded in the navigation database;

(c) a barometric air data system of sufficient accuracy;

(d) a flight guidance system able to provide vertical steering commands;

(e) cockpit control and monitoring displays.

Based on the distance to the origin of the vertical flight path and the specified vertical flight path angle, the FMS computes the required height above the runway threshold or touchdown point and provides data to the aircraft flight guidance system and cockpit displays.

Although, in some respects, a Baro-VNAV-guided approach procedure is similar to an ILS in operation, a fundamental difference is that the actual vertical flight path is dependent upon measurement of air density which changes with ambient conditions. Consequently, the actual vertical flight path will vary, depending on the surrounding air mass conditions. The specified vertical flight path angle is therefore relevant only to ISA conditions. In anything other than ISA conditions, the actual flight path angle will be higher or lower than designed.

Temperature is the major factor. In temperatures above ISA, the actual flight path will be steeper than coded, and, conversely, below ISA temperatures will result in a lower flight path. Temperatures below ISA are therefore of concern because the clearance above terrain or obstacles will be reduced. Above ISA temperatures result in a steeper flight path which may lead to energy management issues. Temperature variations will also result in a lack of correlation between the barometric vertical flight path and the fixed vertical flight path guidance provided by visual flight path guidance (VASIS) and ILS. Flight crew training must include a study of barometric VNAV principles and the effects of temperature to enable crews to understand the variable nature of the barometric VNAV generated flight path.

Procedure design for approaches with barometric vertical guidance takes into account these effects. Maximum and minimum temperature limits may therefore be published on approach charts to ensure obstacle clearance is maintained and steep approach gradientsare avoided. Some barometric vertical navigation systems incorporate temperature compensation which enables the coded flight path angle to be flown without variations due to temperature. For such systems, temperature limits may not apply.

A number of barometric vertical navigation installations are limited by the cockpit indications and may not be suitable for approach operations. Many such systems, while able to provide adequate vertical navigation capability, were not designed with approach operations in mind. Cockpit displays providing indications of deviation from the vertical flight path which, although adequate for climb, cruise and descent, are insufficient for monitoring of flight path in the approach phase.

As the vertical flight path is dependent upon the measurement of air density and is generated in relation to a barometric datum, any error in the setting of barometric pressure results in a direct vertical error in the vertical flight path. An error in barometric subscale setting results in a vertical shift of the flight path of 9m (30ft) per HPa. An error of 10HPa therefore can cause a vertical error throughout the approach of 90m (300ft). It is therefore necessary that the operational approval includes an evaluation of cockpit altimeter setting procedures and the use of other mitigation systems, such as RADALT and TAWS/EGPWS.

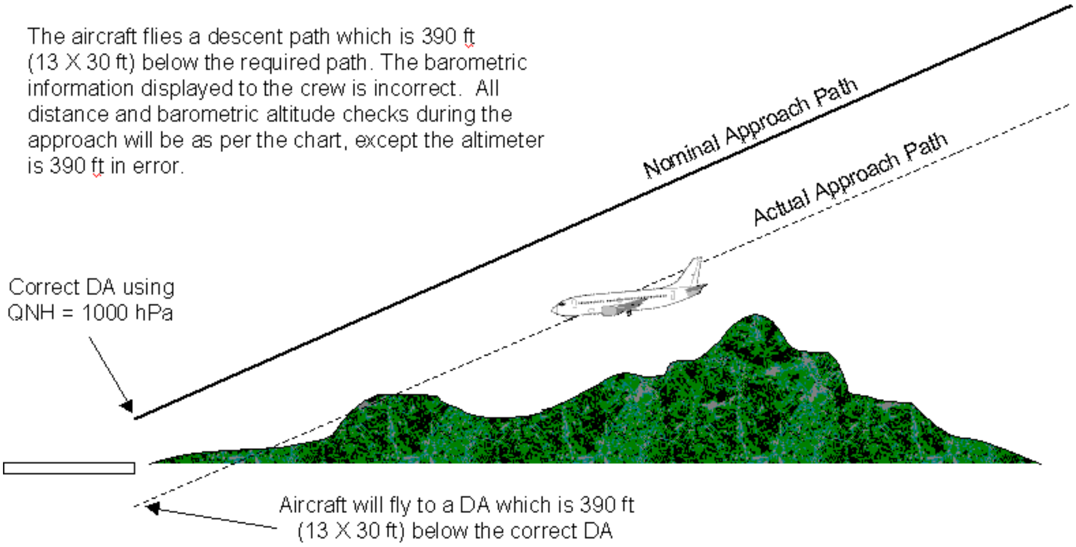


Figure 6.2: Effect of miss-set altimeter subscale on Baro-VNAV vertical path

6.3 Limitations of the Baro-VNAV System:

(a) Nonstandard temperature effect.

(b) Subscale setting round down.

(c) Miss set altimeter subscale.

Non standard temperature effect.

During ISA atmospheric conditions, the altimeter will read correctly and cause the aircraft to fly along the design or nominal profile. If the temperature is above ISA, the altimeter will under read, causing the aircraft to fly an actual profile which is above the nominal profile. The altimeter error is in the order of 4% per each 10 degrees of ISA deviation timesthe height above the airport reference datum. As the altimeter error is related to height above the airport datum, the vertical offset reduces as the aircraft nears the threshold. Typically on an ISA +20 day, the aircraft will be 20 feet above the nominal profile at 250 feet reducing to only 4 feet at the threshold.

Similarly, for each 15º difference from ISA, the VPA will vary by approximately 0.2º i.e. on an ISA + 15 day, the actual flight path angle for a 3º nominal VPA will be 3.2º. Consequently, if the average operating conditions differ significantly from ISA conditions, it is best to use a VPA which will result in an actual VPA in the most common conditions. In the case above, a design VPA of 2.8º would result in an actual VPA close to 3º in average operating conditions. If the atmosphere is below ISA, the effect is reversed with the aircraft below the nominal profile by the same amount. It should be noted that this temperature effect is apparent on all approaches which use barometric altimetry to derive a profile. Inspectors should consider that, whilst this effect is not new, increased awarenessof this effect should be considered during training where Baro VNAV is intended to be deployed. Crews must understand this effect and be aware that a lack of harmonisationwith visual approach slope aids may occur and, indeed, should be anticipated in temperatures which are non-standard.

Subscale setting round down.

Air navigation service providers generally round the subscale setting down. This has the effect of causing altimeters to under-read, causing the aircraft to fly above and parallel to the nominal profile. The effect is small but most pronounced when operating in HPA. Ifthe tower read-out is 1017.9 hPa, the aerodrome QNH will be reported as 1017. This will cause an above nominal path offset of 27 feet. Inspectors should consider that, whilst this effect is unlikely and small, increased awareness of this effect must be considered during training where Baro VNAV is intended to be deployed.

Miss-set altimeter subscale.

Altimeter subscales can be miss-set for a variety of reasons. The effect has been previously discussed. It is important to remember that this issue is not unique to Baro-VNAV operations. Any approach which relies on barometric information for vertical profile will be affected by a miss-set altimeter subscale.

Depending on the aircraft equipment, there are a number of mitigations that contribute to reducing the risks associated with miss-set altimeter subscale. Inspectors must consider the following mitigations when evaluating baro VNAV operations and flight crew training.

Barometric VNAV Mitigations:

Procedural Mitigations:

(a) Independent crew check when recording destination altimeter subscale setting.

(b) Effective crew procedures for setting local altimeter subscale setting at transition level.

Electronic Mitigations:

(a) Electronic alerting if altimeter subscale setting is not reset at transition.

(b) Electronic alerting of altimeter differences.

(c) Terrain Awareness System (TAWS) which incorporates terrain clearance floors along with an accurate terrain model for the intended destination.

(d) Effective crew procedures in support of the TAWS alerts.

6.4 Aircraft Capability

Baro-VNAV systems in common use have normally been approved in accordance with airworthiness requirements that were developed prior to the application of Baro-VNAV systems to approach operations. For example, compliance with FAA AC 20-129 *Airworthiness Approval of Vertical Navigation (VNAV) Systems for use in the U.S. National Airspace system (NAS) and Alaska* is commonly used as the basis for the operational approval of Baro-VNAV operations. The vertical navigation accuracy values for the VNAV system, flight technical error and altimetry contained in such documentation may not be considered sufficient to adequately demonstrate the required level of capability. Operational approval may therefore need to take into account other data, operating procedures or other mitigations.

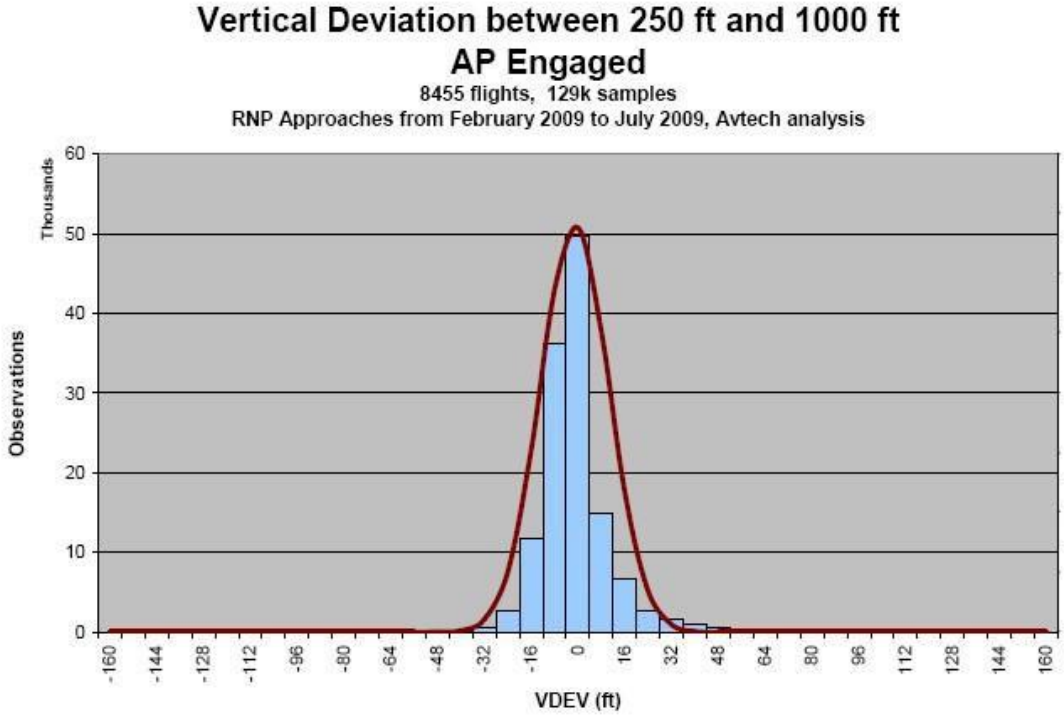


Figure 6.3: In-service Baro-VNAV FTE data

Despite any perceived limitation in the airworthiness documentation, properly managed Barometric VNAV operations in modern air transport aircraft have been demonstrated to provide a high standard of flight guidance. The availability of positive vertical flight guidance offers significant improvement in safety and efficiency over non-precision approach procedures.

Where documentation of barometric VNAV performance is considered insufficient, operational data from in-service trials (e.g. in visual conditions) may be useful in determining the actual in-flight performance for some aircraft.

6.5 Flight Procedure Design

Some basic knowledge of barometric VNAV procedure design is necessary in order that operations are consistent with the assumptions made in the design of approach procedures.

ICAO Doc 8168 PANS OPS and ICAO Doc 9905 RNP AR Procedure Design Manual provide criteria for the design approaches using barometric vertical navigation. Baro VNAV criteria in PANS OPS are applied to the design of RNP APCH procedures. RNP AR Procedure Design Manual criteria are applied to the design of RNP AR procedures.

The basis for VNAV design differs between PANS OPS and the RNP AR Procedure Design Manual.

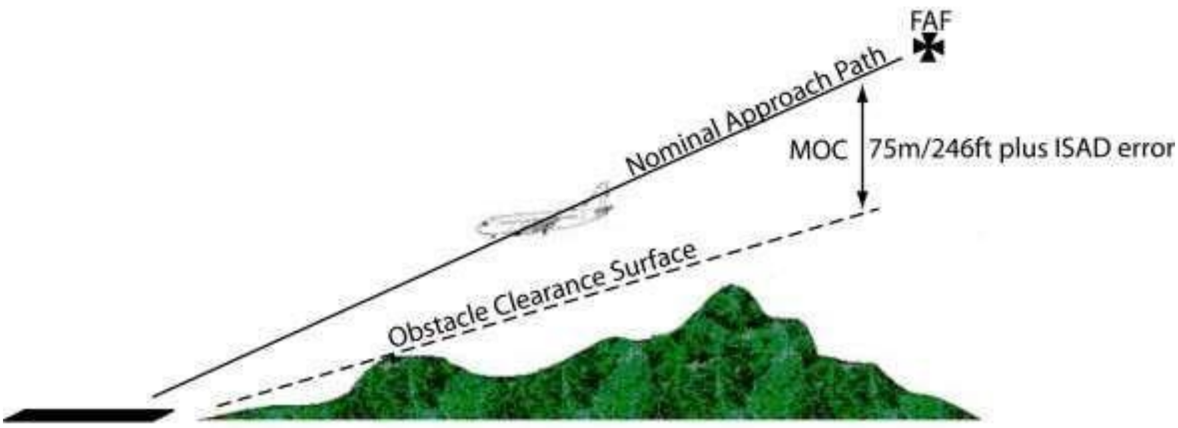


Figure 6.4: RNP APCH (LNAV/VNAV) Final Segment Obstacle Clearance

PANS OPS applies a fixed Minimum Obstacle Clearance (MOC) of 75m (246ft) to the VNAV flight path. This MOC is assumed to provide sufficient clearance from obstacles to accommodate all the errors associated with the ability of the aircraft to conform to the designed flight path. Adjustment to the obstacle clearance surface to allow for low temperature conditions is also applied. No analysis of the individual contributing errors, including Flight Technical Error (FTE), is made. However, guidance to pilots is provided in Volume 1 of Doc 8168 which requires that FTE is limited to 50ft below the VNAV profile. This value is not directly related to either the procedure design MOC or the aircraft capability.

RNP AR APCH procedures, which are designed in accordance with criteria in the RNP AR Procedure Design Manual, utilise a variable obstacle clearance below the VNAV flight path, called the Vertical Error Budget (VEB). The VEB is computed as the statistical sumof the individual contributing errors, including FTE, altimetry system error (ASE) and vertical angle error. The MOC is computed as 4 times the standard distribution of the combination of all the errors. Except for some fixed values, the errors are combined by the root sum square method (RSS).

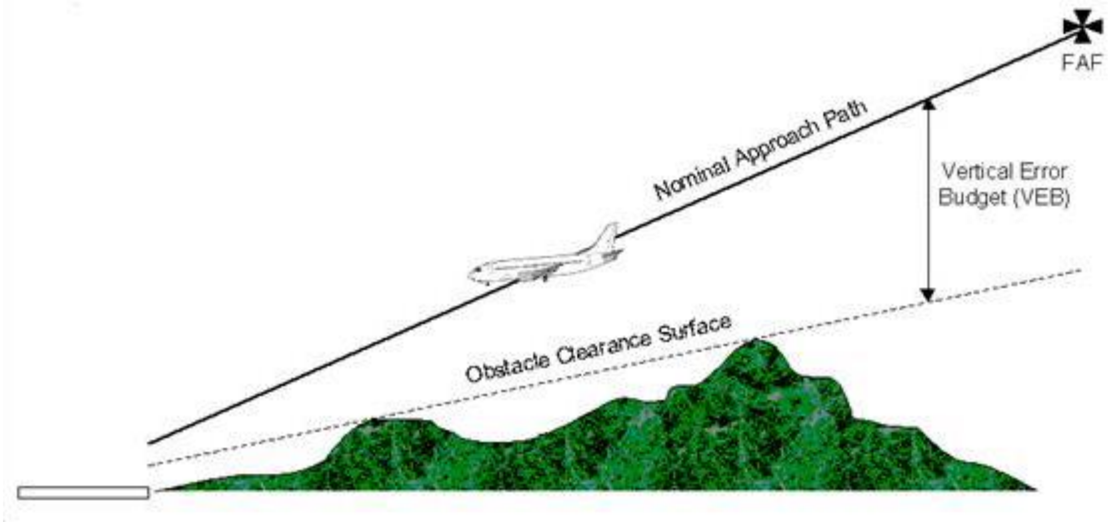


Figure 6.5: RNP AR APCH Vertical Error Budget

The value used for the 95% probability FTE is 23m (75ft). That is, it is expected that an aircraft is capable of following the defined VNAV path +/- 23m for 95% of the time. For most aircraft, the manufacturer is able to provide data to show that this value can be met and, in many cases, the capability is much better. In some cases, the applicant for operational approval may need to provide additional information, analysis or data to substantiate the capability to meet the required level of FTE. Despite the statistical computation of the VEB, CAP 11 Vol. 2 RNP AR APCH navigation specification also requires that flight crews monitor vertical FTE and limit deviations to less than 23m (75ft) below the VNAV profile.

Note: It is proposed that the limit on vertical FTE for RNP APCH operations is amended to 23m/75ft to be consistent with RNP AR APCH operations.

6.6 Baro-VNAV Operations

Baro-VNAV operating procedures for RNP APCH and RNP AR APCH operations are fundamentally the same, despite the differences in procedure design. Operators should therefore be encouraged to adopt common standards in the cockpit.

The design of Baro-VNAV approach procedures is applicable to the final approach segment (FAS). Outside the FAS, procedure design is based on minimum altitudes. Consequently, while the aircraft‟s barometric vertical navigation system is normally available for use in all phases of flight, for an approach using Baro VNAV and all RNPAR APCH procedures, the aircraft must be established on the vertical flight profile with theappropriate vertical navigation mode engage prior to passing the FAF. (e.g. VNAV PATH or FINAL APP mode). Approach operations must not be conducted using modes that are not coupled to the VNAV flight path (e.g. VNAV SPD).

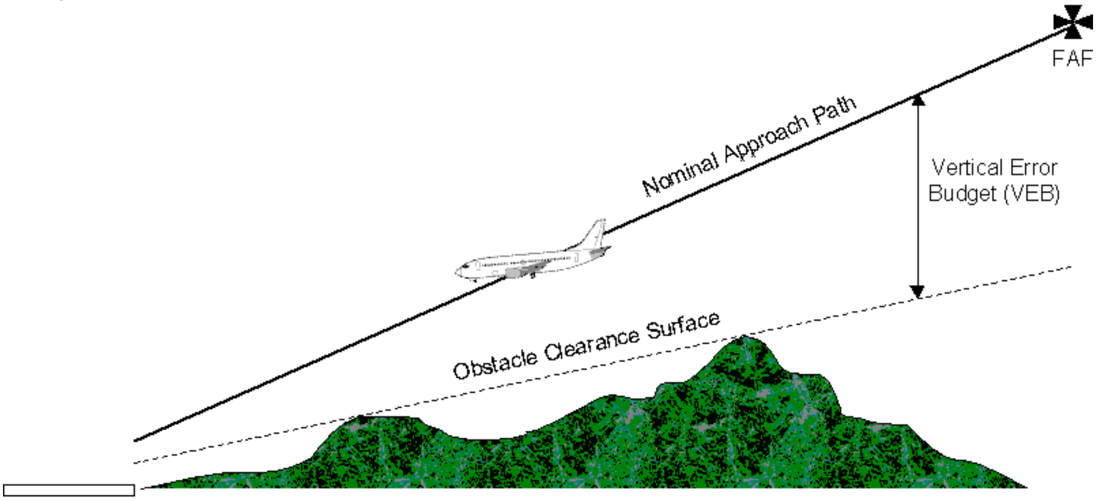


Figure 6.5: RNP AR APCH Vertical Error Budget

It is preferable that the aircraft is established on the vertical profile at some point prior to the FAF. it is therefore becoming increasingly common to nominate on an approach charta point known as the Vertical Intercept Point (VIP). The VIP location is best determined ona case-by-case basis by negotiation between procedure designer, operators, and ATC. The VIP is useful in identifying to ATC the latest point at which the aircraft needs to be established. This concept is therefore similar to the well-established air traffic control practice of establishing an aircraft on an ILS prior to the glide path intercept point. ATC vectoring rules should also require that if an aircraft is either taken off track or is vectoredto join the approach inside the IAF, then both lateral and vertical tracking are established atsome distance (commonly 2NM) prior to the VIP.

As noted earlier, VNAV operating procedures must ensure that the correct altimeter subscale setting is used.

While barometric VNAV operations provide significant safety benefits over non-precision approaches, mismanagement of the VNAV function can introduce significant risk. During the operational approval process, great care and attention should be made to examine the VNAV system management, mode control, annunciation and logic. Crews need to be well trained in recognising situations which can lead to difficulty such as VNAV path capture (from above or below), the effect of speed and altitude modification on approach logic and other characteristics. In some installations, in order to protect the minimum airspeed, mode reversion will cause the aircraft to pitch for airspeed rather than to maintain the flight path. Descent below the vertical flight path may therefore not be obvious to the flight crew.

It is recommended that the final approach segment for barometric VNAV approach is flown with autopilot coupled. Consideration should also be given to the manufacturer's policy and the aircraft functioning at the DA. In some cases, lateral and vertical flight guidance remains available and continued auto-flight below the DA is available. This can be of significant advantage, particularly in complex, difficult or limited terrain and runway environments where continued accurate flight path guidance is available below the DA, thereby reducing potential deviations in the visual segment. Other manufacturer's (and States) adopt different policies where lateral and vertical flight guidance is not available below the DA.

The evaluation of crew procedures and training must include an assessment of the effect that the loss of flight guidance has on safe operations, particularly where the approach procedure does not conform to the normal design rules (e.g. offset final approach or non-standard approach gradient.)

Chapter 7 AIRCRAFT QUALIFICATION

7.1 Eligibility

In the process of issuing an operational approval for PBN, it is necessary to establish that the aircraft and its navigation and other systems are suitable for the specific operation. For PBN operations the AFM must state the exact performance and capabilities of the aircraft systems.

Operational approval needs to consider the capability, functionality, performance and other characteristics of the navigation and other relevant flight systems against the requirements of the particular PBN operation and determine that the operation is sound.

The term "eligibility" is used to describe the fundamental aircraft capability. However, considerable additional evaluation may be needed before an eligible aircraft is determined to be adequate for the issue of an operational approval.

Operational approval process can only be granted to aircraft that have exact specifications in the AFM.

7.2 Aircraft Evaluation

The AFM shall include a statement of RNAV or RNP capability, which often leads to the assumption that the aircraft is approved for a particular PBN operation. The operator must demonstrate that in addition to the aircraft being certified they have crew training and maintenance support.

7.3 Functionality

An area of aircraft capability that generally involves some attention during the operational approval process, is the evaluation of navigation functionality and cockpit control, display, and alerting functions. Many area navigation systems were designed and installed at a time when some of the PBN applications were not envisioned and therefore the need for certain functionality was not considered necessary. These circumstances do not mean that the installed equipment is not capable of PBN operations but, in some cases, the design is such that the minimum regulatory requirements may not have been available when installed.

For example, a cross-track indication in the form of a Course Deviation Indicator (CDI) or Horizontal Situation Indicator (HSI) enabling accurate monitoring of cross-track deviation may not have been considered necessary at the time of certification. An avionics upgrade may be available to meet the later regulatory requirements, but in some aircraft,for a variety of technical or economic reasons, this may not be possible.

Figure 7.1: Cross-track and Vertical Deviations shown on Control and Display Unit

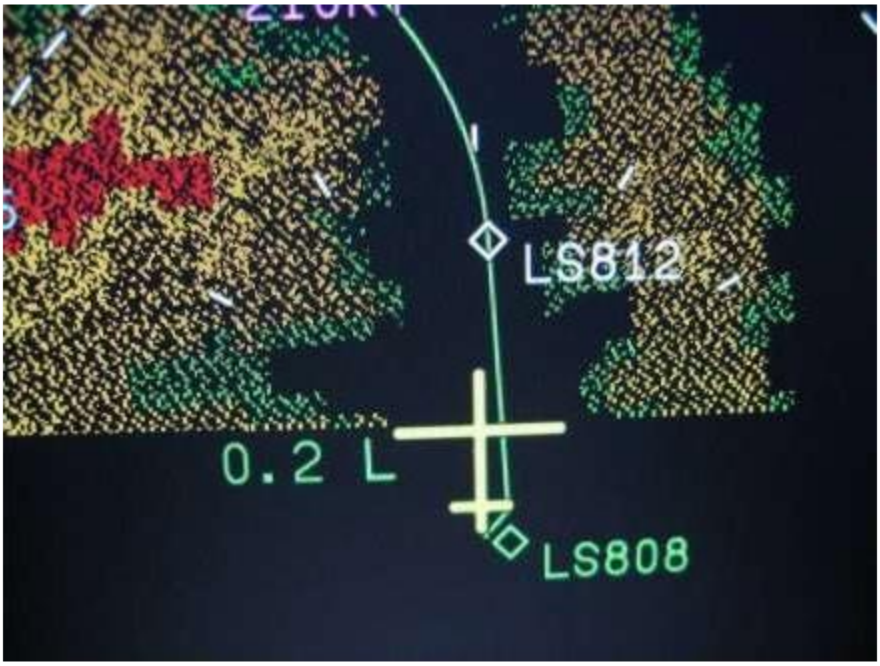


Fig 7.2: Example of cross-track deviation display in 1/10th NM

Chapter 8 FLIGHT CREW TRAINING

8.1 General

The amount and type of training required for flight crews vary significantly depending upon a number of factors, including:

(a) Previous training and experience.

(b) Complexity of operations.

(c) Aircraft equipment.

Consequently, it is not possible to specify for each of the navigation specifications, the particular training that will be required and therefore some judgment is required in determining the content and structure of flight crew training. The navigation specifications in the CAP 11 Vol. 2 cover a wide range of operations, from basic to complex, and therefore training needs to be appropriate to the particular circumstances.

Each navigation specification includes guidance on flight crew training, although it should be noted that the training specified for each operation is generally considered independently. It should be recognised that CAP 11 is a compilation of guidance material, some of which has been in existence in other forms for a number of years, and the training requirements may not be entirely consistent across the range of navigation specifications.

Arrival and departure operations and, particularly, approach operations shall require flight simulator training, in addition to ground training and briefings.

Consideration should also be placed both upon the need for flight crews to demonstrate that competency standards are achieved and upon the need of documentation of qualification. Special considerations shall be made to ensure the simulator has the exact same systems as the operator's aircraft.

8.2 Knowledge requirements

For all PBN operations, the following areas of knowledge will need to be included, with varying content and complexity depending upon the particular operation.

Area navigation principles: Area navigation is the basis for all PBN operations andtherefore the same general knowledge is applicable to all navigation specifications. Note that pilots with previous experience may not be familiar with some more advanced features, such as Radius to Fix legs (RF) and the application of vertical navigation.

Navigation system principles: Flight crews should have a sound knowledge of the navigation system to be used. The relevance of the navigation system to particular navigation specifications should be clearly established. For example, knowledge of inertial navigation and updating is relevant to requirements for some oceanic and remote navigation specifications, as is knowledge of GNSS for RNP AR APCH operations.

Equipment operation and functionality: Considerable variation exists in the operation of navigation equipment, cockpit controls, displays and functionality. Crews with experience on one type of installation or aircraft may require additional training on another type of equipment. Special attention should be placed on the differences between stand- alone GNSS equipment and Flight Management Systems.

Flight planning Knowledge: Knowledge of the relevant aspects of each of the navigation specifications that relate to flight planning is required.

Operating procedures: The complexity of operating procedures varies considerably between PBN operations. RNP APCH and RNP AR APCH require a detailed knowledge of standard operating procedures for both normal and non-normal operations.

Monitoring and alerting. Flight crew responsibilities for performance monitoring and alerting provided by the navigation system or other means (crew procedures) must be understood.

Limitations. Operating limitations (e.g. time limits, minimum equipment) vary both between and within navigation specifications. Flight crews therefore need to be able to recognise and plan accordingly.

Contingencies Alternative means of navigation or other contingency procedures must be included.

Air Traffic Control procedures. Flight crews need to be aware of ATC procedures that may be applicable to PBN operations.

8.3 Flight Training requirements

Approach and departure operations shall require flight training in a simulator and the demonstration of flight crew competency.

Arrival & Departure: As departure and arrival operations require strict adherence to track during periods of high workload and are associated with reduced clearance from terrain and increased traffic, crews need to be fully conversant with the operation of the navigation system. In all cases simulator training is required.

RNP APCH: Training for RNP APCH conducted using stand-alone GNSS equipment, particularly in a single-pilot aircraft, normally requires multiple in-flight exercises each with pre-flight and post-flight briefing. Considerable attention needs to be given to programming and management of the navigation system, including in-flight re-programming, holding, multiple approaches, mode selection awareness, human factors and the navigation system functionality.

Approaches conducted in FMS equipped aircraft are generally much easier to manage. Aircraft are usually fitted with good map displays assisting situational awareness. Simulator training shall be conducted in a simulator that has systems identical to the operator's aircraft. Attention also needs to be placed on the method of vertical navigation, using standard non-precision approach procedures (LNAV) or barometric VNAV (LNAV/VNAV

RNP AR APCH: RNP AR APCH operations are able to deliver improvements in safety and efficiency which are enabled by the Authorisation Required process which ensures that all areas of the operation are carefully examined, and appropriate attention placed on allaspects of the operation, including training. Accordingly, training for RNP AR APCH operations should be thorough and ensure that crews are able to manage operations safely within the additional demands placed on procedure design, aircraft and crew procedures.

As a guide, crews without previous relevant experience (e.g. RNP APCH with Baro-VNAV), will be required a course of ground training (1 - 2 days) plus simulator flight training (4hrs or more) in order to achieve competency.

Additional information regarding flight crew knowledge and training is included in CAP 11, Volume 2.