Chapter 3 NAVIGATION PERFORMANCE

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, then the requirement for GNSS could be removed from the navigation specification.

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. Throughout the PBN manual, accuracy is specified as the probability that the computed position will be within the specified radius 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 are able to provide very high levels of accuracy with a probability far exceeding 95% of the navigation accuracy. Consequently it can be confusing 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 that that observed in actual operations.

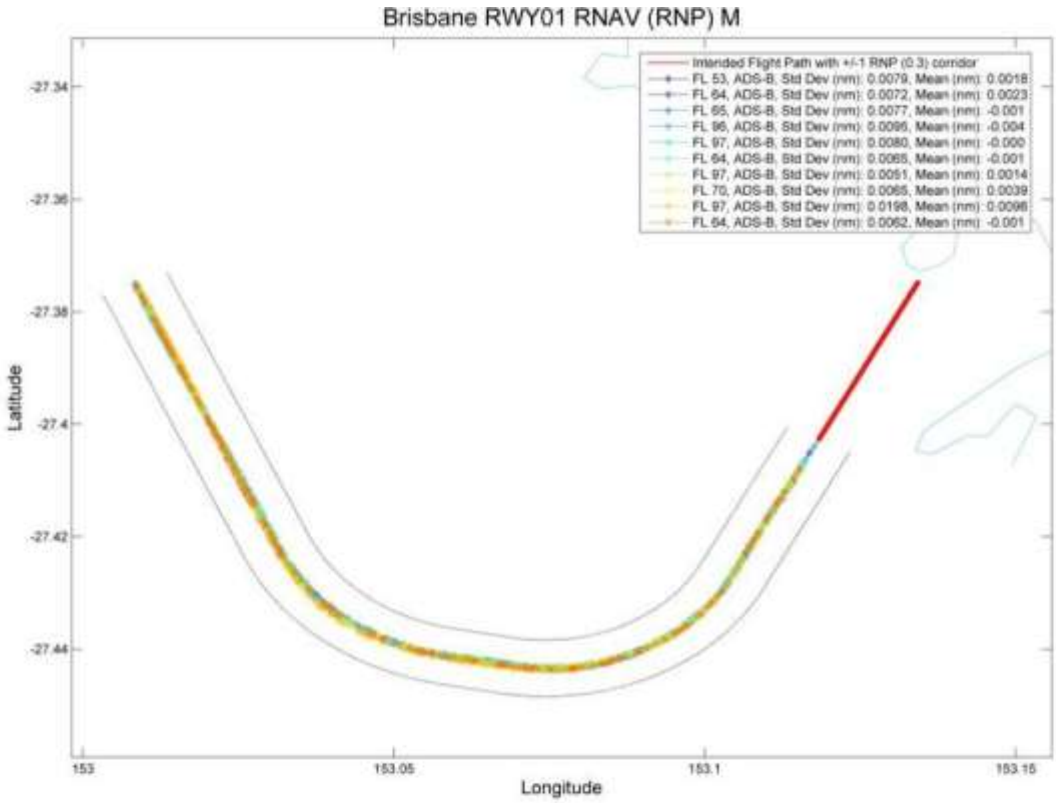

Fig 3.1: In-service tracking data showing TSE in relation to 0.3 NM (1 x RNP) tolerance

Accuracy is only one of a number of considerations when evaluating performance and the overall capability of the navigation system, including cockpit displays, flight control systems and other factors are 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.

In most cases the manufacturer’s published navigation performance was computed some years prior to the publication of the PBN Manual and other relevant State RNAV/RNP guidance. Consequently the operational approval must consider the circumstances in which the manufacturer computed the navigation performance, and the role (if any) of the regulatory authority in accepting the manufacturer’s claims. In many cases, the regulatory authority has “accepted” the manufacturer’s calculations there being no available standard available at the time of initial certification against which the performance statement could be “approved”.
Following publication of the PBN manual and similar State PBN documentation some manufacturers have demonstrated aircraft navigation capability against those published requirements and such aircraft can be accepted as meeting the specified performance without further evaluation. It is expected that in due course many manufacturers will demonstrate compliance with PBN Manual requirements, and this will reduce the workload associated with operational approval.

Other aircraft will require evaluation in order to determine that the required level of performance is consistent with the operational approval. The applicant should be asked to provide substantiation of the aircraft navigation performance supported by manufacturer documentation.

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 need to collect in-service data. FTE values will usually vary for a particular aircraft depending on 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 to be 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 statistical measurements is to compute the square root of the sum of the squares of the component values, or 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 that the specified accuracy is achieved. For example, the FTE might be described as +/- (X) NM / 95%.

In the general PBN Manual case where accuracy is specified as the 95% value, then the 95% TSE is calculated for the 95% values for NSE 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 are 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 the 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.

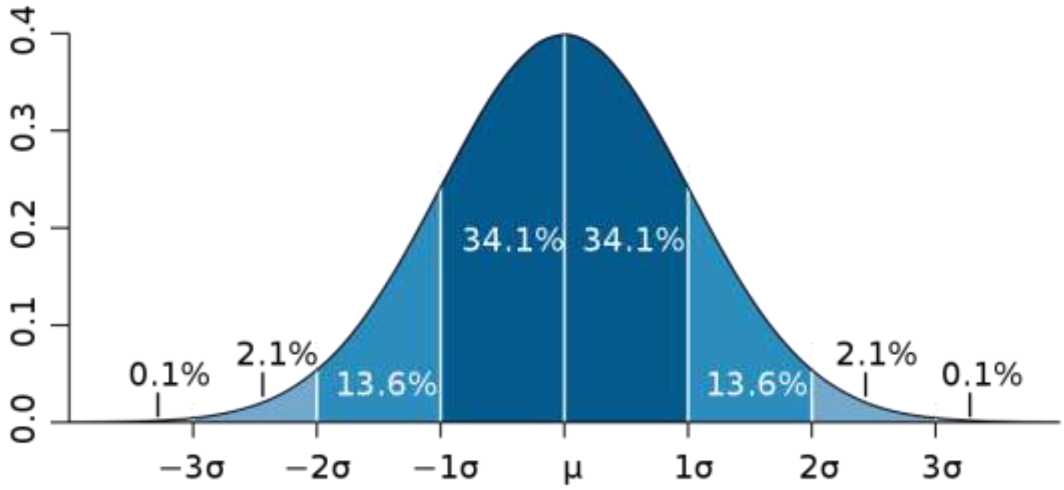

Figure 3.2: A plot of a Gaussian or Normal distribution curve.

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 at 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}.

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 that the reliability of the computation (i.e. the system is operating within its specification without fault), and 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 valid or “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 the general case RNP is based on GNSS. The position accuracy for GNSS is excellent and can support operations with low RNP. The lowest current RNP in use is RNP 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 the ability for the aircraft to follow the defined path. FTE is commonly determined by the ability of the aircraft flight control system, and 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 quality of 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 is 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.

PBN Manual 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.

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, and 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, and 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 $TSE = \sqrt{NSE^2} + FTE^2 + PDE^2$ 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, and commonly varies with phase of flight. In climb, decent and cruise, the sensitivity of flight control systems 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 that the flight crew is 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, and 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, but it may be difficult to justify the same performance when the display of cross-track deviation is taken into consideration.

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, and 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.

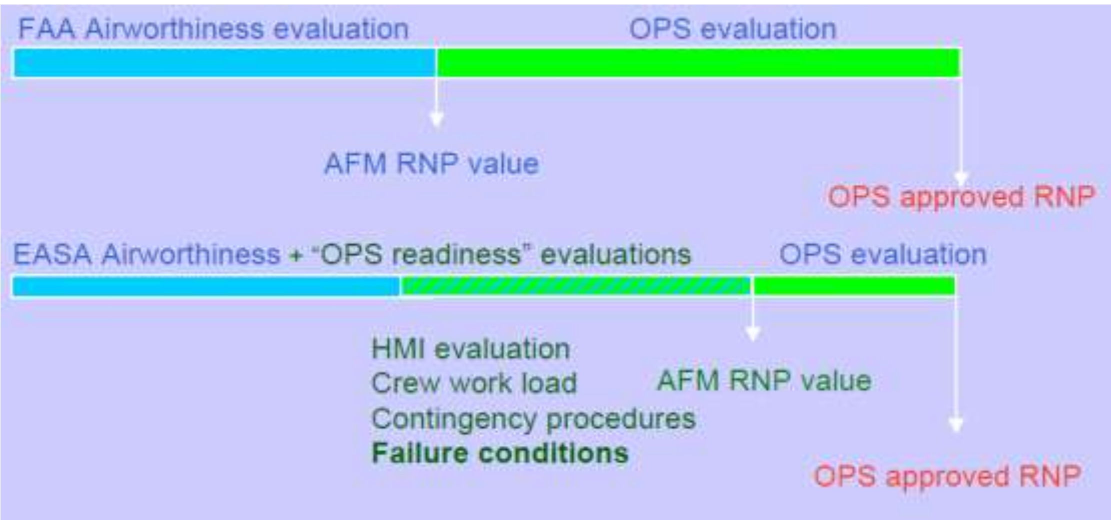

Figure 3.3: Difference between FAA and EASA OPS Approval philosophy

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 by the aircraft system rather than the pilot manipulating the controls.

In the PBN context we need to expand the concept of FTE and there are a number of measures that 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.

PBN Manual 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.

The general PBN Manual requirement is that 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.

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 the PBN Manual

Figure 3.4: Typical FTE values (NM)

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, and avoids 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 judgement 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) that 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 PBN Manual 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 the PBN Manual, and 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 when a 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, and 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, and reasonable instructions 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) that 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.

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. The PBN Manual includes some guidance on the use of a “lateral deviation indicator” or other means such as flight director or autopilot to manage FTE but in practice some judgement on the part of inspectors is required in order to asses 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 a CDI 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 RNAV mode and this type of installation will require evaluation during the approval process.

Although it is not possible to generalize, and there is some variation between manufacturers, in this type of 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 with autopilot engaged, track adherence is generally good and manufacturers have 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. This type of indication is sufficient to allow reasonable estimation, depending on the map scale selected and the aircraft symbol, of deviations as small as 0.1NM. For operations where the cross-track tolerance is relatively large, (RNAV 10, RNAV 5, RNP 4, and RNAV 1 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 contributes to satisfying 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. Implementations vary 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.

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.

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, and 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 stated to be ½ the navigation tolerance i.e. 0.15NM. Consequently indication of small XTK deviation 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 and 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. Flight control using AP or FD is normally used and 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 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.