

Chapter 4 GNSS

1. General

The advent of satellite based navigation provides significant improvement in navigation performance which is available to aircraft of all types. While Performance Based Navigation in general is not dependent upon satellite navigation the benefits available within the PBN concept are multiplied by the use of GNSS.

It is not within the scope of this Handbook to cover the basics of GNSS navigation and 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 general use in general aviation and commuter airline applications, to Flight Management Systems incorporating IRS systems updated by GNSS. Whatever the installation, the navigation capability of GNSS is excellent, and 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.



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 is 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 is insufficient for RNP applications, and 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.

Prior to the PBN Manual, many operations utilising GNSS were classified as RNAV operations, such as RNAV (GNSS) approach procedures. In order to be consistent with the PBN Manual definition 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.

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 metres with a high degree of availability over much of the earth's surface.

Whilst PBN Manual 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 when operating 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. 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 guidance is valid under all reasonable circumstances and various means have been implemented to provide that assurance.

Integrity for conventional navigation aids is indicated by the absence of a warning flag on a VOR or ILS indicator, or the presence of the Morse ident when using an ADF. For GNSS 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, and this can lead to some misconceptions of the role and application of integrity monitoring to performance based navigation.

5. Fault Detection

Integrity and accuracy are both required for valid GNSS navigation. However accuracy and integrity, although in some ways related, 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 and each element incorporates fault detection protection. A GNSS receiver continuously monitors the computed position and will detect and announce 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 and 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.

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 that 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 to the user. The problem is that we cannot be certain that the fault detection system will always work, and as

discussed, due the ambient noise level, under certain circumstances, a fault could be missed. So if we can't be 100% sure about the detection system, something else must be done, and that's where RAIM and HPL (or an equivalent protection system) comes 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 *if a real fault was to 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 that 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 solution is 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 would be 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 at which 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, but 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 accurate 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, that it is necessary to provide an area of "protection" around the aircraft flight path, so that if at some

time whether in the next 30 seconds or 30years a satellite ranging fault of sufficient magnitude was to occur, that the aircraft will 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.

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 PERF-RNP
- GPS PRIMARY LOST



Fig 4.1: Alert annunciated on Boeing 737NG navigation display

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 of 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, and 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 judgement in selecting the best course of action given the circumstances of the emergency.

9. Availability Prediction

Commonly receivers include a prediction function, but 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 to the operating crew and dispatchers 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 availability prediction 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 service and 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.

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 (GBAS Landing System). In the United States GBAS is referred to as the Local Area Augmentation system or LAAS. None of the PBN Manual operations currently depend upon GBAS.

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 the PBN Manual 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.