Chapter 6 BAROMETRIC VERTICAL NAVIGATION

1. General

The PBN Manual does not include a navigation specification for Barometric Vertical Navigation however Baro-VNAV as it is commonly called, is integral to a number of PBN operations and warrants discussion in this Handbook. The PBN Manual includes an Attachment which provides guidance on the application of Baro-VNAV.

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.

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 e.g. the runway threshold.

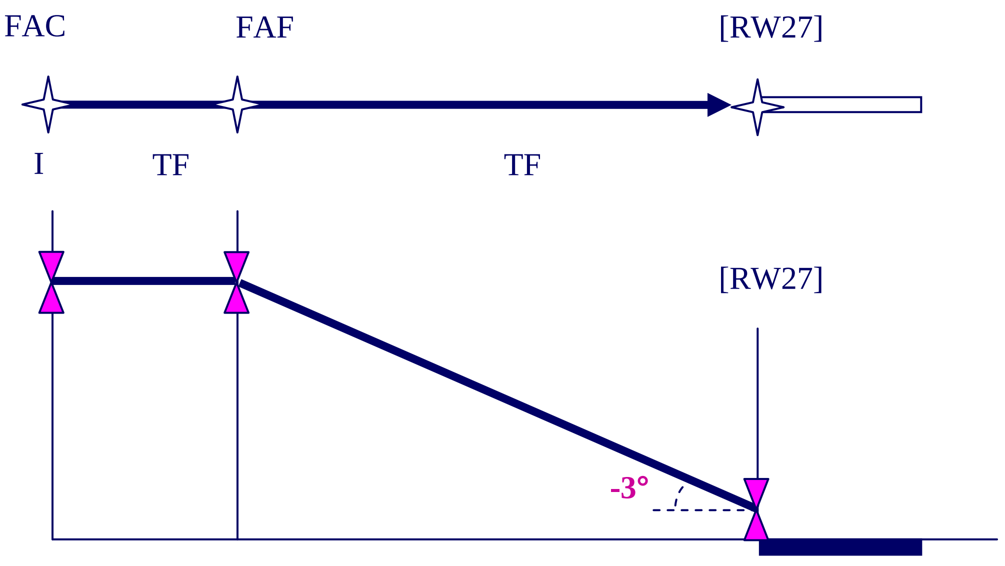


Figure 6.1: Construction of Vertical Flight Path

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

- an area navigation system to enable distance to be determined to a waypoint which is the origin of the vertical flight path;
- the vertical flight path angle from the origin waypoint (normally the runway threshold) coded in the navigation database'
- a barometric air data system of sufficient accuracy;
- a flight guidance system able to provide vertical steering commands;
- 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 and the specified vertical flight path angle is 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 and 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 in lack of correlation of the barometric vertical flight path with 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, so that crews understand the variable nature of the barometric VNAV generated flight path.

Procedure design for approaches with barometric vertical guidance take in to account these effects and maximum and minimum temperature limits may be published on approach charts to ensure obstacle clearance is maintained and steep approach gradients are avoided. Some barometric vertical navigation systems incorporate temperature compensation which enables the coded flight path angle to be flown with out 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 and cockpit displays provide indications of deviation from the vertical flight path which may be adequate for climb, cruise and descent, but insufficient for monitoring of flight path in the approach phase.

As the vertical flight path is dependent upon the measurement of air density and the vertical flight path is generated in relation to a barometric datum, any error in the setting of barometric pressure result 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 10 HPa 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.

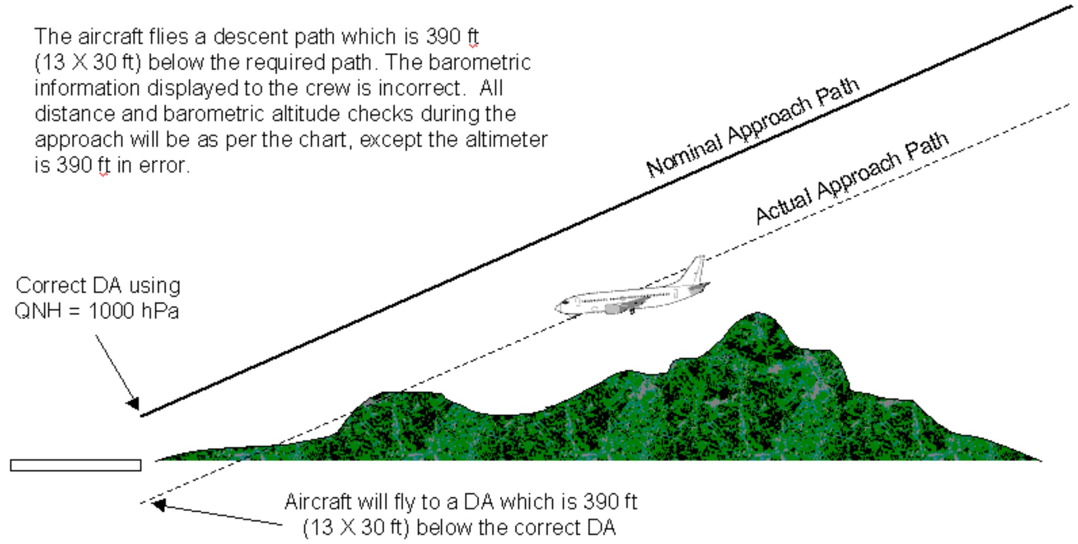


Figure 6.2: Effect of miss-set altimeter subscale on Baro-VNAV vertical path

3. Limitations of the Baro VNAV System

- Non standard temperature effect
- Subscale setting round down
- 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 times the 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, of the average operating conditions differ significantly from ISA conditions it is useful to use 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 amounts. It should be noted that this temperature effect is apparent on all approach which use barometric altimetry to derive a profile. Inspectors should consider that whilst this effect is not new, increased visibility of 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 harmonisation with 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 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. If the 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 visibility 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 profile will be affected by a miss-set altimeter subscale.

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

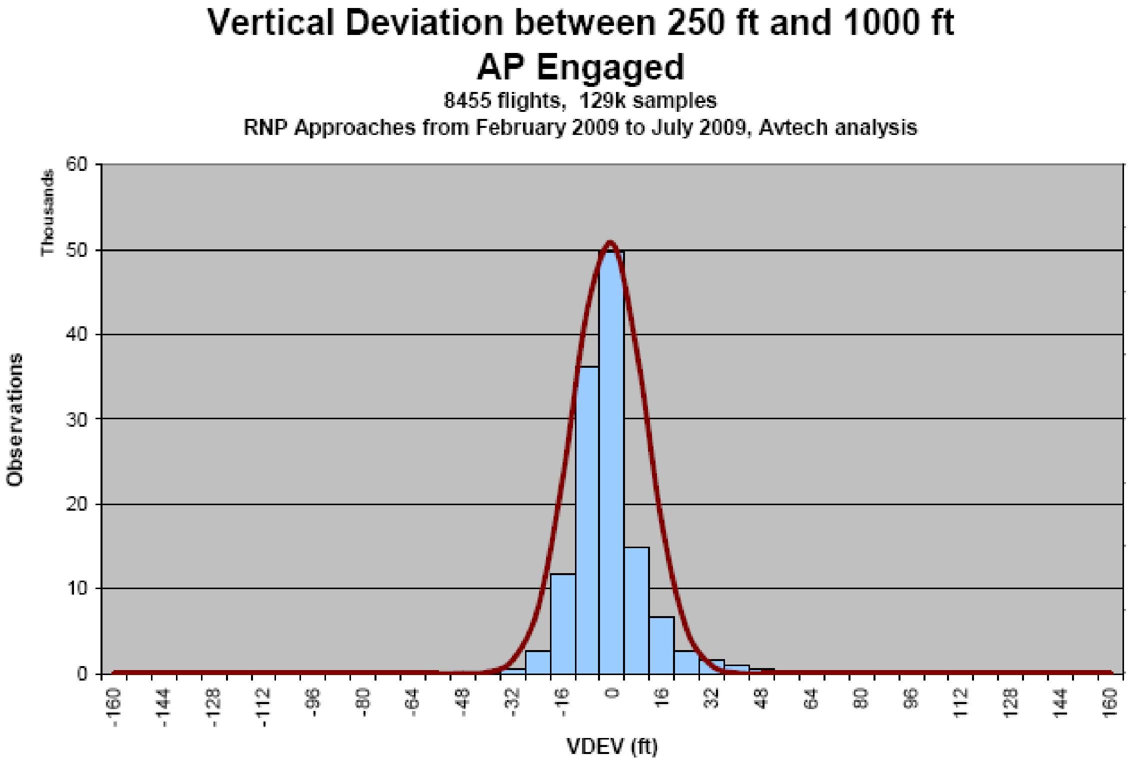
Barometric VNAV Mitigators

Procedural Mitigators:
- Independent crew check when recording destination altimeter subscale setting.
- Effective crew procedures for setting local altimeter subscale setting at transition level.

Electronic Mitigators:
- Electronic alerting if altimeter subscale setting is not reset at transition.
- Electronic alerting of altimeter differences.
- Terrain Awareness System (TAWS) which incorporates terrain clearance floors along with an accurate terrain model for the intended destination.
- Effective crew procedures in support of the TAWS alerts.

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, and operational approval may need to take into account other data, operating procedures or other mitigations.



igure 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 and the availability of positive vertical flight guidance offers offer 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.

5. Flight Procedure Design

Although this Handbook deals with operational approval, 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 is applied to the design of RNP APCH procedures, and RNP AR Procedure Design Manual criteria is applied to the design of RNP AR procedures.

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

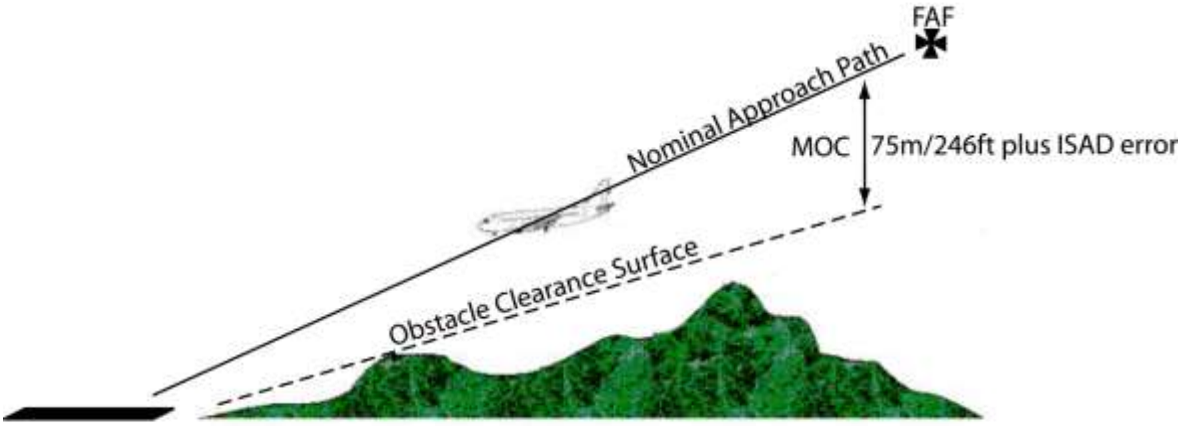


Figure 6.4: RNP APCH (LNAV/VNAV) Final Segment Obstacle Clearance

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 sum of 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).

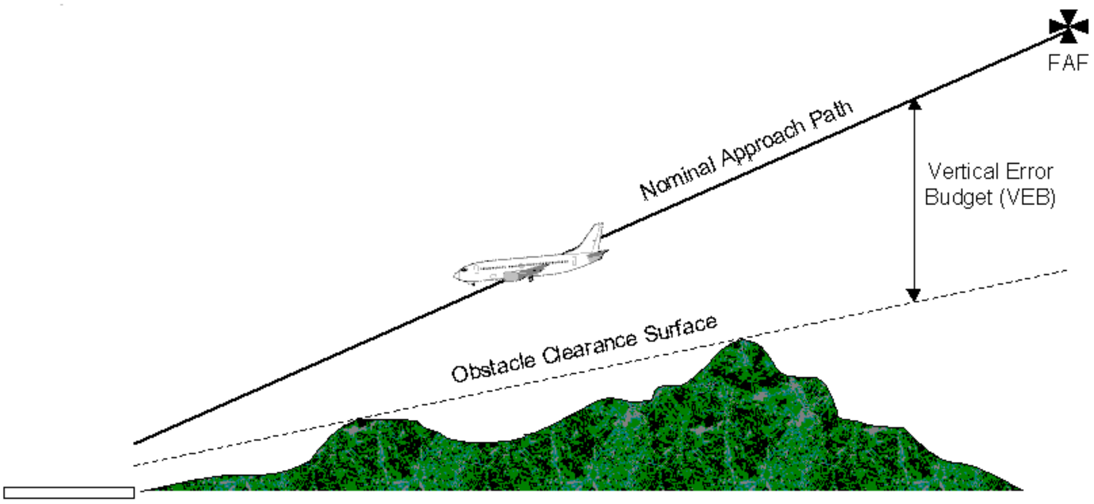


Figure 6.5: RNP AR APCH Vertical Error Budget

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 meet the required level of FTE. Despite the statistical computation of the VEB, the PBN Manual 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. 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, and operators should be encouraged to adopt common standards in the cockpit.

The design of Baro VNAV approach procedures is applicable to the final approach segment (FAS), and 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 RNP AR APCH procedures, the aircraft must be established on the vertical flight profile with the appropriate 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).

It is generally preferable that the aircraft is established on the vertical profile at some point prior to the FAF and it is becoming increasingly common to nominate on an approach chart a point known as the Vertical Intercept Point (VIP). The VIP location is best determined on a 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, and this concept is 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 taken off track, or is vectored to join the approach inside the IAF, then both lateral and vertical tracking is established at some 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), 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 and descent below the vertical flight path may 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 is complex, difficult or limited terrain and runway environments and continued accurate flight path guidance is available below the DA, reducing potential deviations in the visual segment. Other manufacturer's (and States) adopt different policies and 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.)