

Report of the CAA's Post Implementation Review of the implementation of RNAV-1 Standard Instrument Departures at Gatwick Airport

Annex 3: PIR Operational and Technical report

Annex 3 to CAP 1346

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Aircraft Navigation Performance

Introduction

1. Performance-based Navigation (PBN) is the International Civil Aviation Organisation (ICAO) concept which integrates the aircraft in a given navigation infrastructure in accordance with a defined performance specification. The specification reflects not only the navigation accuracy required to be flown, but also the integrity and continuity and the minimum functional capability required of the aircraft on-board systems. PBN covers a range of navigation performance specifications to be applied in oceanic/remote airspace continental en-route airspace, arrival and departure procedures and the final and missed approach elements at an airport.
2. PBN specifications can be categorised as either having RNAV or RNP attributes. Essentially the difference is that RNP specifications require additional on-board integrity monitoring of aircraft positioning usually attributed to position updating from Global Navigation Satellite System (GNSS).
3. From an airspace perspective, Terminal Airspace surrounding an airport or group of airports contains Standard Terminal Arrival Routes (STARs), Standard Instrument Departures (SIDs) and Transitions to the Final Approach. RNAV and RNP specifications with different performance requirement may be applied in the various flight phases in order to provide connectivity between the runway and the en-route network which makes up our national airspace system.
4. In this section, we are discussing the operational and technical outcomes from the approval to deploy 19 Standard Instrument Departure procedures at Gatwick Airport in November 2013. The associated navigation performance specification is RNAV-1.

Navigation Performance

5. The navigation performance (with respect to accuracy) can be described by way of three error terms:
 - How accurately the aircraft determines its position;
 - how accurately the path or track over the ground is defined relative to the desired path; and
 - how accurately the path is being followed.
6. These terms are respectively referred to as Navigation System Error (NSE), Path Definition Error (PDE) and Path Steering Error – the latter usually referred to as

Flight Technical Error (FTE). When summed, these terms form Total System Error (TSE) by which all PBN specifications are associated by either accuracy or by specification name.

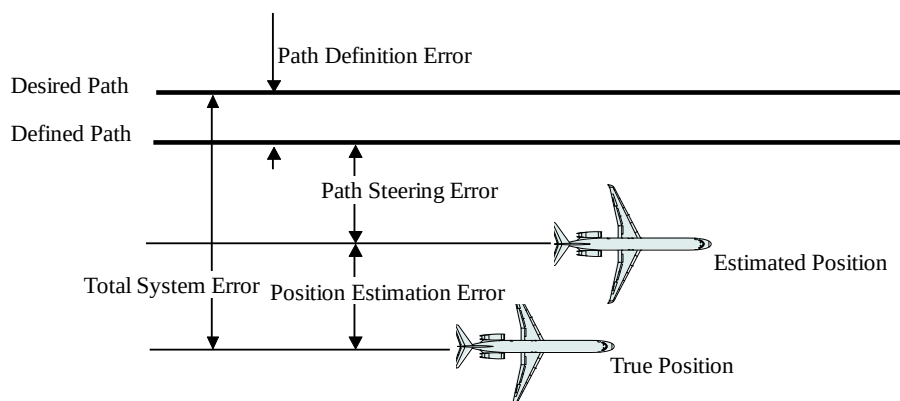


Figure 1 Lateral Components of Navigation Error Terms

7. NSE is a function of the navigational infrastructure and aircraft positioning. In terminal airspace the allowed navigation sensors for departures is through a pair of ground-based Distance Measuring Equipment (DME) ranges providing a DME/DME 'fix' or directly from GNSS – in the UK GNSS services are currently provided by the US Global Positioning System (GPS). DME/DME accuracy is dependent upon the number of ground-based DME facilities, line of sight to the aircraft and the geometry of any two facilities with the aircraft. South East England is considered a 'DME rich' environment although reliable coverage is not generally available until the aircraft are approximately 1600ft AMSL. Navigation accuracies of between 0.3 and 0.5 NM can be achieved in DME environments depending on coverage etc. In general there is no on-board integrity monitoring of DME positioning limiting DME/DME only aircraft to capabilities linked to RNAV specifications.
8. When sufficient satellites are in view (typically four or more), the positioning accuracy associated with GPS is in the order of 0.05 NM. Integrity is provided by an on-board algorithm making any GPS equipped aircraft capable of meeting not only RNAV performance requirements, but also those associated with RNP specifications.
9. Path definition is what the aircraft computes as the path between fixed ground references called waypoints. Usually based on great circle calculations the errors associated with PDE are quite small and usually ignored when considering TSE within a terminal airspace context.
10. The path steering or FTE is the degree of accuracy by which the aircraft flies around the defined path. This is dependent on the means employed by the flight

crew in operating the aircraft. In order of degrees of accuracy, there are three means of providing what is called 'Flight Guidance'. The first is manual guidance with the flight crew 'hand-flying' the aircraft with reference to cross-track errors displayed on a Course Deviation Indicator. The second is with the flight crew again 'hand-flying' but against an engaged Flight Director command in the Primary Flight Display – typically cross-bars. The third and most accurate method is through engagement of the aircraft's autopilot which automatically steers the aircraft such as to null the calculated cross-track error.

11. Figure below shows the relationship at an aircraft functional level between Navigation Positioning, Path Definition and Path Steering. They are then related to other elements of the navigation system including the aircraft displays and alerting system, the navigation data base which hosts the coded procedures and routes and the flight control system providing the guidance of the aircraft.

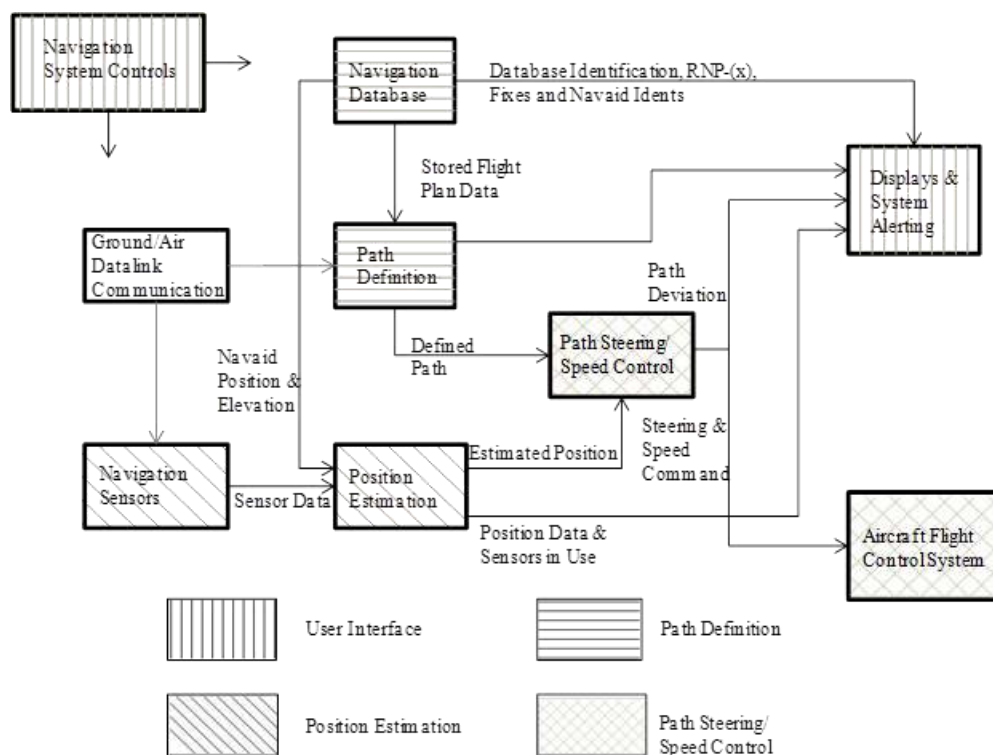


Figure 2 Navigation System Block Diagram

The ICAO RNAV-1 Specification

12. The specification applied at Gatwick Airport for the introduction of new PBN SIDs is the ICAO RNAV-1 specification. As the label indicates, the navigation accuracy is ± 1 NM for 95% of the flight time. Allowable positioning sensors include DME/DME or GPS. There is no specific requirement for use of either Flight Director or Autopilot, although with the fleet and operator mix at Gatwick Airport one would expect flight crews to be engaging Flight Director with lateral navigation as a minimum and then coupling Autopilot shortly after take-off.

13. The RNAV-1 specification includes a minimum requirement for required navigation performance (accuracy, integrity, continuity and functionality). This is then reflected through aircraft certification material which together with criteria supporting an operational approval sets the process required for any operator wishing to become RNAV-1 qualified. In Europe the relevant approval material may be found in Joint Aviation Authorities (JAA¹) Temporary Guidance Leaflet No. 10 rev 1. For US certified products and US operators, the relevant aircraft certification and operational approval material is contained in FAA Advisory Circular (AC) 90-100A.

Navigation System Operations

14. With the navigation system at the heart of PBN, it is worth taking a minute to briefly explain how the system processes navigation information to steer the aircraft along an instrument procedure or route.

Flight Plan

15. The flight plan is a string of instrument flight procedures and airway (en-route) segments denoting the route the aircraft plans to fly. Commencing with a SID procedure, the flight plan then links to the airway structure, via an Air Traffic Services (ATS) route. From the airway, the aircraft is directed (again through an ATS route) to a STAR linking either directly to the runway or via a runway transition. Guidance on the final approach to the runway is provided through reference to an instrument landing system such as ILS or via a PBN approach procedure (Required Navigation Performance – Approach (RNP APCH)). The Flight Management System (FMS) executes the various instrument flight procedures in a sequence depending on the aircraft position and flight crew route selection.

Sequencing of legs

16. Individual SIDs, STARs and ATS routes comprise legs denoting point-to-point navigation. At any one time the aircraft is flying an Active Leg to a fix (also referred to as a waypoint). Close to the fix the navigation system looks ahead to the next leg and depending on the nature of leg currently being flown, begins the transition. The navigation system always attempts to follow the leg sequence as denoted by the instrument flight procedure e.g., SID.

¹ The JAA preceded EASA as the pan-European regulatory body in Europe. However, whilst their certification standards are still applicable in certain circumstances, EASA is now the responsible body to which any related certification and approval matters should be referred.

Path terminators

17. The coding that is used within the FMS to capture the defined path and which is stored in the navigation data base is reflected through an Industry standard called ARINC Specification 424. The current version is ARINC 424-20, although earlier versions are still employed in many navigation databases with varying functional capability. RNAV-1 defines a subset of functional blocks termed as 'Path Terminators' for use in design of instrument flight procedures. In this way, all RNAV-1 qualified aircraft are capable of executing leg transitions and maintain tracks consistent with ARINC 424 path terminators. The required path terminators for RNAV-1 are:
 - Initial Fix (IF)
 - Track to Fix (TF)
 - Course to Fix (CF)
 - Course from a Fix to an Altitude (FA)
 - Direct to a Fix (DF)
18. Although RNAV-1 defines the above Path Terminators, only a subset has been used in the designs for the Gatwick Airport RNAV-1 SIDs. Those used are described as follows:

Track to Fix (TF)

A TF leg is defined as a geodesic path between two fixes. The first fix is either the previous leg termination or an IF leg. The termination fix is normally provided by the navigation database, but may also be a user-defined fix.

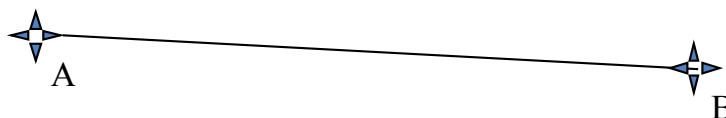


Figure 3 Track to Fix (TF) Leg

Path: Geodesic Path between A and B with Termination at Fix B

Course To Fix (CF)

A CF leg is defined as a geodesic path that terminates at a fix with a specified course at that fix. The inbound course at the termination fix and the fix are provided by the navigation database. If the inbound course is defined as a magnetic course, the source of the magnetic variation is needed in order to convert magnetic courses to true courses.

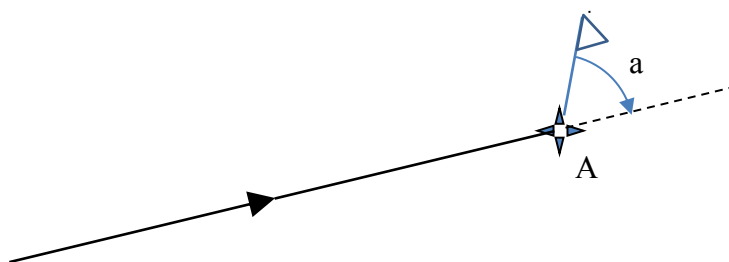


Figure 4 Course to Fix (CF) Leg

Path: Geodesic Path to Fix A with Inbound Track "a" with Termination at Fix A

Waypoint Types and Sequencing

19. The navigation system provides a means to automatically sequence from one leg to another via the Fix – also described as a waypoint. ICAO Doc 8168 PANS-OPS describes a waypoint as a specified geographical location used to define an area navigation route or the flight path of an aircraft employing area navigation. The type of waypoint determines the method by which the sequencing will be executed². Waypoints are identified as either:
 - *Fly-by waypoint.* A waypoint which requires turn anticipation to allow tangential interception of the next segment of a route or procedure; or
 - *Flyover waypoint.* A waypoint at which a turn is initiated in order to join the next segment of a route or procedure.
20. A minimum stabilisation distance is used to compute the required minimum distance between waypoints. It is the minimum distance to complete a turn manoeuvre and after which a new manoeuvre can be initiated. To prevent waypoints being placed so close that RNAV-1 systems are forced to bypass them, a minimum distance between successive waypoints must be taken into account.
21. When course changes exceed the rules as provided in the design criteria, there may be cases where a route could be created in which the expected waypoint sequencing will not be possible due to factors such as aircraft performance, course change and leg length. In effect, the defined path is not fly-able. Under nominal conditions this situation should not occur in a database-defined procedure. Therefore, in the event that the entry requirements for the succeeding leg cannot be satisfied the navigation system may 'by-pass' this leg and instead transition to the next waypoint to be sequenced. In some aircraft types the transition may change from a lateral navigation mode into a basic (heading) mode requiring flight crew intervention. The figure below is taken from

² ICAO Doc 9613, PBN Manual and industry standards refer to the sequencing of legs as leg transitions and the term is used interchangeably with waypoint types.

ICAO Doc 8168 PANS-OPS and indicates the types of waypoint and the allowance for minimum stabilisation distance within a procedure design.

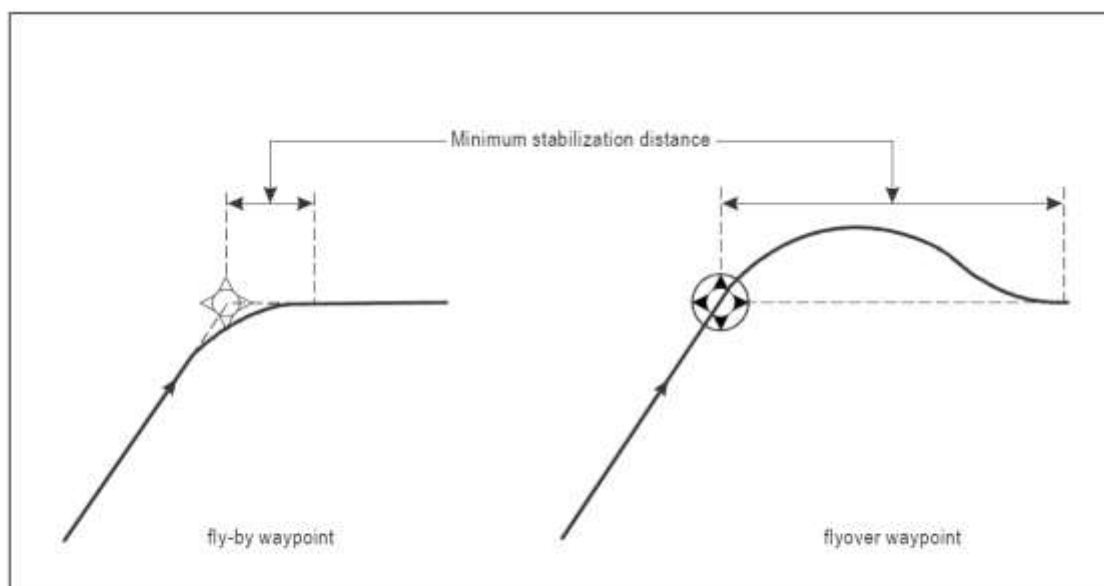


Figure III-2-1-1. Determining the minimum stabilization distance

Figure 5 Extract from ICAO Doc 8168 PANS-OPS

22. For fly-by waypoints, no predictable and repeatable path is specified, because the optimum path varies with airspeed and bank angle. Fly-by waypoints are the default transition in PBN procedures when the transition type is not specified. For fly-by waypoints, a theoretical transition area is defined within which an infinite number of acceptable ground tracks can be defined per individual airborne system design. The fly-by transition areas are significantly larger than that required for acceptable transition performance. This is a result of accommodating near worst-case conditions of ground speed and roll angle. The speed that an aircraft approaches a fly-by turning waypoint will affect where the turn commences. The higher the ground speed of the aircraft, the further from the waypoint the turn will commence and conversely the slower the ground speed the closer to the waypoint the turn will commence. The impact of this can be seen and explained further in the Route 4 technical analysis in the CAA IFP Recommendations report (Annex 6 to CAP 1346).

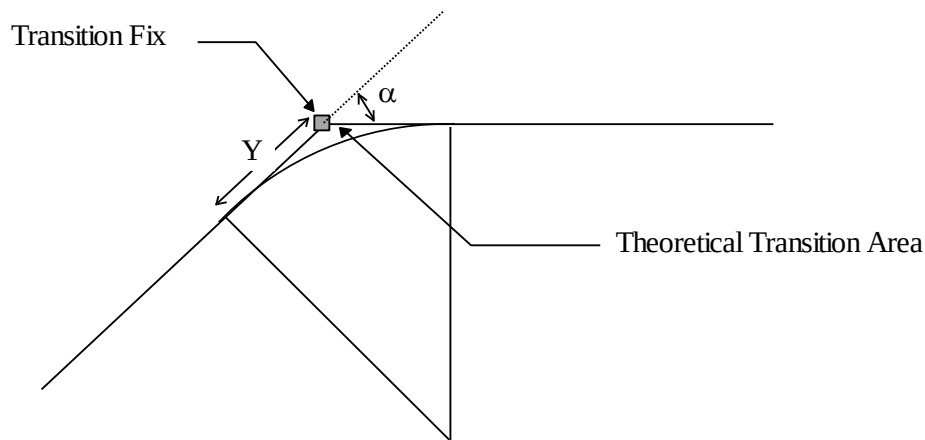


Figure 6 Fly-by Theoretical Transition Area

23. For fly-over waypoints the navigation system will not begin sequencing the next leg until having passed over the fix. Therefore fly-over transitions result in an overshoot of the fix and a required turn back to the outbound leg segment. There is no turn anticipation.

Turn Anticipation at Fly-by Waypoints

24. The navigation system provides a means for look-ahead manoeuvre anticipation and guidance such that the aircraft lateral path will follow a known trajectory. The main factors affecting the commencement of turn anticipation are:
- Turn transition angle (change in course from inbound to outbound leg)
 - Ground speed of aircraft (indicated airspeed taking account of encountered wind speed and direction).
 - Bank angle authority available (a value commanded by the navigation system, but limited by the flight guidance system depending on the altitude of the aircraft and speed).
 - Aircraft loading (available 'g' manoeuvre).
25. The non-deterministic nature of the fly-by turn and therefore the track over the ground is a consequence of when the turn anticipation commences together with the available bank angle authority. If the commanded bank angle required to complete the leg transition exceeds that available, the aircraft will drift according to the wind until such time as the commanded angle can be achieved or until there is a change in the active leg or navigation system mode.
26. The effect on the aircraft of wind (speed and direction) in influencing ground speed cannot be overstated. An aircraft encountering a cross-wind component when turning downwind through 90° will now pick up tailwind component which

sums with the indicated airspeed. Hence an indicated speed of 220 knots encountering a 40 knot cross-wind (to the runway direction) at altitude becomes 260 knots after the turn with no change of aircraft thrust setting. The navigation system sees this ground speed and will use that value for computation of turn anticipation. It is this ground speed that the aircraft has to accommodate in setting bank angle authority in order to manage the turn performance of the aircraft.

Radius to Fix (RF) Turns

27. The other form of transition between two leg segments is the fitting of a fixed radius turn tangential to the inbound and outbound legs. A Radius to Fix (RF) leg is defined as a constant radius circular path about a defined turn centre that terminates at a waypoint. The termination waypoint, the turn direction of the leg and the turn centre are provided by the navigation database. The radius is computed as the distance from the turn centre to the termination waypoint by the navigation computer. The beginning of the leg is defined by the termination waypoint of the previous leg, which also lies on the arc. RF legs use fly-by waypoints with a zero degree leg change.

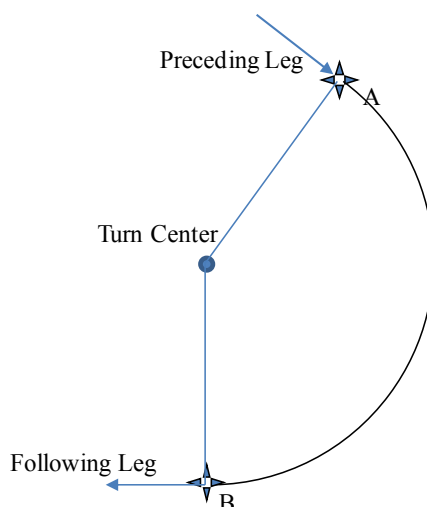


Figure 7 Radius to Fix Leg

Path: Constant Radius Arc to Fix B with Termination at Fix B

Note: Radius to Fix (RF) is associated with Terminal Airspace procedures requiring an RNP specification and therefore is not available for RNAV-1 procedure designs.

Altitude and Speed Constraints

28. The navigation system is not operating in just the horizontal plane. On the modern air transport aircraft it also provides vertical navigation and can issue speed commands in accordance with constraints associated with the instrument

flight procedure design. The navigation system is therefore managing the complete aircraft trajectory including interactions between both vertical and lateral elements of the procedure design. Indeed, behaviour of the aircraft following a vertical or speed command may have a consequence on the lateral performance, especially in the fly-by turn where the speed of the aircraft has a direct bearing on turn anticipation and therefore track over the ground. The ranges of available constraints that can be associated with a waypoint or 'fix' are as follows:

Altitude Constraints

- An "AT" or "ABOVE" altitude constraint (e.g., 2400A may be appropriate for situations where bounding the vertical path is not required);
- An "AT" or "BELOW" altitude constraint (e.g., 4800B may be appropriate for situations where bounding the vertical path is not required);
- An "AT" altitude constraint (e.g., 5200); or
- A "WINDOW" constraint (e.g., 2400A, 3400B).

Note: In the instrument flight procedure design the terms ABOVE and BELOW may be represented in the published coding tables by "+" and "-" respectively.

Speed Constraints

29. Where the navigation system supports airspeed restrictions at altitudes and/or fixes. These restrictions may be a required for tactical airspace operations or as part of a procedure. When speed restrictions are assigned at a waypoint or 'fix', the system should support "AT", "AT or ABOVE" and "AT or BELOW" types when the waypoint is sequenced.

Note: In many aircraft the Flight Management System executes the charted maximum speed constraints as "AT" speeds. For this reason flight crews will on occasions be required to intervene in order to adjust the indicated airspeed to prevent acceleration to the maximum speed constraint and thus ensuring that the navigation system is capable of executing the instrument flight procedure as intended e.g., when encountering a strong tailwind component whereby ground speed increases in the turn.

Note: Flight phase (Climb or Descent) affects the way the speed restriction is applied before and after the waypoint. The navigation system may support speed restrictions through system automation or by suitable information and cues to the flight crew.

Sequencing of Legs and Constraints

30. The fly-by turn look-ahead feature, highlighted previously, begins computation of the next leg at the bi-sector of the turn. Therefore the active leg changes at the bi-sector and the FMS computes path steering according to the new path

terminator. It also means that any altitude or speed constraint previously associated with the sequenced waypoint are dropped and the constraints of the new leg, assumed. As an example, in the Route 4 SIDs where waypoint (KKN06) has a maximum speed constraint of 220 knots associated with it and the subsequent waypoint (KKE14) a maximum speed constraint of 250 knots, the maximum 220 knots constraint will be dropped at the bi-sector of KKN06 and the aircraft will be commanded to accelerate to the new maximum speed constraint of 250 knots.

Flight Guidance System Operations

31. The flight guidance system on modern large air transport aircraft typically comprises the Flight Director command bars presented to the flight crew in the primary flight display, the autopilot and autothrottle. All of these require steering commands but operate within their own limits tied to the flight control envelope of the aircraft. As an example, the navigation system might provide a lateral steering command with a bank angle limited to say 25° whereas the engaged autopilot system could accept commands up to 30° i.e., its bank angle authority has a wider envelope. In a lateral navigation context, the aircraft will only ever be commanded to the value provided by the navigation system, but depending on the lateral mode and the nature of the leg type this may not fully use all of the flight guidance authority.

The Instrument Flight Procedure (IFP) Design

The CAA Role

32. The Airspace Regulation Section, within the CAA is responsible for the formulation of policy relating to the design and approval of Instrument Flight Procedures (IFPs), as documented in CAA Publication CAP 785. This responsibility includes regulatory oversight of external organisations engaged in the design of IFPs for subsequent use in the UK Flight Information Regions (FIRs) and at UK civil airports. Regulation is achieved, as appropriate, through the application of requirements as laid out in the relevant articles to the Air Navigation Order (ANO) by the CAA. The aim of CAA regulation is to ensure that IFPs:
- Are designed to the required standard as stipulated in Section 3, Chapter 1, paragraph 2 of CAP 785;
 - are safe and fly-able;
 - meet Air Traffic Management requirements; and
 - are environmentally acceptable.
33. The criterion for IFP design in UK airspace is based on ICAO Doc 8168-OPS/611, Procedures for Air Navigation Services – Aircraft Operations Volume II, Construction of Visual and Instrument Flight Procedures (PANS-OPS Volume II). In accordance with the latest ICAO policy, UK national differences to Doc 8168 are notified in the UK Aeronautical Information Publication (AIP).
34. PANS-OPS Volume II, is intended for the guidance of procedure design specialists and describes the essential areas and obstacle clearance requirements and design assumptions for the achievement of safe, regular instrument flight operations. It provides the basic guidelines to States, and those operators and organisations producing instrument flight charts that will result in uniform practices at all aerodromes where instrument flight procedures are carried out. As an example, it includes guidance for turn protection with allowance of up to 30 knots of wind.
35. The design of procedures in accordance with PANS-OPS criteria assumes normal operations. It is the responsibility of the operator to provide contingency procedures for abnormal and emergency operations.