Boeing now offers 737-600/-700/-800/-900 operators a common display system enhancement that takes full advantage of the best navigation system available in commercial aviation today. The new displays involve lateral and vertical navigation deviation scales that reduce the already low required navigation performance rating of the new 737 family. The reduced rating provides access to runways previously considered impossible to use because of infrastructure or terrain. The common display system enhancement is available on all 737-600/-700/-800/-900 airplanes in production and in service.
pathway or containment boundary. This boundary provides safe separation from terrain, other airplanes, and adjacent airspace. The RNP values for a given airplane model, and the actual navigation performance (ANP) of an airplane during flight. The first two concepts often are referred to as RNP.

RNP extends the capabilities of modern airplane navigation systems by providing a precise characterization of airplane navigation performance. The navigation accuracy of an airplane is based on its system capabilities rather than specific ground-based navigation aids. RNP defines the navigation accuracy that an airplane must have to operate on a specific route segment. (See "Required Navigation Performance for Improved Flight Operations and Efficient Use of Airspace," in Aero no. 12, October 2000.)

The navigation accuracy required for a particular flight phase varies. For example, the accuracy can be 4.0 nmi for oceanic airspace or 0.1 nmi for near category I approaches. The specific RNP for a particular flight path ensures that airplanes with adequate navigation accuracy remain within a defined pathway or containment boundary. This boundary provides safe separation from terrain, other airplanes, and adjacent airspace. The RNP values for flight phases are stored in the airplane’s flight management computer (FMC) database and are available to the flight crew as a digital readout on the control display unit (CDU).

The flight crew can override the RNP values, both lateral and vertical, for specific situations in which the database RNP value is not applicable. (Page 4 of the RNP PROGRESS pages, displayed on the CDU, reviews all relevant components of total system error and flight crew override of RNP for lateral and vertical navigation. It also gives a preview of the lateral and vertical RNP values for the approach in the FMC flight plan.)

To determine whether an airplane is eligible to fly in a given RNP-defined airspace, the flight crew must know the RNP rating of the airplane. RNP ratings vary by model and operational mode. The 737 has the lowest RNP rating of all Boeing models for each of the three defined operational modes: autopilot, flight director (FD), and hand flown. Lower RNP ratings for an airplane, when overlaid onto RNP-defined airspace, result in lower decision heights (fig. 1). If RNP is a measure of how good the airplane’s navigation system actually is, whereas ANP defines the allowable airplane error in terms of distance and probability relative to the procedurally defined path, ANP is based on probable airplane position determination and guidance errors.

On Boeing airplanes, multiple sources of navigation data are integrated to determine the system navigation solution. Inertial systems initially are very accurate throughout the flight. Global positioning system (GPS) units generally provide exceptionally accurate data but must be monitored for undetected failures and lack of satellite coverage. Ground-based radio navigation aids vary in accuracy and availability.

These sources of data are analyzed continuously by the FMC to calculate the best estimate of current airplane position and estimated airplane position uncertainty. If any one source is deleted, the confidence in the navigation position will decrease. Thus, the ANP value will increase. Displaying ANP can be a great help to the flight crew when trying to verify airplane position because the crew no longer must tune, identify, and cross-plot navigation aids. The FMC logic uses the best sources of data available to provide the flight crew with a real-time navigation solution. (See "ANP Algorithms" and "Navigation and Time" on p. 35.)

Neither RNP nor ANP contains any data that indicate how close the airplane is flying to the designated flight path. To explain how ANP and RNP relate to the relative position of the airplane requires a discussion of the concept of error budget.

REQUIRED AND ACTUAL NAVIGATION PERFORMANCE

Three concepts need to be understood when discussing required navigation performance (RNP) operations: the RNP required by a regulatory agency for a defined flight path, the RNP rating of a given airplane model, and the actual navigation performance (ANP) of an airplane during flight. The first two concepts often are referred to as RNP.

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BUDGET FOR TECHNICAL ERROR

To fly safely on the designated flight path, the airplane navigation system must ensure that the airplane remains within the RNP-specified airspace. The statistical navigation system error is characterized by ANP. Because the airplane’s navigation sources and sensors are not perfect, a difference, or error, may exist between the estimated, or calculated, airplane position and the actual airplane position. If system failures or flight crew selections reduce the number or degrade the quality of the navigation sources, ANP will increase. For example, an ANP value of 0.06 nmi means that the airplane very probably is within a 720-ft-diameter circle of its estimated position. If this is the only error in the
total navigation system, the runway probably will be at most 360 ft to the left or right when the airplane breaks out of the clouds at the minimum descent altitude.

**Flight technical error.**

Flight technical error (FTE) is a measure of how well the airplane is tracking the lateral and vertical paths estimated by the navigation system. The flight crew observes FTE with deviation scales by using digital CDU readouts or by noting how far the airplane symbol on the navigation display is off the route. FTE is the one component of the error budget that can be controlled by the flight crew. (See “Flight Technical Error” box below.)

To ensure that the airplane remains on the desired path, the flight crew limits the errors in total navigation performance over which it has control and monitors the errors that it cannot control. FTE can be controlled by the flight crew and should be minimized. Navigation system error cannot be controlled by the flight crew but should be monitored to ensure that it remains within acceptable limits. Path computation error cannot be monitored or controlled but generally is sufficiently small that it can be ignored.

**FLIGHT TECHNICAL ERROR**

With the advent of the first flight director (FD) systems in the 1940s, the question arose: Just how accurately can a flight crew fly by the guidance provided by the FD? The error between the actual track and the desired track (sometimes referred to as “the ability to fly the flight director”) is defined as the flight technical error (FTE).

Initially, an industry standard FTE of 0.5 nmi was established for airplanes equipped with moving map displays. In the early 1990s, Boeing performed a series of tests with the 737-300 and 747-400 flight decks to update the FTE and establish the flight crews’ ability to use the map generated by the flight management computer (FMC) for lateral guidance alone and in conjunction with FD.

For 737s with FMC software version 8.4 or later (i.e., 737-300/-400/-500/-600/-700/-800/-900 airplanes), the value of FTE for the flight crew using FD is comparable to that of autopilot. The new lateral and vertical navigation deviation scales give a clear enough indication of the error from the desired path, which allows for timely detection of excessive errors. This timely detection results in a lower minimum demonstrated RNP.

Boeing has developed flight deck displays that enhance the ability of the flight crew to monitor the dynamic relationship among ANP, RNP, and current flight path deviations. The LNAV and VNAV deviation scales—which are based on the familiar concepts of a centerline indication, scale limits, and a deviation pointer—incorporate additional symbols to provide the flight crew with a clear indication of current position in relation to desired position and the total allowable error budget (fig. 2).

The LNAV deviation scale is active anytime LNAV is in the engaged FD or autopilot mode. If ANP is a relatively small portion of the total allowable error for a given flight path, then room exists in the error budget for the flight crew to purposely increase FTE. For example, if RNP is 4.0 nmi and ANP is 0.05 nmi, then the flight crew could deviate from track by 3.94 nmi (to miss a thunderstorm, for example) without requesting a deviation. The allowable deviation from centerline and the limit are clearly indicated on the LNAV deviation scale (fig. 3).

On the other hand, when the ANP value is relatively large and begins to approach RNP, the flight crew does not have room to deviate from the desired track and still remain within the desired route constraints. This is best illustrated in the final approach environment, where RNP may be 0.1 nmi and ANP may be 0.08 nmi. In this case, the allowable flight crew error from centerline would be only 0.02 nmi, or 120 ft. The deviation scale would clearly show that ANP is a large percentage of RNP and that the flight crew has a very small margin for technical error (fig. 4). When ANP equals RNP, it is not possible to ensure that the airplane is within the desired navigational limits, and an alternate plan must be executed. This case will result in an appropriate indication on the scale and a concurrent UNABLE REQD NAV PERF-RNP message (fig. 5, p. 34). The same scale also is presented for the vertical path. A maximum deviation indication is presented by flight leg. When RNP or ANP is defined for the vertical path in the technical standards, the vertical scale uses the same philosophy as the LNAV deviation. Because the LNAV and VNAV deviation scales provide enhanced awareness and alert the flight crew to the position of the airplane, the RNP rating of the airplane can be reduced. Current estimates indicate that the RNP rating of 737-600/-700/-800/-900 airplanes can be reduced to approximately 0.10 nmi for autopilot command and FD LNAV.

**Transition to traditional runway approach.**

The best method for providing precision guidance to the end of the
ANP ALGORITHMS

Various manufacturers of flight management computers (FMC) use different mathematical equations, or algorithms, to calculate actual navigation performance (ANP). Weighted values are assigned to different navigation data sources, and monitors, filters, and averaging terms are used to compute an ANP value. By watching ANP change, the flight crew can become familiar with ANP response as navigation conditions change. In addition, the flight crew can deselect specific navigation sensors on the FMC control display unit (CDU) to observe the effects on ANP.

For example, with the 737-600/-700/-800/-900 family of airplanes, a flight crew can deselect the global positioning system (GPS), distance measuring equipment (DME), or very-high-frequency omnirange navigation equipment (VOR) updating on the NAV OPTIONS page of the FMC CDU. Turning off a single updating source results in a larger ANP value after a period of time. Turning off GPS updating causes the ANP value to increase by approximately 0.02 nmi/min until the system reaches an ANP value that is provided for by DME and VOR updating. Turning off all three sensors causes the ANP value to increase at a faster rate.

In a 777, turning off the GPS causes the ANP value to increase in a single step to the non-GPS ANP value.

With either airplane model, selectively turning off a navigation source provides the flight crew with an indication, by observing the rate of increase in ANP, if the flight crew loses a navigation source because RNP is a database value and does not depend on navigation data.

When ANP exceeds the current RNP, an alerting message is displayed. Manually entering a low RNP value also triggers the message. Flight crews need to remember to return all navigation systems to on and delete the manually entered RNP so that the database value is used for alerting.

NAVIGATION AND TIME

For centuries, the great navigational problem was how to find longitude. Latitude was fairly easy to calculate by star sightings. Decades of celestial observations were performed to chart longitude, with very limited success. It was known that if a navigator had an accurate clock, then the difference in time from the noon sun to a standard would yield longitude. The difficulty was building a clock that kept accurate time at sea. It had to account for large temperature changes, barometric pressure changes, and the swaying motion of an ocean-going vessel.

The British inventor John Harrison built such a clock in the late 18th century. On a five-month voyage in 1761, the clock was shown to err by only 1.25 deg of longitude, and was quickly put to sea. For the epic voyage of discovery, the ship’s captain was so concerned with accurate time that he went to sea with 43 clocks.

In today’s world of navigation, time is still the key parameter. Each global positioning system satellite uses four cesium clocks, with errors of 1 sec per 1 million years; the clocks are corrected for the speed of the satellite using Albert Einstein’s theory of relativity. The ability of a global positioning system satellite to keep accurate time enables flight crews to know their positions to within 300 ft. With additional augmentation, this can be reduced to less than 1 ft.

SUMMARY

Operators of 737-600/-700/-800/-900 airplanes can now implement a new navigation feature that provides flight crews with increased operational capability and enhanced situation awareness. The new LNAV and VNAV deviation scale displays are available on 737-600/-700/-800/-900 airplanes in production and by retrofit. Application of the system on other Boeing models currently is under consideration.