Flight management systems have evolved to a level of sophistication that helps flight crews fly commercial airplanes more safely and efficiently.

Contribution of Flight Systems to Performance-Based Navigation

Flight Management Systems (FMS) and associated airplane flight systems are the primary navigation tools on board today's commercial airplanes. The evolution of these systems has led the way for performance-based navigation (PBN) and the U.S. Federal Aviation Administration's (FAA) Next Generation Air Transportation System.

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PBN is a concept used to describe navigation performance along a route, procedure, or airspace within the bounds of which the airplane must operate. For transport airplanes, it typically is specified in terms of required navigation performance (RNP). The PBN concept defines navigation performance in terms of accuracy, integrity, availability, continuity, and functionality. These operations provide a basis for designing and implementing automated flight paths that will facilitate airspace design, terminal area procedure design, traffic flow capacity, and improved access to runways (more information about PBN can be found in *AERO* second-quarter 2008). The PBN concept is made possible largely by advances in the capabilities of airplane FMS.

This article helps operators better understand how the FMS and other airplane flight systems have evolved over time, how they contribute to PBN operations, and plans for further advancement.

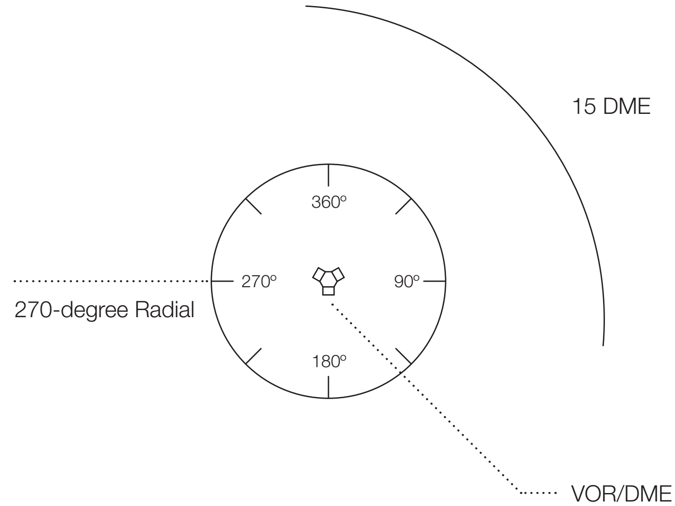
AIR NAVIGATION TOOLS LEADING UP TO THE FMS

Early aviators relied on very basic instrumentation to keep the airplane upright and navigating toward the desired destination. Early "turn and slip" indicators and ground references such as lighted beacons enabled aviators to fly coast to coast across the United States. However, these early flights were filled with uncertainties and their use of visual flight rules soon gave way to reliable attitude indicators and ground-based navigation aids, or navaids. Non-directional radio beacons and the airplane's airborne automatic direction finder equipment allowed aviators to "home in" on the beacon and navigate reliably from station to station. Non-directional radio beacons are still being used today throughout the world.

In the 1940s, the introduction of a radio-magnetic indicator or dual-bearing distance-heading indicator facilitated the use of ground-based navaids, including

Figure 1: Typical VOR installation

By 1952, more than 45,000 miles of airways using the VOR were in operation. A DME transmitter was usually located on the ground with VOR stations. DME transmitters would respond to interrogation by transceiver equipment installed on airplanes and provide the pilot with a reliable distance in nautical miles to the transmitter. Pilots operating in areas where VOR and DME coverage was available had both distance and course information readily available.



the very-high-frequency omni-directional range (VOR) navigation system and distance measuring equipment (DME). VORs came into wide use in the 1950s and quickly became the preferred navigation radio aid for flying airways and instrument approaches (see fig. 1). VOR and DME provided the framework for a permanent network of low-altitude victor airways (e.g., V-4) and high-altitude jet routes (e.g., J-2), which are still in place today.

Long-range navigation over remote and oceanic areas, where navigation radio transmitters did not exist, was originally accomplished by dead reckoning and celestial navigation. The introduction of the inertial navigation system (INS) on airplanes facilitated long-range capability by providing a continuous calculation and display of the airplane's position. Flight crews could enter waypoints and the INS would calculate heading, distance, and estimated time of arrival to the respective waypoint.

At the same time, the 1970s fuel crisis provided the drive to optimize navigation capabilities in commercial airplanes. As a result, avionics manufacturers began producing performance management computers and navigation computers to help operators improve the efficiency of their airline operations. Boeing's initial entry into this arena was represented by the implementation of the early Sperry (now Honeywell) automatic navigation systems on the 727, 707, and 747-100. During this same time, Collins produced the AINS-70, an area navigation (RNAV) computer on the DC-10. Each of these steps reduced the amount of interpretation by the flight crew by presenting more specific indications of airplane positional and situational status. Even so, the reliance on the flight crew to manually interpret and integrate flight information still provided opportunities for operational errors.

THE FIRST INTEGRATED FLIGHT MANAGEMENT COMPUTER

When Boeing began work on the 767 airplane program in the late 1970s, the company created a flight deck technology group with engineers dedicated to the development of the flight management computer (FMC) and the control display unit (CDU) (see fig. 2). Boeing merged previous designs of the performance management computer and the navigation computer into a single FMC that integrated many functions beyond navigation and performance operations. The company used experience gained from Boeing's other research projects to develop advanced implementations of performance management functions and navigation into a single FMC. The new FMC system was envisioned as the heart of an airplane's flight planning and navigation function.

While Boeing was continuing work on new commercial airplane navigation systems for the new "glass" flight decks, a debate was under way among the airlines about the need for a dedicated flight engineer crewmember. In July 1981, an industry task force determined that two-crew operation was no less safe than three-crew operation. This decision would have a profound effect on the design of all Boeing commercial airplanes, including a short-notice implementation for the new 767. With one fewer crewmember, Boeing engineers focused on a flight deck design that would reduce crew workload, simplify older piloting functions, and enhance flight deck efficiencies.

The early 767 FMC provided airplane performance predictions using stored airframe/engine data and real-time inputs from other onboard systems, such as the air data computer and inertial reference system (IRS). This performance function replaced flight crew back-of-the-envelope-type estimates with relatively precise time and fuel predictions based upon actual airplane performance parameters, such as gross weight, speed, altitude, temperature, and winds.

Then, as now, the navigation function was based on the IRS position and used ground-based navaids (e.g., DMEs, VORs, localizers) to refine the IRS position and correct for IRS drift. A navigation database (NDB) was included in the FMC's memory

Figure 2: 757/767 FMC CDU
One of the first implementations of an FMC CDU was designed for the 757 and 767 in the early 1980s.

and contained approximately 100 kilobytes of data consisting of navaids, airways, approach procedures, and airports. The NDB allowed flight crews to easily enter flight plans from takeoff to landing and make real-time route changes in response to air traffic control (ATC) clearances. The FMC also provided guidance to the flight plan route using the lateral navigation (LNAV) and vertical navigation (VNAV) functions. Initially, the FMC was equipped with LNAV only. VNAV was a new challenge and required a significant effort on the part of Boeing and Sperry (now Honeywell) engineers to make the vertical guidance component operational.

After the development of the 757 and 767, Boeing also worked with Smiths Aerospace (now GE Aviation) to develop an FMC as part of a major update to the 737 family. The operation of the 737 FMC, the appearance of the CDU, and the CDU menu structure were designed to parallel those on the 757 and 767. The FMC became part of the design of the 737 Classic family, which included the 737-300, 737-400, and 737-500. The 737-300 was the first of the family to be certified in 1984. Boeing offered the 737 Classic family with either single or dual FMCs and with either the traditional electro-mechanical attitude director indicator/horizontal situation indication flight instrument suite or the EADI/EHSI "glass" flight deck derived from the 757/767 design.

For several years following the initial FMS certifications, minor changes were made to enhance the FMS operation, but no significant hardware or software changes were made until the early 1990s.

DEVELOPING THE MODERN FMC

In the late 1980s and 1990s, the airline industry requested the capability of direct routing from one location to another, without the need to follow airways based upon ground-based navaids. Modern FMS equipped with a multi-sensor navigation algorithm for airplane position determination using VOR, DME, localizer, and IRS data made this possible, and RNAV was transformed from concept to operational reality.

But oceanic operations and flight over remote areas — where multi-sensor updating of the FMC could not occur with accuracy better than the drift of IRS systems — made RNAV operations difficult. Operations in these areas of the world were increasing during the 1990s, and there was pressure on avionics suppliers, airplane manufacturers, and regulatory agencies to find a way to support precise navigation in remote and oceanic areas. As a result, the concept of a future air navigation system (FANS) was conceived in the early 1990s (see *AERO* second-quarter 1998). Subsequently, Boeing and Honeywell introduced the first FANS 1-capable FMC

An RNP system should contain both performance monitoring and alerting: a caution alert is initiated by the FMC and annunciated on the display system to draw flight crew attention in the event that ANP exceeds RNP.

on the 747-400. At the heart of the system was a new, more capable FMC that implemented several new operations:

- Airline operational communications — Digital communication of data (data link) such as flight plans, weather data, and text messaging directly from the airline operations facility to the FMC.
- Controller-pilot data link communications — Digital communication between ATC and the airplane in the form of predefined messages.
- Automatic dependent surveillance — Information about position and intent generated from an ATC request.
- Global positioning system (GPS) — Incorporation of satellite navigation functions in the FMS for the primary means of navigation.
- Air traffic services facilities notification — ATC communication protocol initialization.
- RNP — A statement of the navigation performance necessary for operation within a defined airspace.
- Required time of arrival — Enablement of airplane performance adjustments to meet specified waypoints at set times, when possible.

Although each feature was individually significant, the three primary enablers for FANS operations were RNP, GPS, and data link. RNP defined the confines of the lateral route, and the FMC provided guidance to reliably remain on the route centerline. The FMC's RNP function also provided alerting to the flight crew when this containment might not be assured. GPS was originally a military navigation sensor that was allowed for commercial use with some limitations. Integrated as the primary FMC position update sensor, GPS provided exceptionally precise position accuracy compared to ground-based sensors and enabled the FMC's capability for precise navigation and path tracking. GPS remains the primary sensor for the current generation FMCs. Data link provided a reliable method of digital communication between the airplane and the air traffic controller. A comprehensive list of preformatted messages was implemented to provide for efficient traffic separation referred to as controller-pilot data link communications.

Concurrent with the FANS 1 FMC, Alaska Airlines teamed with Boeing, Smiths Aerospace (now GE Aviation), and the FAA to develop procedures that would provide reliable access to airports that are surrounded by difficult terrain. By virtue of the surrounding rough terrain, the Juneau, Alaska, airport became the prime candidate for the certification effort. Because the approach to runway (RW) 26 was the most challenging air corridor to Juneau, it was selected as the most rigorous test to prove the real performance capability of RNP (see fig. 3).

In 1995, Alaska Airlines successfully demonstrated its ability to safely fly airplanes to RW 26 using RNP and soon began commercial operations using RNP, which was a first for commercial aviation.

RNP: ENABLER OF PBN

The concept of a reliable and repeatable defined path with containment limits was not new. Early conceptual work was done at the Massachusetts Institute of Technology in the 1970s, but the modern FMC, with its position accuracy and guidance algorithms, made reliable path maintenance practical.

The first demonstration of the FMC's terminal area precision came at Eagle, Colorado, in the mid-1980s. A team comprising American Airlines, the FAA, and Sperry (now Honeywell) applied RNP-like principles to approach and departure procedures to the terrain-challenged runway. Following simulator trials, the procedures were successfully flown into Eagle and subsequently approved by the FAA. The result: reliable approach and departure procedures that provide improved access to Eagle.

Although Eagle demonstrated the FMC's capability to execute precisely designed terminal area procedures, in the mid-1980s, it would take another 10 years until RNP equipment was available for airline operators. The FMC's navigation position accuracy enhanced with GPS and lateral and vertical guidance algorithms, the development of the vertical error budget, and additions to crew alerting enabled RNP and its future applications.

RNP is a statement of the navigation performance necessary for operation within

Figure 3: Juneau, Alaska: Site of initial RNP certification efforts

RNP enabled an approach to runway 26 and access to Juneau that in some weather conditions was not otherwise practical.

a defined airspace. The FMC's navigation function ensures containment within the defined airspace by continuously computing the airplane's position. The FMC's actual navigation performance (ANP) is the computed navigation system accuracy, plus the associated integrity for the current FMC position. It is expressed in terms of nautical miles and represents a radius of a circle centered on the computed FMC position, where the probability of the airplane continuously being inside the circle is 95 percent per flight hour.

Boeing flight decks display both ANP and RNP. With the advent of the navigation performance scales (NPS) and associated display features, RNP and ANP are digitally displayed on the navigation display. Additionally, and as defined in regulatory guidance, an RNP system should contain both performance monitoring and alerting: a caution alert is initiated by the FMC and annunciated on the display system to draw flight crew attention in the event that ANP exceeds RNP. That alert typically signifies that the performance of an FMC position update sensor has deteriorated, and, subsequently, the computed navigation system accuracy can no longer ensure containment (see fig. 4).

The FMC's LNAV function continually provides guidance to maintain the lateral path centerline and any deviation from the path centerline is displayed as lateral cross-track error. In Boeing airplanes, cross-track error is displayed on the FMC's "PROGRESS" page or under the navigational display's airplane symbol when NPS is on board. The display provides flight crews with a precise assessment of lateral deviation, particularly important in low RNP environments. Display of cross-track error on the "PROGRESS" page was an original feature in the Boeing FMCs and continues as a fundamental indication of path deviation.

Although RNP operations are increasing in numbers and applications and will provide for the future for PBN, RNAV is also being increasingly implemented for operations where consistent ground tracks are desired. RNAV approaches, standard instrument departures (SID) and standard terminal arrival (STAR) procedures are being produced primarily throughout the United States and in selected areas of the world. RNAV leverages the original path management capability of the FMC and, unlike RNP, lateral containment was not specified. From an operational point of view, RNP is RNAV with containment. If a path is defined and active in the route, the FMC is designed to maintain the centerline of the path. That basic operation has not changed since the original 767 FMC.

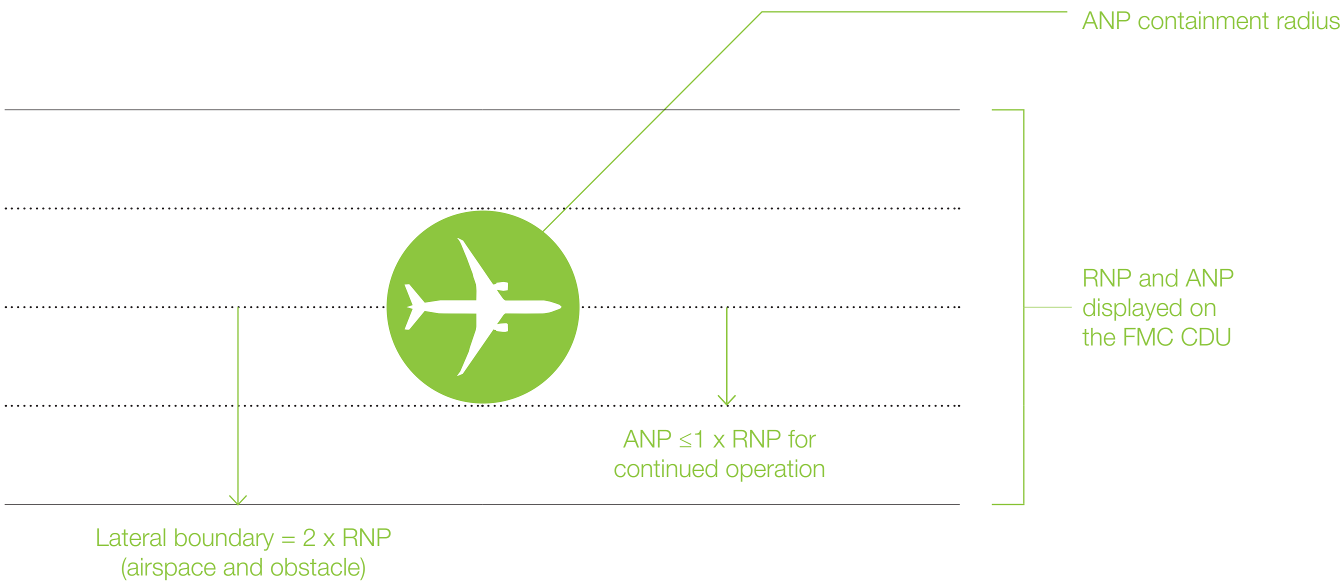
CONTINUED FMC MODERNIZATION

The 737, 747-400, MD-80, and MD-11 FMC functions that enabled RNP were reasonably robust for the initial RNAV and RNP operations, but each of the Smiths (now GE) and Honeywell FMCs on Boeing airplanes continued to be updated with software improvements and new hardware versions with enhanced processing power and memory. Some enhancements specifically related to RNP include:

- Vertical RNP — Introduced the capability with which to define containment relative to the computed VNAV path (see fig 5).
- Radius to fix legs — Implemented the ARINC 424 leg type that provided a fixed radius ground path (similar to a DME arc but without the required navaid).
- En-route fixed radius transitions — Implemented a fixed radius transition between en-route path segments, to enable the implementation of reduced route spacing in higher-density traffic environments (currently 737 only).
- GPS availability — Refined algorithms that enhanced the navigation performance for very low RNP procedures.
- LNAV tracking — Enhanced the precision and aggressiveness of LNAV path tracking.
- NPS — Provided data to the display system for lateral and vertical path deviation scales, deviation pointers, and sensor performance indications.
- RNP from the NDB — Enabled application of RNP values coded in the NDB for routes and procedures.

Figure 4: RNP in practice

RNP defines the path and allowable tolerance for continuous operation (+ 1 RNP). Containment to ensure obstacle clearance is defined as + 2 x RNP. ANP less than the prescribed RNP provides position assurance for continued operation.



As a result of these enhancements and additions to other FMC functions, the modern FMC is well-equipped for RNP operations that will enable future airspace management concepts.

THE PROMISE OF PBN

PBN, which comprises both RNAV and RNP specifications, provides the basis for global standardization, which will facilitate future airspace design, traffic flow, and improved access to runways. This change offers a number of operational benefits, including enhanced safety, increased efficiency, reduced carbon footprint, and reduced costs. To fully realize these benefits, operators may need to make changes to their airplanes and operations.

The primary premise of a PBN system is to move away from restricted, sensor-based operations to a performance-based navigation system that incorporates RNP as the foundation and a system in which operational cost efficiencies are emphasized (see fig. 5). According to the International Civil Aviation Organization Performance-Based Navigation Manual, airspace procedures should be designed to reduce track miles, avoid noise-sensitive areas, and reduce emissions through the use of efficient descent paths by minimizing terminal area maneuvering (i.e., unwanted throttle movement) and periodic altitude constraints.

AIRSPACE MODERNIZATION

The current airspace system of airways and jet routes has not changed significantly since the inception of non-directional beacons and VORs in the middle of the last century. Incremental improvements,

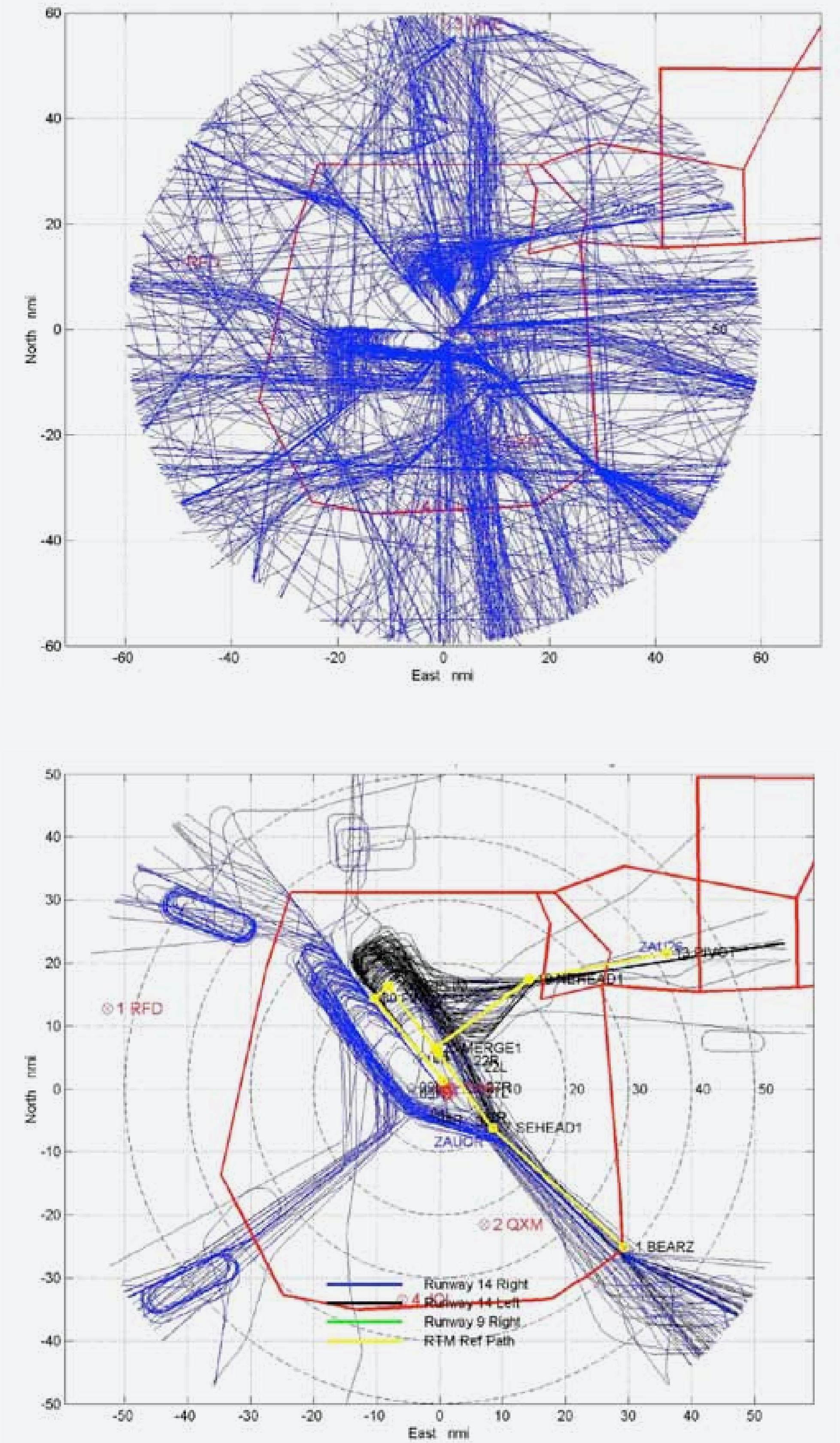


Figure 5: Benefits of PBN

These actual traffic plots at a major airport demonstrate the efficiencies that can be realized when a PBN design is implemented. Track miles can be significantly reduced through reduced vectoring, saving time, fuel, and emissions. Additionally, convective weather, restricted airspace, and noise-sensitive areas can be avoided using either designed procedures or dynamic rerouting.

such as RNAV en-route waypoints, RNAV SIDs and STARs, FANS dynamic rerouting, and Q-routes, have been implemented, but the general structure of the airspace still reflects historic ATC methods.

In a direct contrast to the PBN approach, the increased traffic since the early 1990s has necessitated more complex arrival and departure procedures — procedures that frequently inflict a penalty on fuel efficiency with an added consequence of increased potential for flight crew error.

The PBN concept is centered on operational efficiencies. Several successes have already been realized. Procedure and airspace designers in Canada and Australia have worked with operators to plan routes and terminal area procedures that reduce track miles while addressing environmental issues that are receiving increased scrutiny by the public and government. Both Europe and the United States are implementing RNAV and RNP procedures.

FUTURE CONCEPTS

Advanced airspace environments include the FAA's Next Generation Air Transportation System, which will transform the current ground-based ATC system to satellite-based, and Europe's Single European Sky ATM Research (SESAR). Migrating to these environments will require fundamental changes to air traffic management methodology. The airspace structure, procedure design, and traffic control methodology will need to focus on safety *and* efficiency if capacities are to increase at major airports and operators are able to maintain fuel costs within reason.

Concurrent with the airspace evolution, the FMC will continue to require enhancements that either control or participate with other onboard systems for new traffic control methods. These methods include time-based metering, merging and spacing, self-separation during continuous descent arrivals and/or during the final segment, automated dependent surveillance broadcast, and cockpit display of traffic information. New terminal procedures, such as a hybrid RNP procedure that terminates in an instrument landing system or a global navigation satellite system landing system final and autoland, are already in the FMC's repertoire. However, considerations to the associated flight mode annunciator changes during the transition from FMC-based guidance to autopilot guidance on short final and other crew distractions will require attention. The new 787 and 747-8 FMCs are addressing some of these issues and implementing enhancements that position those models for future PBN operations. Additionally, each of the FMC designs has incorporated growth options so that changes to the FMC can be made with minimal impact to the FMC software.

Flight crews will see significant improvements in speed, capability, and operation of the 737 FMC and the new FMCs in the 787 and 747-8 airplanes. Although modern in every respect, each of the FMCs is operationally similar to the original 767 FMC of the early 1980s. To address system complexity and enhance the operational capability of the flight crew for the transition to the Next Generation Air Transportation System, Boeing and its partners are investigating new flight management methodologies that focus on flight path trajectory management and ease of operation. Such new systems will assist the flight crew in managing the trip costs and contribute to a safe conclusion to each flight.

SUMMARY

Flight management systems have evolved to a level of sophistication that helps flight crews fly commercial airplanes more safely and efficiently, while enabling PBN through application of RNP and the evolution to future airspace management systems.

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