Aircraft Landings: The GPS Approach

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The Global Positioning System, considered by many to be the greatest advance in aviation since the invention of the jet engine, will revolutionize the operation of aircraft all around the world. Not only will it direct pilots to the vicinity of an airport, it will also be able to guide a plane along a runway approach route and even permit automatic landings. To enable more efficient operations, air navigation service providers are designing new approach procedures for aircraft using GPS. In this month's column, George Dewar examines these new GPS approaches and how they differ from approaches using conventional navigation aids.

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"Innovation" is a regular column featuring discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who appreciates receiving your comments as well as topic suggestions for future columns. To contact him, see the "Columnists" section on page 4 of this issue.

You might not notice it from the passenger seat, but the next time you fly, your pilot could be using GPS to navigate the plane. Many regulatory agencies, including Transport Canada and the U.S. Federal Aviation Administration (FAA), have sanctioned the use of unaugmented (stand-alone) GPS as a supplemental navigation system for all phases of flight, including nonprecision approaches and landings. Unaugmented GPS does not have the accuracy or integrity required to use it as a primary navigation system for precision approaches; however, in remote areas and over oceans, GPS can be used as a primary system.

Within the next few years, the Wide Area and Local Area Augmentation Systems (WAAS and LAAS) will come into use, permitting GPS use as a primary system for all phases of flight and, in the case of LAAS, enabling aircraft landings with extremely limited visibility. In the meantime, the use of unaugmented supplementary GPS in the cockpit is growing exponentially.

Flying with GPS, especially in the last stages of flight (the approach and landing) is different from conventional flying, and special procedures have been developed for GPS use. In this article, we'll examine those procedures and how they are designed. But first, let's learn the rules of the "road."

APPROACH BASICS

Just as we have rules to govern how we drive our cars and thereby maintain order on the roads, pilots have rules to maintain order in the air. There are actually two sets of rules — visual flight rules (VFR) and instrument flight rules (IFR) — and they apply to aircraft both small and large, depending on the situation.

VFR operations require the pilot to fly clear of clouds and conduct landings and takeoffs in good visual conditions. This is basically a "see and be seen" situation. GPS allows VFR pilots to maintain an accurate track if conventional navigation aids don't exist or map reading is difficult.

IFR operations can be conducted in conditions of zero or restricted visibility, for example, during the night and when landing and taking off in low cloud ceilings. When flying IFR, pilots rely on navigation instruments in conjunction with instructions from air traffic control agencies issuing clearances for routes and altitudes. In congested areas, air traffic controllers essentially "steer" aircraft using radar vectoring.

To ensure an orderly flow of traffic, most phases of flight must follow a track, or flight path, that coincides with ground-based navigation facilities. This requirement has always been a major constraint on IFR operations. The ability to navigate with a high degree of accuracy, independent of ground-based facilities, is considered the most beneficial aspect of GPS with regard to aviation.

Precision and Nonprecision Approaches. Aeronautical navigation involves four phases of flight: en route, terminal, approach, and departure. En route navigation encompasses point-to-point navigation, usually between cities. Departure navigation is the portion of flight from take-off to the en route phase. And terminal navigation refers to the transition between the en route phase and the approach, or landing phase. For approaches, there are two basic procedures: precision and nonprecision.

A navigation system permitting a precision approach provides both lateral (horizontal) and vertical guidance to a decision altitude/height (DA/H). If the required visual references, such as approach lights or the runway environment, are not in view at the DA/H, a pilot must execute a missed approach — that is, a specified, controlled routing away from the runway.

A nonprecision approach (NPA) provides lateral guidance only and uses a minimum descent altitude (MDA). MDA is defined as an altitude below which an aircraft must not descend until visual reference has been established (see Figure 1). Typically, MDAs range from 300 to 500 feet, but the actual value depends on the presence of obstacles such as hills, buildings, or towers in the airport's vicinity.

The International Civil Aviation Organization is in the process of introducing a new approach term — a nonprecision instrument approach procedure with vertical guidance (IPV). IPV bridges the gap between the precision approach lateral and vertical guidance and the nonprecision approach lateral-only guidance, allowing procedure designers to isolate obstacles that constrain the landing limits on a typical NPA. It recognizes the capability of modern aircraft to establish onboard system–derived vertical guidance using a navigation database and barometric altimetry. IPVs can be based on GPS, and some are already being evaluated by commercial operators in VFR weather conditions.

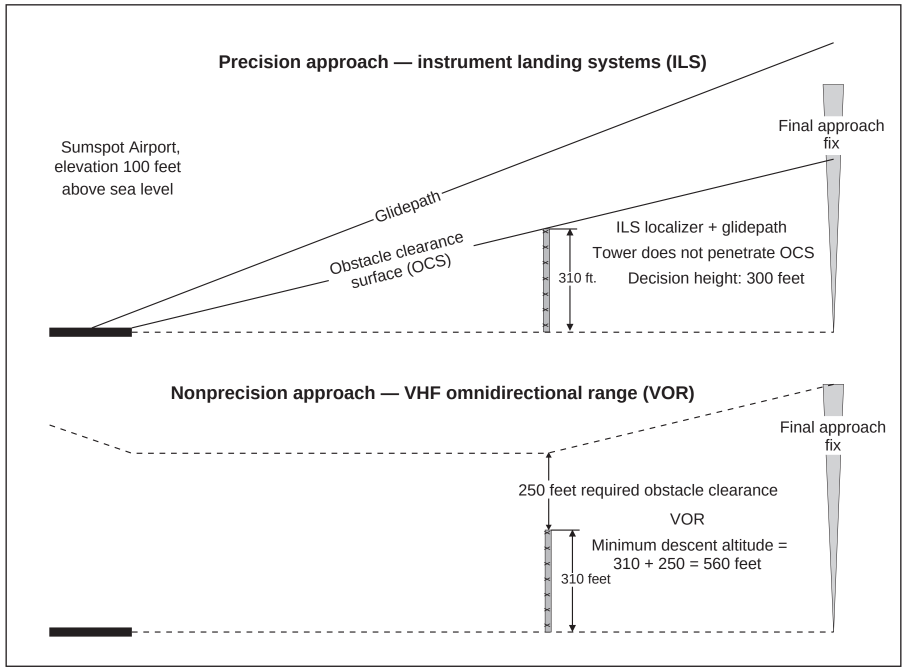

Figure 1. Profile views of a nonprecision VHF omnidirectional range (VOR) procedure and a precision instrument landing system (ILS) procedure illustrate how lower landing limits are achieved with a glide slope.

CONVENTIONAL PROCEDURES

Large urban centers typically have an airport equipped with expensive precision approach facilities, such as an instrument landing system, which allows operations in weather conditions of 200-foot ceilings and 0.5-mile visibility or less. Some of these airports have facilities installed that allow appropriately-equipped aircraft and trained flight crews to land under conditions of very low visibility without any weather ceiling restrictions.

An NPA based on GPS would not significantly enhance operations at these large urban airports. Instead GPS's potential is currently greatest at second- or third-level locations where the traffic counts do not warrant expenditures on the more conventional navigation aids. Nonetheless, to understand the benefits of GPS NPAs, it is important to review how conventional navigation tools are employed in nonprecision approaches.

VORs and NDBs. One of the most common ways of providing NPA capability is with a VHF omnidirectional range (VOR) or a nondirectional beacon (NDB) system. VORs are primarily used as en route navigation aids for operations that demand relatively precise guidance. In some cases, though, VORs are located in such proximity to an airport that they can also provide approach guidance. VOR stations transmit modulated signals in the 108–117.975-MHz band. A receiver on board an aircraft measures the relative phase of the signal modulations to determine the azimuth of the aircraft relative to the transmitter.

NDBs are also employed as en route and approach navigation aids, and because of comparatively low costs, their use is widespread. These nondirectional transmitters operate in the low- and medium-frequency bands (190–435 kHz and 510–535 kHz in North America). The signals are modulated to aid identification. An automatic direction finder on the plane establishes the bearing of the transmitter with respect to the aircraft heading.

If an NDB is placed on the approach path to a runway, it is possible — though rarely achieved — to obtain an MDA as low as 300 feet above the runway. Typically, the presence of obstacles along the approach path necessitates higher MDAs. If it is not possible to locate the NDB on the runway approach path, the situation becomes even worse because of the requirement to assess a larger area for obstacles. An NDB placed at the airport requires obstacle assessment in an area that may extend to as much as 15–20 nautical miles. In some extreme cases, MDAs may be above what is required to fly under the visual flight rules!

A VOR has an inherent advantage over an NDB because of smaller obstacle assessment areas resulting from more precise guidance. In addition, most VORs have associated distance measuring equipment (DME) that can provide an aircraft with more precise positioning along flight paths, enabling obstacles behind the aircraft to be excluded from assessment. DMEs work on a two-way ranging principle. An interrogator in the aircraft sends out a pulsed signal that a DME ground station picks up. The station then replies with a similar signal. The DME instrument on board the aircraft computes the distance to the station from the signals' round-trip travel time. This technique uses frequencies in the 960–1215-MHz range. In some cases, DMEs have been installed and collocated with NDBs in an effort to achieve lower MDAs.

GPS APPROACHES

Conventional navigation aids have a high degree of reliability, but this is offset by costs of installation and ongoing maintenance. In the early part of this decade, therefore, various agencies that regulate aviation began to formulate specific plans to take advantage of the less expensive and more reliable navigation potential of the growing GPS constellation. But the existing design standards and criteria for instrument approach procedures (IAPs) based on existing navigation aids could not be used to define the obstacle assessment areas required to accommodate GPS (see Figure 2).

"T" Configuration. GPS NPAs can be configured in many ways, with the most common configuration referred to as the "T" and composed of at least five segments delineated by geographic waypoints (see Figure 3). A waypoint is nothing more than a ground point with assigned coordinates. Essentially, a GPS NPA is a series of waypoints joined by tracks, with each waypoint contained within an obstacle clearance area (see Figure 4). Each obstacle clearance area has primary and secondary zones, and the extremities of successive areas are joined to create a procedure's various segments. The typical configuration consists of two initial segments, one intermediate, one final approach, and one missed approach.

In the initial segments, an aircraft transitions from the en route phase to the terminal phase. The intermediate segment is designed to allow an aircraft to reduce speed and configure for approach and landing. The speed reduction can be significant and the intermediate segment must be long enough to allow the gradual reduction of air speed. At the final segment, the aircraft stabilizes at the approach speed and descends toward the runway. In the event a pilot does not obtain the visual references required for landing by a specified point along the final approach, he or she must fly the missed approach segment to the missed approach holding waypoint. While situations requiring a missed approach are relatively uncommon, they do occur (especially in bad weather conditions), so the missed approach is an integral part of any procedure.

DESIGN PROCESS

There are numerous methods used to design GPS NPAs, with differences mostly in the degree of automation adopted during the design process. The most basic method relies on drafting the procedure on a map. Typically, a designer will use a 1:50,000-scale topographical chart, which provides terrain information as well as functions as a base for plotting data — usually obtained from databases maintained by aeronautical information agencies — about human-made structures. In addition to basic drafting tools, a computer program capable of calculating geographic positions is essential.

The starting point for designing most procedures is the first usable portion, or threshold, of the runway. Threshold positions and runway profiles are obtained from airport operators and plotted on the procedure chart. In addition, designers also need to take into account such factors as terrain, traffic patterns, noise-sensitive areas, restricted zones (for example, military areas), and aircraft performance. With these basics in place, the designer, whose primary mission is to

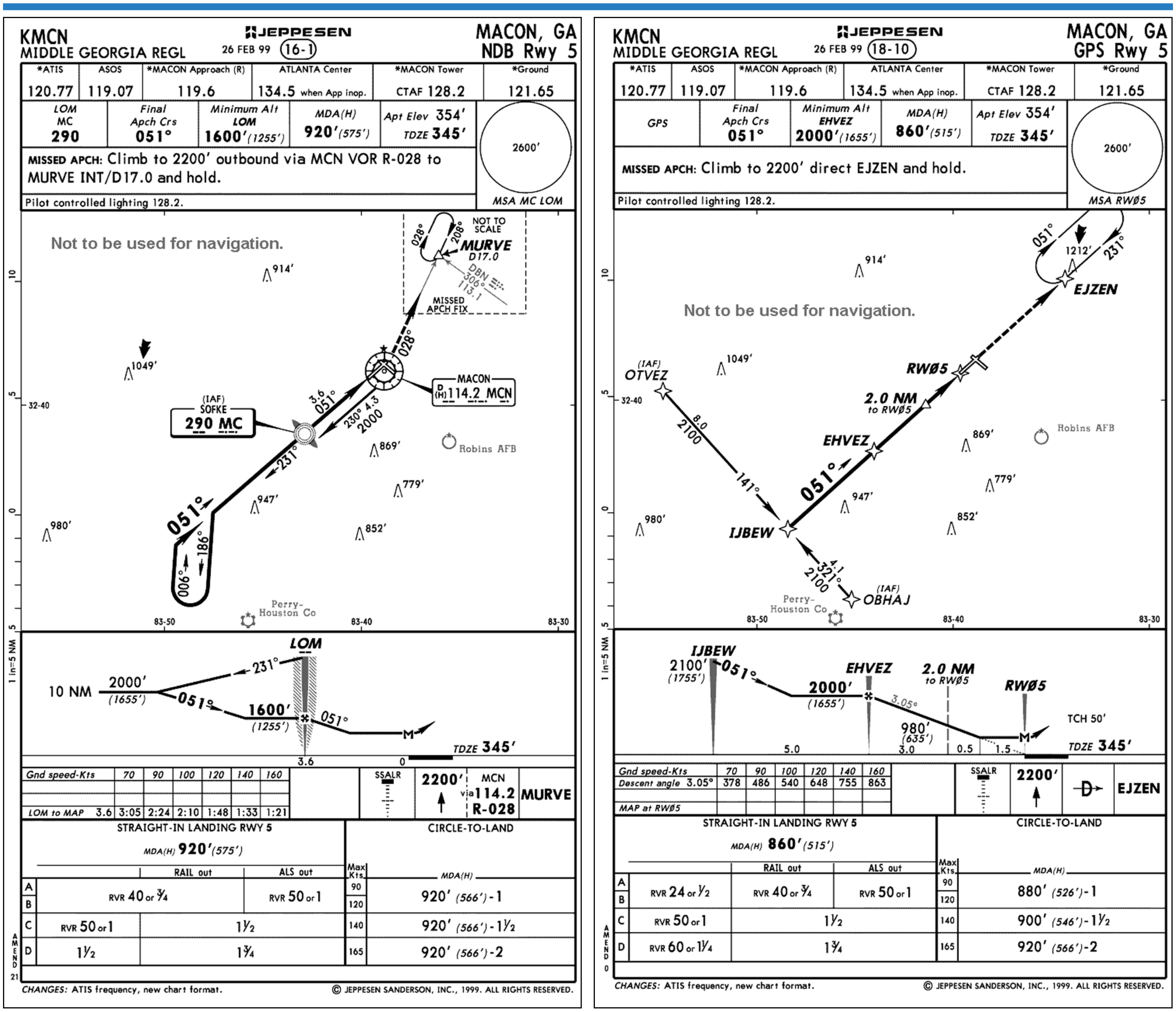

Figure 2. NDB (left) and GPS (right) procedures for runway 05 at Middle Georgia Regional Airport, Macon, Georgia. Slightly lower landing limits are obtained with the GPS procedure.

achieve the lowest MDA consistent with safety, can begin to develop the GPS approach procedure. He or she starts with the final segment to make optimizing MDA as easy as possible.

Final Segment. The final segment (see Figure 5) starts at the final approach waypoint (FAWP) and ends at the missed approach waypoint (MAWP). MAWP is usually located at the landing runway threshold.

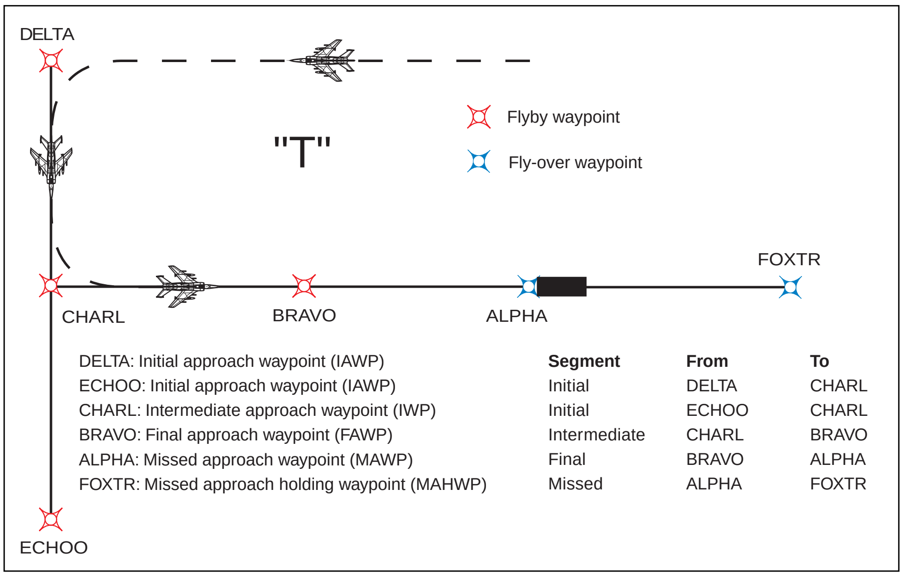

Figure 3. A typical GPS "T" configuration. Waypoints are usually identified using five-letter names.

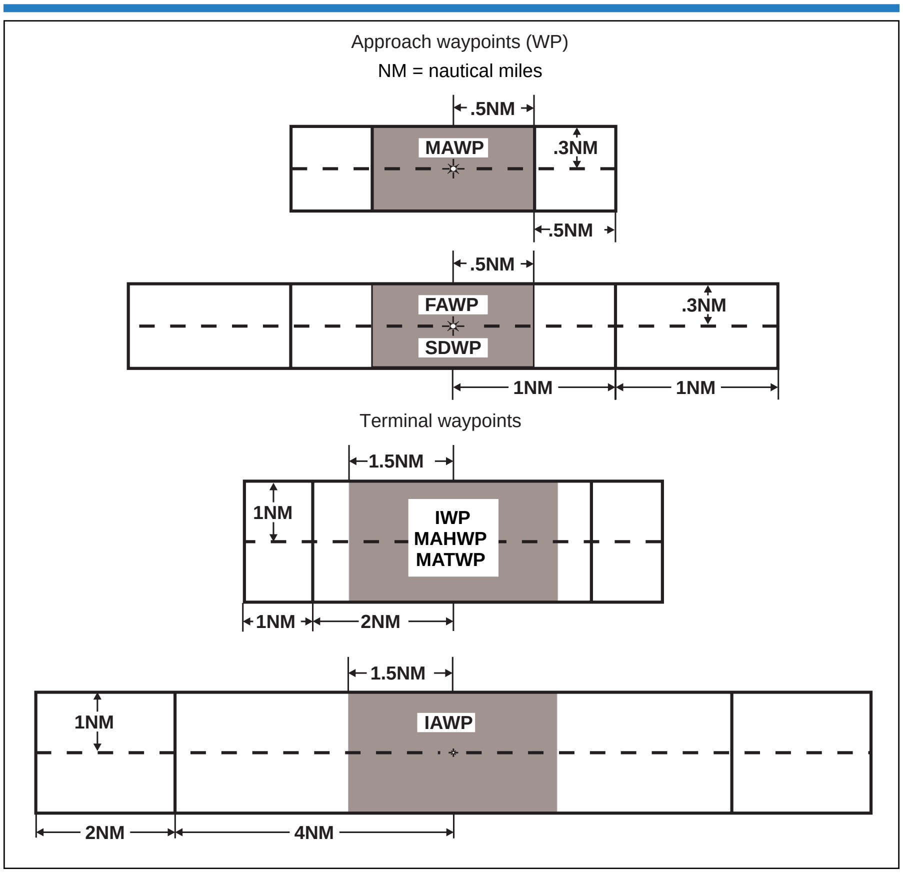

Figure 4. Fix displacement tolerance areas (shaded) and obstacle clearance areas associated with the various waypoints used in a GPS procedure

The designer begins by locating natural obstacles and plotting the positions of human-made obstructions in the general area of the runway approach. He or she can then use transparent templates, scaled to various segment lengths, to determine how to minimize the effect of those obstacles.

Ideally, the final segment should be aligned with the extended runway centerline (RCL), but, if this alignment results in too high an MDA, the designer has the option of realigning the approach track as much as 15 degrees from RCL. Realignment can result in some obstacles falling outside the segment or within the secondary areas, lessening the required obstacle clearance (ROC).

Another option is to use a stepdown waypoint to divide the segment, thus isolating an obstacle. In some extreme cases, the final segment can be made as long as 10 nautical miles to effectively narrow the areas and reduce ROC. However, this long final approach invokes other procedural penalties, such as the excessive time required to fly the procedure.

Once the final segment is configured, one must calculate MDA. In the primary area, a 250-foot ROC is added to the height of the controlling (highest) obstacle within the

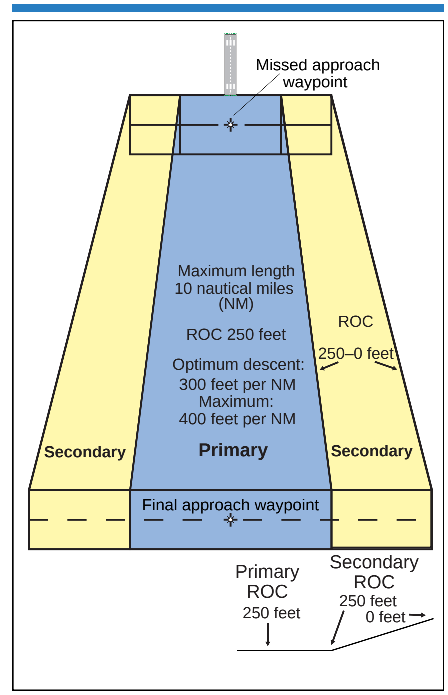

Figure 5. The primary and secondary areas plus operational parameters of a final approach segment. The required obstacle clearance (ROC) within the primary area is 250 feet. This reduces linearly to zero feet at the periphery of the secondary area.

final approach segment. This value is then rounded up to the next highest 20-foot increment. ROC in a secondary area is 250 feet at the inner boundary and zero feet at the outer boundary — resulting in a 125-foot ROC if an obstacle lies halfway between the two boundaries.

A designer must also account for the maximum allowable rate of descent in developing the final segment to enable an aircraft to smoothly transition to level or ascending flight. This maximum rate is 400 feet per nautical mile, which corresponds to a glide slope of about 4 degrees with respect to a horizontal plane. Ideally, an aircraft should descend at 300 feet per nautical mile (an approximately 3-degree glide slope), but in an extreme case, a procedure could require a 1,600-foot decent in a 4-mile final segment, thus yielding the maximum rate.

Missed Approach Segment. Coincident with configuring the final segment, the designer must ensure that the target MDA will allow for obstacle clearance in the missed approach segment. The missed approach segment starts at MAWP and ends at the missed approach holding waypoint (MAHWP), where an aircraft either transitions to an en route phase leading to another airport or enters a holding pattern while awaiting clearance to commence another approach.

Approximately half the GPS IAP standards manual issued by FAA is devoted to describing the various missed approach options available to the designer. The most desirable option is one that is easiest to fly — usually a straight segment that essentially continues the final segment. If obstacles prevent a straight segment, the designer can elect to design a turning segment or even a combination of straight and turning segments. In a missed approach procedure using a turn, a missed approach turning waypoint (MATWP) is established. Although the available options are many, all are based on the requirement that an aircraft maintain a minimum climb rate of 200 feet per nautical mile, which provides increasing absolute altitude above a 1:40 obstacle clearance slope throughout the entire missed approach segment.

The areas assessed for obstacles in a basic straight missed approach start at MAWP and splay to a width of 6 nautical miles on either side of the required flight path along a 15–nautical mile track distance. If the aircraft maintains a prescribed track while flying the segment (positive track guidance), the designer can use secondary areas to minimize the effect of obstacles much the same as in the final segment. Figure 6 illustrates the effects of a 1,000-foot obstacle on MDA both with and without secondary area reduction.

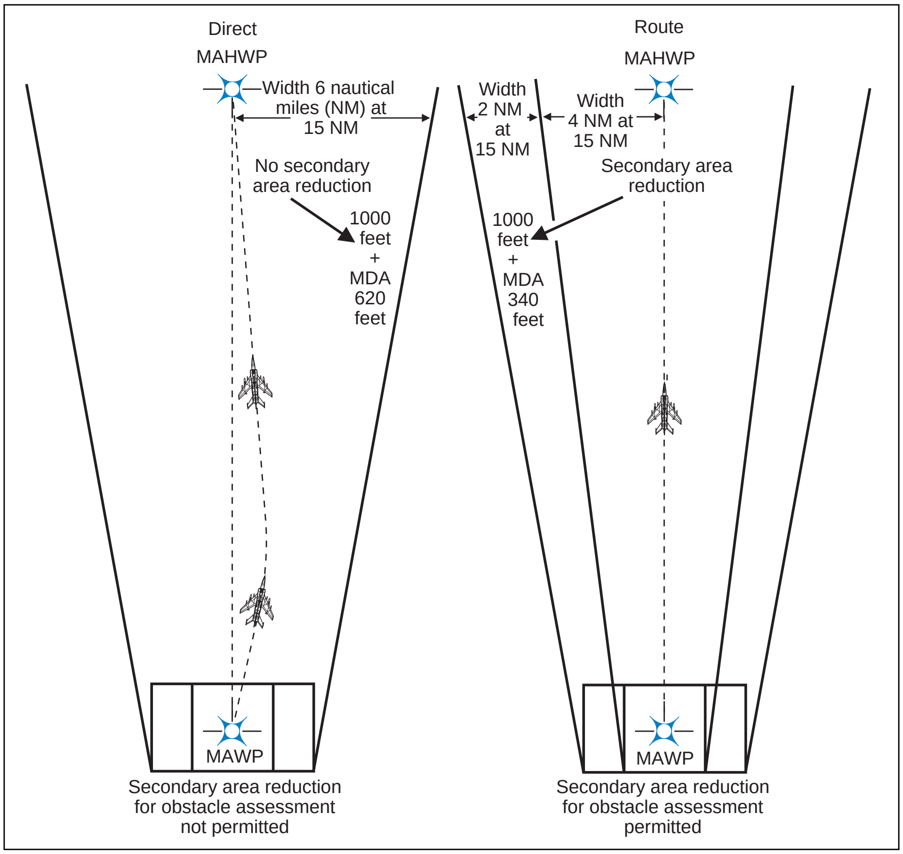

Figure 6. Two types of missed approach segments (from the missed approach waypoint [MAWP] to the missed approach holding waypoint [MAHWP]) showing the lower minimum descent altitude (MDA) possible using secondary area reduction

When the designer has located the obstacles in the primary area, he or she determines whether there is an obstacle identification surface rising at 1:40, penetrating the missed approach segment. This surface starts at the farthest point of the MAWP obstacle clearance area at an elevation 250 feet below MDA. If an obstacle crosses this surface, the designer would be forced to raise MDA to ensure a 250-foot ROC above that obstacle. If there is positive track guidance, an obstacle in the secondary area is assessed using the 1:40 surface to a point on the primary/secondary boundary line and then a 1:12 slope. (It is assumed that the probability of an aircraft deviating into the secondary area is reduced through positive track guidance, thus justifying the less restrictive 1:12 slope.) Obstacles falling under the 1:12 slope have less impact and thus may allow the designer to lower the MDA.

Waypoint Position Calculation. With the obstacle assessment of the final and missed approach segments complete, and assuming that MAWP is coincident with the threshold, the designer can start calculating waypoint positions. If the final approach and missed approach segments are aligned with the extended RCL, the position of FAWP and MAHWP can be calculated employing both runway threshold positions. The designer calculates the forward bearing of the runway and then uses the runway reciprocal bearing along with the final segment's required length (usually 5 nautical miles) to determine the FAWP position. If the intermediate segment is aligned with the final segment, the position of the intermediate waypoint (IWP) can also be calculated using the reciprocal of the runway bearing and the total length of the final and intermediate segments. The MAHWP position is calculated using the missed approach segment length and the runway's forward bearing.

When an operational necessity requires a procedure configuration other than the basic "T," the designer may have to deal with one of four possible scenarios when placing MAWP: 1) MAWP is at the threshold, but the final segment track is not aligned with the runway; 2) MAWP is on the extended RCL but displaced to a position prior to the threshold; 3) MAWP is on the extended centerline with the final segment track but not aligned with the runway; or 4) MAWP is displaced from the centerline and, in accordance with FAA criteria, the final segment track extends to the runway threshold. In all cases, MAWP is used as the reference for calculating FAWP and MAHWP positions, but the runway threshold becomes the reference for calculating the position of MAWP. Calculating the MAWP position, in these situations, has to account for distance from the threshold and, if applicable, the final segment track's displacement from the reciprocal of the runway bearing.

Intermediate Segment. With the final segment in place and the FAWP calculated, the designer must decide the length and alignment of the intermediate segment, which starts at the earliest point of the IWP obstacle assessment area and ends at the plotted FAWP position. This transition between the terminal and approach phases basically allows a reduction in airspeed, constraining the designer to a maximum allowable descent rate of 300 feet per nautical mile.

The intermediate segment must be 5–15 nautical miles long and aligned within 30 degrees of the final segment. ROC in the primary area is 500 feet with secondary reductions allowed. If the segment is realigned to gain an operational advantage, such as avoiding obstacles, FAWP is used as a reference, with the bearing change and distance determining the IWP position.

Initial Segment. The initial segment starts at the earliest point of the initial approach waypoint obstacle assessment area and ends at the plotted IWP position. The segment has no standard length but should not exceed 50 nautical miles. In addition, alignment relative to the intermediate segment should be 120 degrees or less. In the primary area, 1,000 feet of ROC is applied, and in the secondary area, ROC is 500 feet at the inner boundary decreasing to zero feet at the outer boundary.

To allow approaches from either direction, the "T" configuration will have two initial segments placed at 90 degrees to the intermediate segment. If the designer wishes to deviate from the "T," he or she can develop procedures without initial legs or with more than two initial segments to accommodate unique traffic flows or extreme terrain.

FLYBY, FLYOVER WAYPOINTS

With all segments in place, the designer must address an aspect of GPS procedures that is not a factor in the design of procedures based on conventional navigation aids. Flyby and flyover denote the two basic types of waypoints that join various segments in a GPS nonprecision approach. As the names imply, an aircraft will either go directly over a waypoint before transitioning to the next segment or transition to a succeeding segment by turning prior to a waypoint.

Turning prior to a waypoint is referred to as *automatic turn anticipation*, which is defined by FAA, in its GPS criteria, as "the capability of GPS airborne equipment to determine the point along a course, prior to a turn waypoint, where a turn should be initiated to provide a smooth path to intercept the succeeding course, and to enunciate the information to the pilot." The two waypoints designated as flyover in a procedure are MAWP and MAHWP, whereas the rest of the waypoints are flyby. Automatic turn anticipation for flyby waypoints requires the designer to expand the obstacle clearance areas if there are turns of more than 15 degrees at IWP, FAWP, or MATWP.

FLIGHT INSPECTION

With the paper phase of the design process complete, the procedure now has to undergo an operational evaluation before it can be published. Different service providers have various types of organizations set up to design and publish procedures.

An operational pilot may design a procedure as well as complete the flight check. Or a technician may design the procedure for a flight inspection group to operationally evaluate. In either case, the flight inspection will assess the procedure's "flyability" and confirm the presence of obstacles, waypoint positions, and GPS signal availability. The procedure for a given airport will only be released for publication after a flight inspection pilot has certified that it is safe and flyable.

System Errors. The development of standards and criteria for any navigation system takes into account total system error (TSE). TSE is the result of two error components: navigation system error (NSE) and flight technical error (FTE). Regulatory agencies standardize and publish NSEs, which are based on the signal characteristics of a particular navigation source. FTE compares the actual aircraft position to the required position.

To obtain accuracy measurements, analysts usually employ a "truth system," such as a laser tracker, to gather data from a large number of flights (more than 100). They then use the data to establish a profile or "distribution" of errors from which they calculate TSE.

With TSE and NSE known, FTE can be determined. All errors are usually expressed as a standard deviation (sigma or SD) about the mean. Two SDs correspond to a 95-percent chance that the true value is within the stated range. The 95-percent value is usually regarded as acceptable for defining primary area dimensions when assessing obstacles in the various IAP segments. The necessary total protection from obstacles, taking into account a large number of aircraft, has been targeted at 1×10^{-7}. This value corresponds to about 5.3 SDs or 99.99999 percent. The total area considered for obstacle protection is then said to capture approximately 5.3 SDs of the population.

FURTHER READING

For an introduction to GPS use in aviation, see

■ *Aviator's Guide to GPS,* by Bill Clarke, 3rd edition, McGraw-Hill Book Company, New York, 1999.

For an overview of U.S. air navigation policy, see

■ *1996 Federal Radionavigation Plan,* published by the U.S. Departments of Transportation and Defense, DOT-VNTSC-RSPA-97-2/DOD-4650.5, Washington, D.C., 1997. A PDF file of the plan is available online from the U.S. Coast Guard Web site: <http://www.navcen.uscg.mil/policy/>. The 1998 version of the plan is due imminently.

For details about the design of instrument procedures, see

■ *U.S. Standard for Terminal Instrument Procedures (TERPS),* Publication 8260.3C with amendments through Change 17, Federal Aviation Administration, Washington, D.C., 1993. A PDF file of this publication is available online from a U.S. Air Force Web site: <http://afpubs.hq.af.mil/elec-products/pubpages/11-pubs.stm>.

■ *Procedures for Air Navigation Services (PANS) Aircraft Operations (OPS),* Vol. 1, *Flight Procedures (8168-1)* and Vol. 2, *Construction of Visual and Instrument Flight Procedures (8168-2)* plus amendments, International Civil Aviation Organization, Montreal, Canada, 1993.

For recent developments concerning instrument approach procedures and a pilot's assessment of those developments, see

■ <http://www.terps.com/>.

CONCLUSION

An experienced designer will begin the design process by developing a concept of how the procedure can accommodate terrain, traffic flow, and aircraft type. Once the designer has this concept formed, the process of fitting the individual segments together can begin. Each segment described in this article has defined dimensions and parameters that guide the designer toward an approach that meets published standards and operational needs. The most desirable procedure is one that will allow the type of aircraft using it to be operated efficiently.

FAA and Transport Canada have already published over 1,000 GPS approaches, with more being added each month. The increased navigation accuracy that GPS provides, and the ability to define routes in three dimensions, will lead to much more efficient use of airspace. Eventually, with the full implementation of the concept of "free flight," in which GPS plays a prominent role, a pilot will be able to choose and vary his or her route essentially at will. Among other advantages, direct routings between airports will result in reduced fuel usage. The financial savings for commercial operators will be enormous.

ACKNOWLEDGMENT

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