All-Weather Ops

Approach guidance has evolved from four-course ranges to satellites.

BY TOM IMRICH

"All-weather operations" is a term typically used to describe the use of nonprecision and precision instrument procedures to conduct low-visibility takeoff and landing operations. This article briefly outlines the history of all-weather operations — focusing on the progression from road maps, pilotage and dead reckoning to the first generations of approach guidance to modern satellite-based instrument approach procedures — and takes a look at where we likely are heading for future all-weather operations.

The ability to conduct all-weather operations is critical to both the safety and regularity of global air carrier operations. Without this capability, air carrier operations would not be practical, economical or even possible. But all of the tools available are not being used to their full potential. Safety in all-weather operations today can be significantly improved by applying methods and techniques based on instrument procedures with vertical as well as lateral precision guidance. These include required navigation performance (RNP) procedures and continuous-descent approach operating procedures for aircraft not equipped with flight management systems (FMSs).

The Early Years

The need for all-weather operations, to expand operational capabilities and improve safety, was recognized in the earliest days of aviation. In the 1930s, the ability to conduct all-weather operations was deemed vital to ensure essential activities such as mail delivery and military operations in bad weather and at night.

The need to fly at any time drove the requirements for marking and lighting airways, designating landmarks and lighting and marking airports. It also led to the replacement of road maps with aviation-specific charting, beginning with the detailed notes taken by Elrey Jeppesen during mail runs, and the establishment of rules of the air, including instrument flight rules (IFR) and visual flight rules (VFR), and air traffic separation services, primarily for flying in bad weather.

The evolutionary steps included improvements of aircraft equipment — gyroscopic flight instruments and radios, for example — and external aids, including light beacons at first and later radio beacons such as the four-course visual-aural radio range (VAR), nondirectional beacon (NDB), marker beacons and eventually the VHF omnidirectional radio (VOR).

Simply finding the destination airport in bad weather was hard enough in the early years of aviation. Aligning with the runway and descending precisely during the final stages of a flight typically were tasks accomplished after visual contact was made with the field. The early goals of instrument approach procedures were to define a safe lateral path and specify safe minimum altitudes for the approach and, if unsuccessful, the missed approach. This led to the largely two-dimensional nature of nonprecision instrument approach procedures based on the four-course range, NDB, VOR and later the localizer.

Vertical Guidance Evolves

By the end of World War II, instrument flying had evolved to the point of enabling aircraft to fly in most instrument meteorological conditions (IMC), albeit with significant safety risk remaining in some situations. A comprehensive system of radio navigation aids (navaids), including radio ranges and NDBs, was deployed; charts depicting airways and instrument approach procedures were published; and the early foundations were laid for an airway system largely based on VORs. Early instrument landing systems (ILSs), which provide precise alignment with the runway centerline as well as high-quality vertical guidance to a relatively low height, began to appear.

ILS and ground-controlled approaches (GCAs) were the first real attempts to define a precise lateral path to a runway centerline and a corresponding precise vertical path to fly until the pilot could see the runway to visually complete the approach. These approaches that added the vertical guidance component later became known as precision approaches, or three-dimensional approaches.

Meanwhile, NDB, VOR and tactical air navigation (TACAN) systems and procedures continued to evolve.[1] Their use expanded globally, in parallel with evolving ILS approaches and ground-controlled approaches using precision approach radar (PAR), systems that were significantly more expensive to install at airports. Some approaches also required additional expensive airborne equipment. Hence, ILS and PAR installations were limited to large, busy airports with a high demand for all-weather-operations capability. ILS was predominant for air carriers that could afford to install the required aircraft equipment.

As en route surveillance radars became increasingly used for air traffic separation, airport surveillance radar (ASR) approach procedures also proliferated, but they remained largely two-dimensional.

The localizer centerline guidance component of the ILS could be used by aircraft — typically, general aviation aircraft — that did not have glideslope receivers, leading to the establishment of localizer and back course localizer approach procedures to provide at least a partial benefit from ILS systems, albeit only two-dimensional guidance.

Instrument approach design criteria were incorporated in the *United States Standard for Terminal Instrument Procedures* (TERPS) and later in the International Civil Aviation Organization (ICAO) *Procedures for Air Navigation Services–Aircraft Operations* (PANS-OPS).

The minimum height to which an aircraft could descend on a nonprecision approach originally was called the minimum descent altitude (MDA); for a precision approach, the label decision altitude (DA) was applied.[2] Weather minimums for landing and takeoff were specified with both a visibility component and a ceiling, or cloud base, component.

Systems Mature

ILS eventually prevailed over PAR and ground-controlled approaches, initially for civil operations, because ILS technology provided more operational flexibility at lower cost and supported lower landing minimums.

When the airline industry transitioned from propeller aircraft — such as the Douglas DC-4, DC-6 and DC-7, and the Lockheed Constellation — to the early jets — including the Boeing 707, Convair 880 and DC-8 — turbojet aircraft landing minimums were set higher because of the typically higher approach speed, different landing attitude, limited visibility from the cockpit, slower engine response, and perceived different handling characteristics. The resulting "basic turbojet minimums" included a 300-ft ceiling and 3/4-mi (1,200-m) visibility.

Seeking to restore turbojet aircraft landing minimums to the equivalent values used for the earlier propeller-driven aircraft — a 200-ft ceiling and 1/2-mi visibility — the industry, regulatory authorities and ICAO in the early 1960s identified new technology that would permit this operational capability. Autopilot, flight director and flight instrument technologies were applied in stages as the earlier landing minimums were restored.

Civil ILS operations further evolved with technology such as fail-operational autoland systems with rollout capability, to permit Category III operations with runway visual ranges (RVRs) as low as 300 ft (75 m). Head-up display (HUD) guidance systems and fail-passive autoland systems eventually allowed more limited Category III capability for aircraft in which the installation of a fail-operational autoland system was not economically viable.[3]

Despite these advances, the use of NDB, VOR and localizer approaches increased globally during the 1960s through 1980s, primarily for economic reasons, including the lower cost of ground and aircraft equipment compared

Light beacons replaced bonfires as an early method of guiding aviators to landing sites at night or in low visibility.

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with ILS. Unfortunately, the safety record of flying nonprecision approaches did not match the improved safety record of precision approaches flown with ILS.

In the 1970s and 1980s, aircraft navigation systems significantly evolved to include multi-sensor flight management systems, electronic displays and area navigation (RNAV) equipment. RNAV capability, which constructs navigation routes using selected points in space, initially at a designated bearing and distance from a VOR, included either two-dimensional lateral navigation (LNAV) alone or three-dimensional navigation employing both LNAV and vertical navigation (VNAV). Many general aviation aircraft systems used only two-dimensional RNAV. Air carrier flight management systems were designed from the start to use three-dimensional path indications based on barometric VNAV (BARO VNAV) information.

Accordingly, air carriers with aircraft having FMSs incorporating navigational databases — for example, the Airbus A320 and the Boeing 757, 767 and 737-300 — began to fly NDB, VOR and localizer approaches using the FMS LNAV/VNAV capability.

Although RNAV instrument approach procedures were implemented widely during this period, the procedures typically were defined and classified as two-dimensional. Landing minimums for all approach procedures were based principally on minimum visibility values, including RVR, and were no longer tied to a required ceiling minimum.

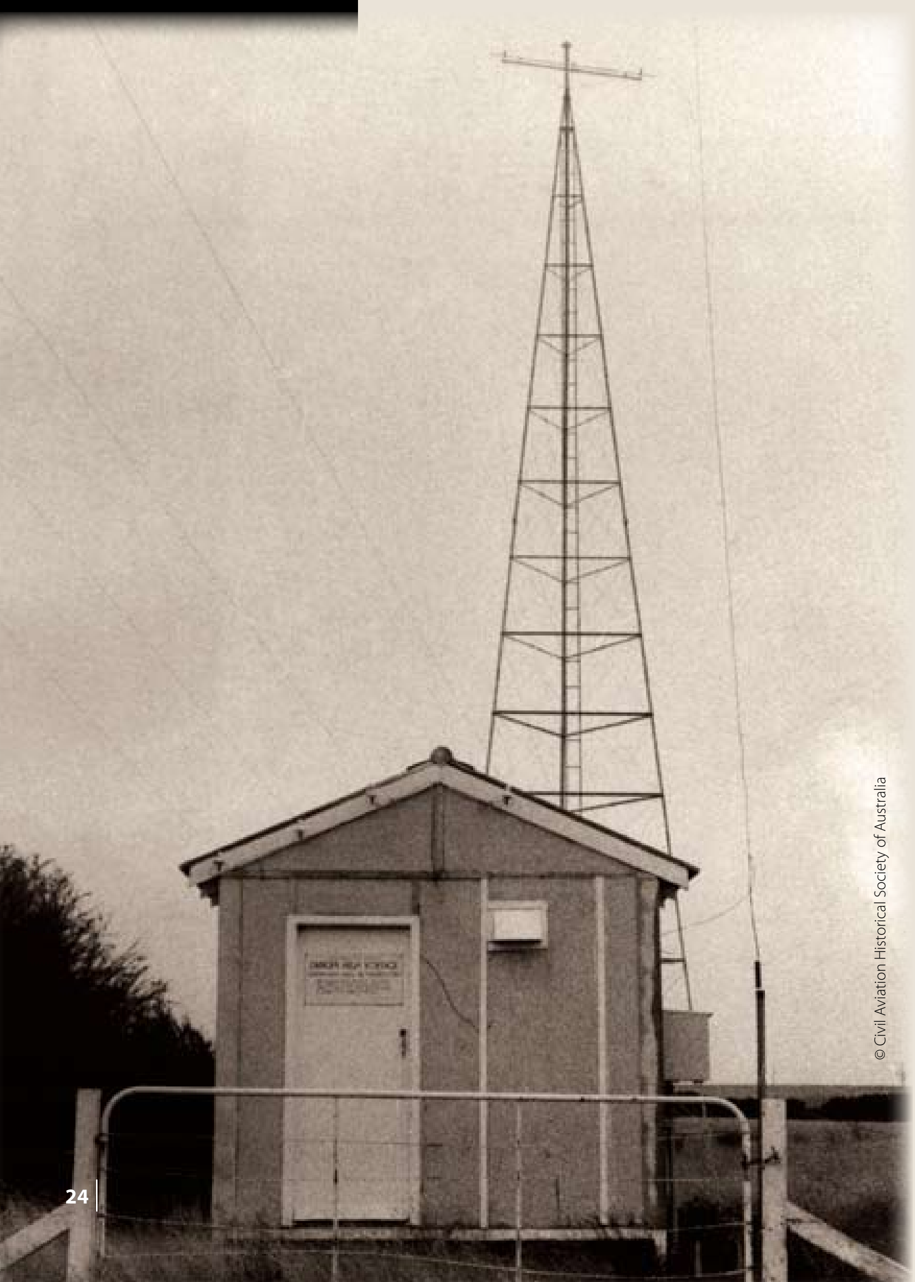
Published MDAs and DAs increasingly included specifications of height above the highest elevation in the runway touchdown zone, as well as minimum mean sea level altitudes. The resulting MDA(H) and DA(H) values were better suited to the use of radio altimeters, which by the 1970s had become common in air carrier operations.

By the end of the 1980s, it became apparent that the stability and accuracy of a well-defined three-dimensional FMS-based path continuing to the runway had both safety and operational benefits, including simpler crew procedures and reduced noise emissions.

Technology Surges

The increased installation of ILS facilities at airports and the widespread availability of fail-operational autopilots in air carrier aircraft during the 1990s enabled the broad use of low Category III landing minimums with specified alert heights.[4]

FMSs enabled the use of RNAV-direct routings and LNAV/VNAV navigation on published standard instrument departures (SIDs) and standard terminal arrival routes (STARs). Where ILS approaches were not available, RNAV techniques could be applied to most other instrument approach procedures. RNAV approach



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The transmitter shack and antenna of an early nondirectional beacon (NDB). A radio compass or automatic direction finder aboard the airplane enabled the crew to “home” on the beacon.

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The Ford Tri-Motor flew in an era of transition from dead reckoning and pilotage to the dawn of all-weather operations.

procedures became ubiquitous. Air carriers applied three-dimensional RNAV using BARO VNAV on a large scale.

For FMS-equipped aircraft, which became the air carrier norm, nearly all nonprecision instrument approach procedures could be flown using the LNAV and VNAV modes. Global positioning system (GPS) inputs became commonly available for multi-sensor FMSs in air carrier aircraft. GPS inputs, together with inertial reference systems (IRSs) and BARO VNAV, significantly increased the accuracy and reliability of guidance available to fly any three-dimensional instrument approach trajectory.

Even though FMS-equipped aircraft have been taking advantage of VNAV capabilities, many nonprecision instrument approach procedures still do not have vertically defined final approach paths. However, because of the widely recognized safety advantage of flying vertically stabilized VNAV paths to the runway, operators have been using FMS BARO VNAV capabilities while conducting NDB, VOR and localizer approaches. As a result of these initiatives, even more operators now are using VNAV for any suitable nonprecision approach procedure, even if a vertical path is not published as part of the procedure.

Similarly, for aircraft that do not have an FMS or VNAV capability, the constant-descent approach (CDA) technique was developed to obtain at least some of the benefit of a stabilized approach and to avoid procedures that have been most vulnerable to human failures, particularly step-down — "dive-and-drive" — nonprecision approach procedures. The CDA technique is based on the use of distance-altitude checks or a pre-planned vertical speed to mimic a VNAV path.

Air carriers have achieved ILS-like performance from their FMSs and, in some instances, even better approach guidance. Multi-sensor FMSs, GPS sensors, IRSs and BARO VNAV systems have matured to provide significantly improved accuracy, integrity and availability, with flexible, defined three-dimensional or even four-dimensional flight path performance. Time, the fourth dimension, is the required time of arrival.

Required navigation performance (RNP) is a refinement of RNAV, applied in a much more systematic and uniform way. RNP, which is used in a number of different levels of performance required of an aircraft's capabilities, more accurately and reliably defines the intended lateral or vertical path. Other types of approach procedures rely on angular navigation information emanating from a specific point that, like the spokes of a wheel, spread out as distance from the navaid or waypoint increases, reducing accuracy. RNP, on the other hand, can have linear navigation design criteria, a thin line in space that can be bent in three dimensions as needed. A typical RNP approach performance value is 0.3 nm, meaning that the aircraft is capable of being flown within 0.3 nm of the course or path centerline, regardless of its distance from the waypoint. To ensure optimum access to airports, or for departure, some RNP procedures now have an RNP performance value of 0.1 nm.

RNP has shown major operational and safety benefits and has become the foundation for the future of global navigation, according to ICAO's Future Air Navigation System (FANS) plan and the U.S. Federal Aviation Administration's Performance-Based Navigation Roadmap.

New Constellations

With the advent of GPS, many general aviation aircraft in the 1990s became capable of conducting two-dimensional RNAV approaches. GPS "overlays" of traditional VOR and NDB approaches were introduced first. Then stand-alone GPS approaches were authorized. GPS approaches were still largely defined as two-dimensional procedures, since general aviation aircraft with panel-mount GPS receivers typically did not have BARO VNAV capability. Eventually, the GPS approaches were reclassified as RNAV approaches.

GPS use initially was subject to "selective availability," in which signal accuracy was intentionally degraded by the U.S. military for security reasons. The U.S. Department of Defense, which owns, operates and monitors the GPS satellite constellation, canceled selective availability in 2000, making signals received by civil aircraft worldwide as much as 10 times more accurate.

Several augmentation systems — collectively called the satellite-based augmentation system (SBAS) by ICAO — have been implemented to further improve GPS accuracy, integrity and availability. These systems include the U.S.-developed local area augmentation system (LAAS) and wide area augmentation system (WAAS), the European geostationary navigation overlay system (EGNOS), India's GPS-aided geo-augmented navigation (GAGAN) system and Japan's multifunction transport satellite augmentation (MTSA) system.

Similar to ICAO's definition of a ground-based augmentation system (GBAS), LAAS originally was proposed with air carrier aircraft in mind, to provide reliable and accurate precision approach guidance ranging from more economical Category I operations to the most demanding Category III landings, as well as low-visibility takeoffs and some airport-surface operations.

Introduced primarily for general aviation aircraft, WAAS eventually led to the development of the localizer performance with vertical guidance (LPV) approach, a GPS approach procedure that provides localizer-equivalent lateral guidance accuracy, an electronic glide path and minimums as low as 200 ft and 1/2 mi for suitably equipped aircraft.

Conference discussions about these technologies led the ICAO Obstacle Clearance Panel to propose a new classification of RNAV procedures called approach procedures with vertical

Instrument landing systems and ground-controlled radar approaches guided the crews of prop-driven airliners, like this Lockheed Constellation, to landings in most instrument weather conditions during the 1950s.

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The development of VHF omnidirectional radios (VORs), which emit radio signals 360 degrees in azimuth, provided more precise en route and instrument approach capability.

guidance (APVs). This classification would include subgroups, such as APV I and APV II, to designate various levels of performance accuracy or integrity.

Europe now has committed itself to the deployment of a global navigation satellite system (GNSS) called Galileo, which will be similar to GPS but will include 30 satellites, compared with the current 24 GPS satellites. U.S. policy, however, is evolving toward providing a greater number of operational satellites; the GPS constellation could someday include 32 satellites. A new generation of dual-mode receivers must evolve to simultaneously take advantage of both systems.

In addition to canceling selective availability, the United States has promised long-term global civil GPS use without fees. Hence, with the significantly improved accuracy, availability and integrity currently afforded by GPS, and the greater number of GPS satellites likely to be available, the future role of the satellite-based augmentation systems is somewhat unclear. Eventually, there may be more than 50 active GNSS satellites, likely making SBAS largely redundant and dispensable.

Ground-based augmentation likely will be needed indefinitely to support GNSS-based landing system (GLS) approaches and RNP approaches, and to provide comprehensive navigation services, including air carrier Category III landing and low-visibility takeoff operations. GLS approaches likely will replace ILS approaches, because GLS, using GBAS, can provide significantly better capability and reliability than ILS at significantly lower life-cycle and user costs.

The Future Is Now

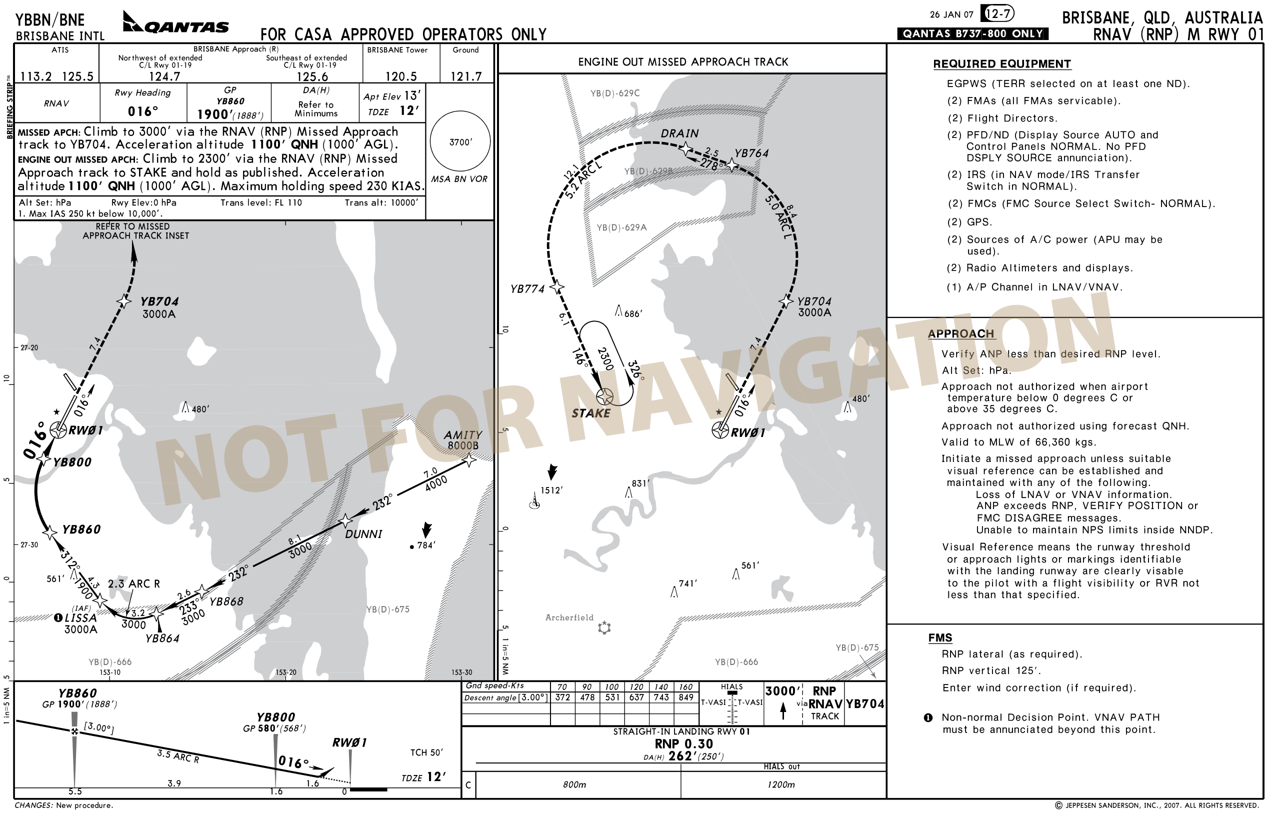
RNP and GLS are a reality. RNP has been in operation for over a decade in air carrier service, both for en route operations and for instrument approach and departure operations. RNP has demonstrated significant safety, economic and operational benefits.

All Airbus and Boeing aircraft currently in production are RNP-capable, and increasing numbers of other aircraft types are being RNP-equipped. RNP is an ICAO standard, an element of the FAA's Performance-Based Navigation Roadmap and is being implemented in many other states — including Australia, Canada, China and New Zealand — as well as states in Europe.

An example of an RNAV RNP instrument approach procedure is shown in Figure 1 (p. 28). RNP can serve virtually any runway. With appropriate criteria and with suitably equipped aircraft, RNP can provide low Category I approach minimums and safe three-dimensional paths to the runway touchdown zone and beyond for a missed approach. The use of RNP can unlock previously unusable airspace and increase runway capacity.

Now entering commercial service, GLS approach procedures provide "better-than-ILS" capability and extend flight operations for suitably equipped aircraft to the lowest Category III landing minimums at any airport with a GBAS, as well as nearby airports that are covered by the primary airport's GBAS.

Three-Dimensional RNAV RNP Procedure



Source: Tom Imrich, from Boeing/Jeppesen

Figure 1

A sample of a GLS/RNAV RNP approach procedure is shown in Figure 2. The procedure is typical of what will be used during the transition to stand-alone GLS approach procedures.

Among evolving beneficial trends, the implementation of both RNP and GLS is likely to:

- Significantly improve safety;
- Reduce operator cost;
- Reduce air navigation service provider cost;
- Reduce vulnerability to human error;
- Simplify training and pilot qualification;
- Reduce cost of aviation system infrastructure;
- Improve and increase air carrier transport operating capability; and,
- Increase airspace system capacity and airport capacity.

The details of these will be discussed in later articles.●

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Notes

1. Tactical air navigation (TACAN) is primarily a U.S. military UHF navigation system that provides continuous indications of bearing and distance to TACAN stations. The U.S. Federal Aviation Administration has integrated TACAN facilities

> Ground-based ILS equipment may someday go the way of four-course ranges as satellite systems and procedures predominate in providing three-dimensional precision approach capability

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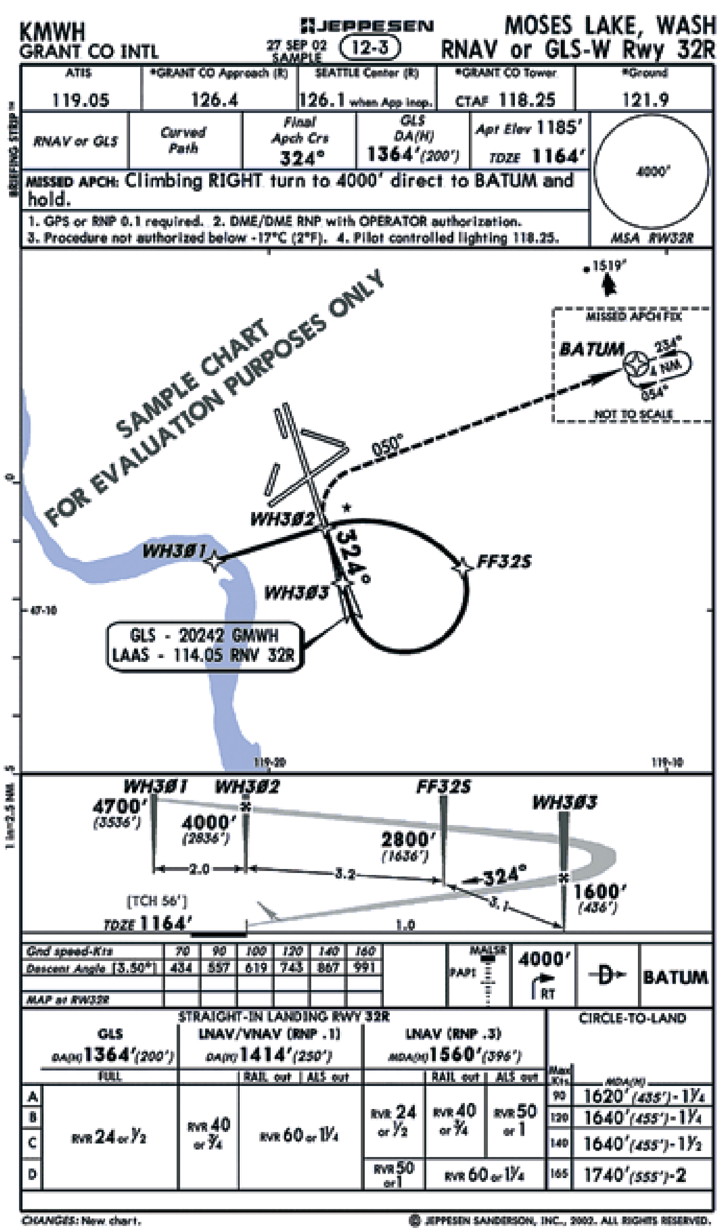
GNSS-Based Landing System Approach



Source: Tom Imrich, from Boeing/Jeppesen

Figure 2

with civil VOR/DME (VHF omnidirectional radio/distance measuring equipment) facilities; the integrated facilities are called VORTACs.

2. In the United States, the term decision height (DH) has been used to specify, as an altitude above mean sea level, the height above the highest elevation in the runway touchdown zone. To harmonize with international terminology, the U.S. has adopted the term decision altitude (DA) and is replacing DHs with DAs on all charts of instrument approach procedures with vertical guidance.

3. A fail-operational autoland system continues to operate safely after the failure of a single component. A fail-passive autoland system is automatically deactivated when a component failure occurs.

4. The alert height is the minimum height above the runway at which a Category III approach must be discontinued and a missed approach begun if a failure occurs in one of the redundant parts of the aircraft's fail-operational autopilot. The approach generally can be continued if the failure occurs below the specified alert height, which is established during aircraft certification and has no relation to decision height.