NextGen for Airports, Volume 1: Understanding the Airport's Role in Performance-Based Navigation: Resource Guide

DETAILS

155 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-37546-7 | DOI 10.17226/23574

AUTHORS

Sebastian Timar, Robb Varani, Brian Townsend, and Wayne MacKenzie; Airport Cooperative Research Program; Transportation Research Board; National Academies of Sciences, Engineering, and Medicine

11 Procedure Design and Execution

The trajectories of aircraft flying PBN procedures determine the noise profile, fuel burn and emissions, flight time, track mileage, capacity, efficiency, and safety. All of these performance factors and impacts, representing the range of interests among the stakeholders in PBN, must be balanced in the design of PBN procedures. These trajectories are influenced by the design parameters of the procedure, including the phase of flight or segments of a procedure, waypoints, leg types, and altitude restrictions. The trajectories of aircraft flying PBN procedures are also influenced by the accuracy of navigational systems, including the path planning and following characteristics of the aircraft's flight management system (FMS).

Flight Procedure Design

The trajectories of aircraft flying IFPs determine the noise profile, fuel burn and emissions, and other impacts on the airport and its surrounding community. These trajectories are influenced by the design parameters of the procedure, including the phase of flight or segments of a procedure, waypoints, leg types, and altitude restrictions of the procedure.

Phase of Flight and Segments of an IFP

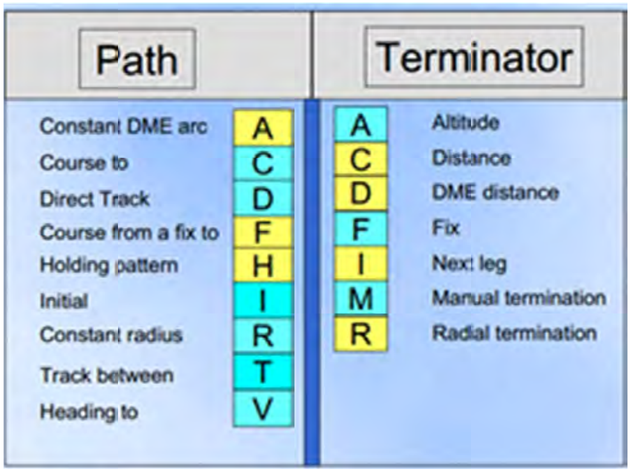
An IFP is composed of several segments as the aircraft transitions to or from the runway, terminal, and en route phase of the flight environment. The purpose of a standard terminal arrival route (STAR) is to descend and transition aircraft from the en route environment to the terminal approach environment. The segments of a STAR include an en route transition, a common waypoint or route, and a runway transition. The purpose of a standard instrument departure (SID) is to transition aircraft from the runway environment to the en route structure. The segments of a SID include a runway transition, a common waypoint or route, and an en route transition. The names of STARs and SIDs are based on the common waypoint in the route of flight.

The purpose of a standard instrument approach procedure (SIAP) is to provide navigation from the terminal environment to the runway environment. A SIAP is composed of multiple segments including a feeder route, initial approach, intermediate approach, final approach, missed approach, and holding segments. SIAPs are named based on the type of navigation used [e.g., area naviation (RNAV), required navigation performance (RNP), instrument landing system (ILS)] and the runway they serve.

Waypoints and Leg Types

Waypoints are sets of coordinates that identify a point in physical space and are named based on a five letter system in a manner that is phonetically pronounceable. Waypoints are combined together in an IFP to establish a route of flight. There are two types of waypoints: Fly-by and fly-over. With fly-by waypoints, aircraft initiate the turn to the next leg prior to the waypoint where the leg begins. With fly-over waypoints, aircraft fly directly over the waypoint and initiate the turn to the next leg after the waypoint where the leg begins.

The combination of two waypoints in a route constitutes a flight leg of a procedure. There are different types of flight legs, which are named according to a two-letter convention. The first letter corresponds to the path type of the flight leg, and the second letter corresponds to the type of terminator for the flight leg. Figure 11-1 presents the types of paths and terminators that are the foundations of different leg types.



DME = distance measuring equipment

Source: Rawlings/Eurocontrol 2007.

Figure 11-1. *Path and terminator elements for all possible leg types.*

Among the breadth of possible leg types, there are 23 leg types specified in the ARINC 424 Specification (ARINC 2015) and in the FAA's Instrument Procedures Handbook FAA-H-8083-16A (Federal Aviation Administration 2015c), which enable RNAV SIDs, STARs, approach transitions, and missed approaches listed in Table 11-1.

Table 11-1. RNAV Leg Types.

LEG TYPE	DESCRIPTION
IF	The initial fix (IF) leg defines a database fix as a point in space. It is only required to define the beginning of a route or procedure.
TF	The track to a fix (TF) leg defines a great circle track over ground between two known databases fixes. This is the preferred method for specifying straight legs. While course or heading can be mentioned on charts, the designer should ensure a TF leg is used for coding.
RF	The radius-to-fix (RF) constant radius arc leg defines a constant radius turn between two fixes in the navigation database (NDB), lines tangent to the arc and a center fix.
CF	The course to a fix (CF) leg defines a specified course to a specific fix in the NDB. TF legs should be used instead of CF whenever possible.

Table 11-1. Continued

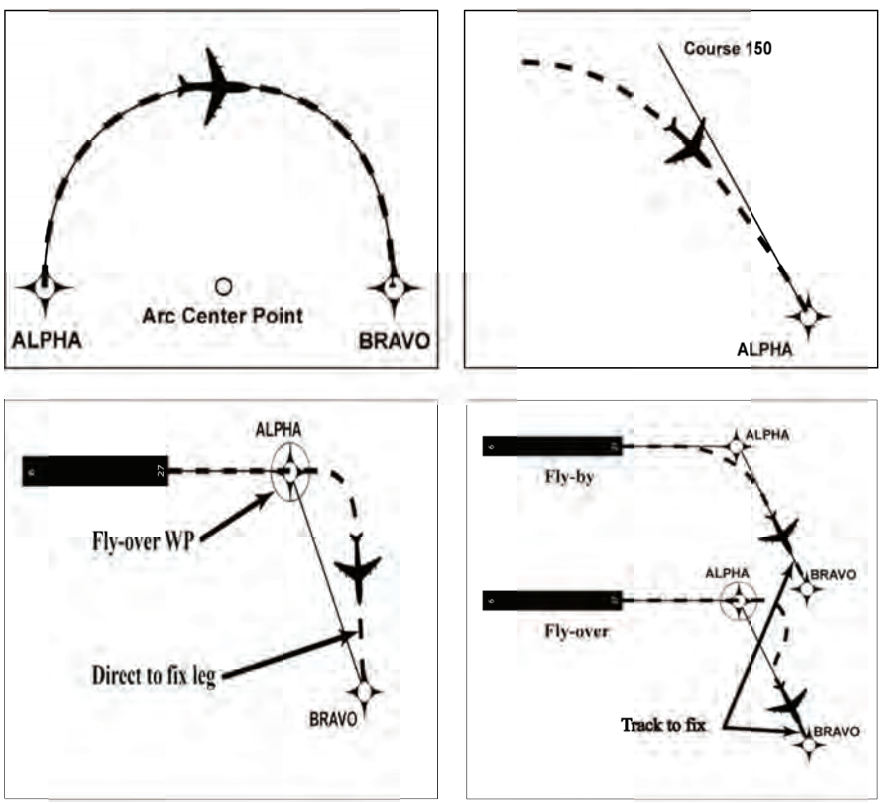
LEG TYPE	DESCRIPTION
DF	The direct to a fix (DF) leg defines an unspecified track starting from an undefined position to a specified fix. Procedure designers should take into account that the flight management system (FMS) flight path depends on initial aircraft heading.
FA	The fix to an altitude (FA) leg defines a specified track over ground from a fix in the NDB to a specified altitude at an unspecified position.
FC	The track from a fix from a distance (FC) leg defines a track over ground for a specific distance from a fix in the NDB.
FD	The track from a fix to a distance measuring equipment (DME) distance (FD) leg specifies a track over ground from a fix to a particular DME distance from a DME navigational aid. The fix and DME navigational aid are in the NDB.
FM	The track from a fix to a manual termination (FM) leg defines a specified track over ground from a NDB fix until manual termination of the leg.
CA	The course to an altitude (CA) leg defines a specified course to a specific altitude at an unspecified position.
CD	The course to a DME distance (CD) leg defines a specified course to a specific DME distance which is from a specific DME navigational aid in the NDB.
CI	The course to an interceptor (CI) leg defines a specified course to intercept a subsequent leg.
CR	The course to a radial termination (CR) leg defines a course to a specified radial from a specific very high frequency (VHF) omnidirectional radio range (VOR) navigational aid in the NDB.
AF	The arc to a fix (AF) leg defines a track over ground at specified constant distance from a DME navigational aid in the NDB.
VA	The heading to an altitude termination (VA) leg defines a specific heading to a specific altitude at which the leg terminates. The specific position at which the leg terminates is unspecified, and is an outcome of achieving the termination altitude.
VD	The heading to a DME distance termination (VD) leg defines a specified heading terminating at a specified DME distance from a specific DME navigational aid in the NDB.
VI	The heading to an interceptor (VI) leg defines a specified heading to intercept the subsequent leg at an unspecified position.
VM	The heading to a manual termination (VM) leg defines a specified heading until a manual termination.
VR	The heading to a radial termination (VR) leg defines a specified heading to a specified radial from a specific VOR navigational aid in the NDB.

Table 11-1. Continued

LEG TYPE	DESCRIPTION
PI	The procedure turn (PI) leg defines a course reversal starting at a specific database fix, including an outbound leg followed by a left or right turn and 180 degree course reversal to intercept the next leg.
HA, HF, HM	The racetrack course reversal (HA, HF and HM) leg types define racetrack pattern or course reversals at a specified fix in the NDB.

Source: ARINC 2015.

Among the 23 leg types, the RTCA DO-9236C (RTCA 2013c) specifies the permissible leg types for SIDs, STARs, approaches, and missed approaches in the navigation database to be IF, TF, RF, CF, DF, FA, HM, HA, and HF legs because these leg types are fixed and not subject to interpretation. Examples of RF, CF, DF, and TF leg types and the hypothetical flight paths of aircraft flying those legs are depicted in Figure 11-2.



Source: Federal Aviation Administration 2015b.

Figure 11-2. *Leg types for RNAV procedures include RF (top left), CF (top right), DF (bottom left) and TF (bottom right).*

The notional flight tracks depicted for the leg types in Figure 11-2 indicate that the selection of a particular leg type for the design of a procedure determines the resulting flight paths of aircraft conducting the procedure, and that the resulting flight path may not follow the path implied by the sequence or structure of the waypoints bounding the flight leg and may not be immediately clear from the depiction of the procedure as published on the charts. The particular flight legs and the characteristic flight paths of aircraft along those legs determine the areas surrounding the airport that are exposed to overflights of aircraft to and from the airport, and the noise contours associated with arrival and departure traffic of the airport. Therefore, understanding and specification of leg types is important in meeting procedure design objectives and in interpreting a published procedure and estimating its local impact.

Lateral Precision

The required LNAV precision for aircraft flying an IFP also determine the flight tracks of aircraft executing the IFP; the more precise the RNP, the less lateral dispersion in the flight paths of the aircraft conducting the procedure. Table 11-2 lists the standard lateral precisions for IFP approach procedures, and for IFPs in the terminal, en route, and oceanic airspace domains.

Table 11-2. RNAV Leg Types.

REQUIRED NAVIGATION PERFORMANCE (RNP) LEVEL (NAUTICAL MILES)	TYPICAL APPLICATION	PRIMARY ROUTE WIDTH (NAUTICAL MILES)
0.1 to 0.3	RNP Approval Required (AR) Approach Segments	0.2 to 0.6
0.3 to 1.0	RNP Approach Segments	0.6 to 2.0
1.0	Terminal Airspace, En Route Airspace	2.0
2.0	En Route Airspace	4.0
4.0	Oceanic Airspace	Not applicable
10.0	Oceanic Airspace	Not applicable

Source: RTCA 2013c.

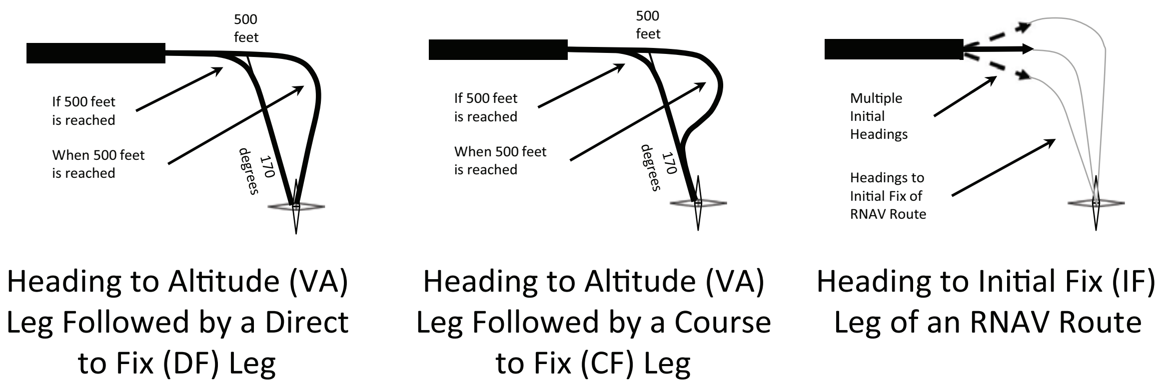
The values indicate that the highest level of precision is required for approach procedures to an airport, and that the precision required decreases as the traffic density of the airspace decreases.

Lateral Path and Vertical Profile

There are limitations to what can be accomplished in the procedure design due to performance limitations of aircraft. For example, the distance of turn anticipation (DTA) is addressed in multiple FAA 8260 series orders and is defined as the earliest distance at which the next waypoint can be achieved, thereby constraining the minimum length of the leg. DTA requirements are based on performance characteristics of FMS and autopilot systems operating in the NAS today. If these requirements are not met, the aircraft will not be able to maintain an intended track. These requirements may also constrain the design of flight procedures that are desired to meet the requirements of the airport, aircraft operator, community and other stakeholders, such as conforming to noise corridors.

For the design of OPD arrival procedures, the lateral path must be designed to balance the interests of multiple stakeholders, and specification requires the collaboration and consideration of the needs of the individual project stakeholders. For example, aircraft operators prefer the most efficient routing possible with the fewest track miles. However, because optimal profiles may vary between different aircraft types, some efficiency may have to be sacrificed for operational, noise, or community interests. The runway transitions should connect to instrument approach procedures, when possible. The airspace must be modified to accommodate the optimal vertical profile generated by the aircraft's FMS. The designer should seek to minimize the altitude constraints, while meeting traffic separation and airspace needs. In general, at-or-above altitude constraints at a waypoint are preferred, followed by a range of acceptable altitudes, otherwise known as "altitude windowing," achieved with simultaneous at-or-above and at-or-below altitude constraints at a waypoint.

For the design of SIDs, there are several techniques available to manage departure ground tracks. Three common design (leg coding) techniques include a heading to an altitude followed by a DF, a VA followed by a CF leg, or a vector to join an RNAV route. Common techniques are show in Figure 11-3.



Source: Federal Aviation Administration 2015b and 2016c.

Figure 11-3. *Effects of waypoint and leg type sequences.*

The ground track in the VA to DF design example will vary based on when the aircraft reaches the initial coded altitude. Each aircraft will reach the desired altitude at a different point due to variable performance characteristics and takeoff profiles (weight, flaps, etc.) Once the altitude is reached, the aircraft will proceed directly to the next fix.

The ground track in the VA to CF design example will vary based on when the aircraft reaches the initial coded altitude and the established course designed in the procedure. If the altitude is reached prior to the course (170° used in the example), the aircraft will attempt to reach the course and execute the turn considering DTA similar to a fly-by waypoint. If the aircraft reaches altitude beyond the established course, it will execute a turn considering DTA and fly back to the course and proceed to the next fix.

The ground track in the vector to join an RNAV design example will vary directly off the runway end based on the initial heading given by the ATCT. Once the pilots establish communication with the TRACON, they will be vectored to the IF of the RNAV route, which will bring the aircraft through to the en route environment. This technique results in a "fanning" of aircraft off the end of the runway and may be useful to airports with noise abatement procedures where the noise is distributed over a community equitably.

In addition to these design techniques, *ACRP Report 86: Environmental Optimization of Aircraft Departures: Fuel Burn, Emissions, and Noise* (Kim et al. 2013) provides detailed guidance and analysis methods for the design of departure procedures to optimally balance fuel burn, emissions and noise. The reference includes a working spreadsheet model to use to design procedures.

Aircraft Performance Variables

The trajectories of aircraft flying PBN procedures determine the noise profile, fuel burn and emissions, and other impacts on the airport and its surrounding community. The trajectories of aircraft flying PBN procedures are influenced by the accuracy of navigational aids and the path planning and following characteristics of the aircraft's FMS.

Navigation System Accuracy

The accuracy of different navigation systems can influence the spatial dispersion in trajectories. As indicated in Table 2-1, GPS, wide area augmentation system (WAAS), ground-based augmentation system (GBAS), DME, and inertial reference unit (IRU) provide different levels of accuracy in their estimates of aircraft lateral position. IRU has bias error due to the initial position programmed by the pilot. GPS, WAAS, and barometric pressure-based vertical navigation (baro-VNAV) provide different levels of accuracy in aircraft vertical position estimation. Navigation aid accuracy impacts the planning of flight trajectories and the ability of the aircraft to adhere to the desired flight path.

Flight Path Planning

The path planning characteristics of the pilot or FMS can impact the lateral and vertical profiles of the aircraft's trajectory in flying PBN procedures. In particular, the vertical component can vary greatly based on the characteristics of the FMS flight path planning algorithms and associated modeling errors. The impact of different economical or geometrical FMS descent planning methods, ambient conditions, and flight path modeling errors such as headwind or tailwind on the flight paths of aircraft are succinctly presented in a report on *Flight Management Computer Systems (FMCS): Vertical Navigation (VNAV)* (The MITRE Corporation 2010).

The economical and geometrical vertical flight path planning methods vary in the vertical profiles they plan for the aircraft. The economical method provides a vertical flight path that minimizes fuel burn for given conditions, such as winds and aircraft weight. This flight path, and its resulting noise contour and fuel burn, will change under different conditions. The geometrical method provides a fixed flight path that will not change for the given conditions. However, the resulting fuel burn and noise of the aircraft transiting the fixed path will change as aircraft and ambient conditions change, as required to maintain the fixed flight path. Nevertheless, although noise exposure may vary based on meteorological conditions, an arrival using an OPD will typically be less noisy than a conventional, step-down descent.

Flight Path Following

The flight path following characteristics of the pilot or FMS can impact the lateral and vertical profiles of the aircraft's trajectory in flying PBN procedures. In particular, the aircraft guidance and control algorithms, the aircraft configuration, and the ambient conditions can impact the vertical profile.

Headwinds and tailwinds unaccounted for in the flight path planning introduce variation in the actual flight paths of aircraft as they fly the procedure. Headwinds may require more throttle for the aircraft to maintain its planned flight path, thereby increasing fuel burn, emissions, and noise. Tailwinds may result in changes to the actual flight path of the aircraft to avoid over-speed, thereby impacting the noise profile, and likely the fuel burn and emissions, as well.

The dispersion of the altitude profiles of aircraft flying the same arrival procedure can be extensive, as demonstrated in flight trials of a prototype OPD arrival procedure, the RNAV STAR arrival procedure called VIKNN at Hartsfield-Jackson Atlanta International airport (ATL) (Nagle et al. 2009). The procedure was designed with altitude windows to enable aircraft to conduct OPDs. The evaluations were conducted for different types of aircraft: Boeing B757-200, B767-300 and B767-400ER, and Airbus A300F and A310F. The results indicate the vertical profiles of flight tracks are dispersed by thousands of feet, even for the same type of aircraft, due to FMS differences, aircraft characteristics, wind variation, and radar accuracy.

Flyability

Flyability is a common term used in air traffic procedures design and validation. The flyability of a flight procedure is a check or system of checks to ensure the procedure can be safely flown by aircraft as designed. This is a coupled evaluation of the flight procedure design in conjunction with the characteristics of the aircraft that are to use the procedure. These checks may include, but are not limited to, the acceptability of any deviations from standards, bank angles, airspeeds, climb/descent gradients, roll rates, track lengths, pilot workload issues, procedure complexity, runway alignment, and other considerations. Also, if a ground-based or space-based navigational aid is used solely as a waypoint (latitude/longitude coordinates only), a flight validation is necessary for the flyability of the fix in the procedure design.

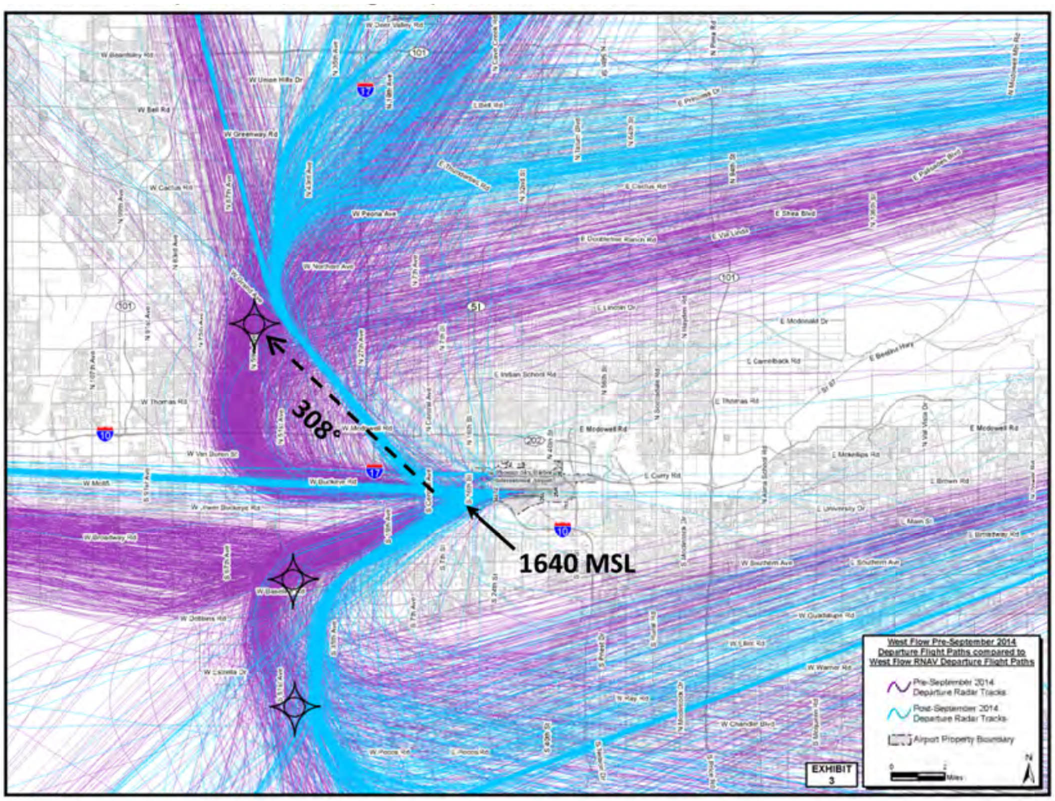
FAA criteria drive the construct of a given procedure, which is integrated in the terminal area route generation, evaluation, and traffic simulation (TARGETS) software. This aids the procedure designers in assuring that the appropriate leg types, path terminators, turn anticipation, as well as the desired speed and altitude constraints meet the capabilities of a wide cross section of aircraft types and FMSs. TARGETS will generate a flyability check that will indicate if the proposed procedure meets the criteria standards. It should be noted this does not always guarantee the desired or expected results of the actual published procedure. Tools are under development to augment the current process.

As proposed procedures mature through the design process, flyability is also accounted for in various flight simulator tests and trials. Flight simulators are specific to flight management computers (FMCs) and aircraft manufacturers, and range from desktop to full motion simulators, with a variation of fidelity. Full-motion simulators provide the highest level of fidelity for flyability checks for the obvious reasons of providing realistic atmospheric and operational conditions that aircraft would encounter with the actual procedure. Desktop simulators may not possess the needed fidelity, so consideration should be given for true flyability checks.

In some cases, it is not always possible to know exactly how well a procedure will perform until the procedure is actually in use. An effective tool used for flyability checks is the actual aircraft. The FAA and aircraft operators have worked together on numerous initiatives involving pre-coordinated flights of approved procedures prior to their actual implementation. This affords a controlled environment to identify any adjustments that may be needed and validates that the procedure is delivering as expected for ATC and operators.

Procedure Design Example

The resulting ground tracks from the implementation of an RNAV procedure can provide dramatic improvement in efficiency, noise, and emissions. The results may also concentrate flight tracks and create more noise over a tight corridor. In many cases this result is acceptable, especially if the land use below the flight track is compatible with airport noise. Figure 11-4 depicts a comparison of west departure flight tracks before and after RNAV implementation at Phoenix International airport (PHX).



Source: City of Phoenix Aviation Department

Figure 11-4. *Ground tracks at PHX—before and after RNAV implementation.*

The dark purple lines represent departure flight tracks to the west before RNAV implementation and the blue lines represent departure flight tracks to the west after RNAV implementation. The RNAV design for north- and eastbound departures turning right requires aircraft climb on an initial runway heading and intercept a 308 degree course to the initial flyby fix where aircraft make a turn toward the en route transition. The RNAV design technique for south- and east-bound departures turning left require an aircraft to climb to 500 feet above the airport [1640 mean sea level (MSL)] and make a turn, to the first flyby waypoint where aircraft make a turn toward the en route transition.