## AIRCRAFT NAVIGATION

Historically, pilots flew paths defined by VOR (VHF Omnidirectional Radiorange) radials or by nondirectional beacon signals using basic display of sensor data. Such paths are restricted to be defined as a path directly to or from a navigation station. Modern aircraft use computer-based equipment, designated RNAV (Area Navigation) equipment, to navigate without such restrictions. The desired path can then be direct to any geographic location. The RNAV equipment calculates the aircraft position and synthesizes a display of data as if the navigation station were located at the destination. However, much airspace is still made available to the minimally equipped pilot by defining the paths in terms of the basic navigation stations.

Aircraft navigation requires the definition of the intended flight path, the aircraft position estimation function, and the steering function. A commonly understood definition of the intended flight path is necessary to allow an orderly flow of traffic with proper separation. The position estimation function and the steering function are necessary to keep the aircraft on the intended flight path.

Navigation accuracy is a measure of the ability of the pilot or equipment to maintain the true aircraft position near the intended flight path. Generally, navigation accuracy focuses mostly on crosstrack error, although in some cases the alongtrack error can be significant. Figure 1 shows three components of lateral navigation accuracy.

Standardized flight paths are provided by government agencies to control and separate aircraft in the airspace. Path definition error is the error in defining the intended path. This error may include the effects of data resolution, magnetic variation, location survey, and so on.

Position estimation error is the difference between the position estimate and the true position of the aircraft. This component is primarily dependent upon the quality of the navigation sensors used to form the position estimate.

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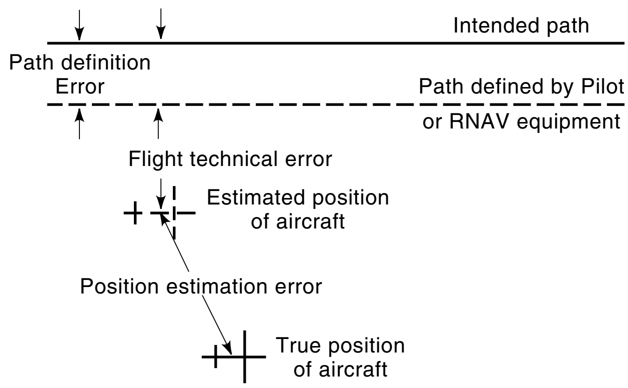


**Figure 1.** Aircraft navigation errors.

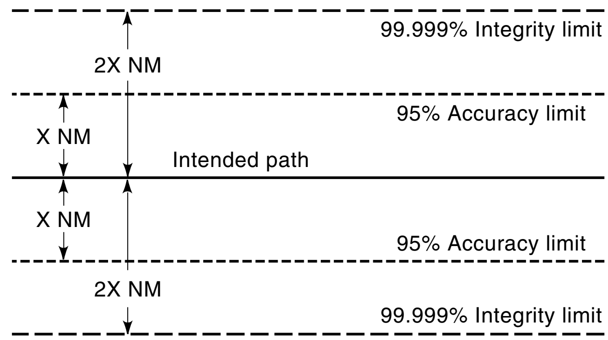


**Figure 2.** RNP–*X* accuracy and integrity limits.

Flight technical error is the indicated lateral deviation of the aircraft position with respect to the defined path. RNAV systems in larger aircraft have provisions to couple a steering signal to a control system to automatically steer the aircraft to the intended path. In less equipped aircraft, the RNAV system simply provides a display indication of the crosstrack distance to the intended path, and the pilot manually provides the steering correction.

## RNP–RNAV STANDARDS

In the interest of standardizing the performance characteristics of airborne navigation systems and the airspace, the concept of required navigation performance (RNP) for RNAV, denoted as RNP–RNAV, is being developed. Reference 1 provides the current state of the concept. Because the separation requirements for airspace depend on the proximity of obstacles, density of traffic, and other factors, the RNP–RNAV characteristic includes a measure, expressed in nautical miles (NM), that is correlated to the accuracy and integrity requirements for the airspace. To be more specific, the airspace or route will be defined as RNP-*X*, where *X* is the associated measure in nautical miles. This allows a consistent means of designation for airspace from the en route environment to the approach environment.

The main navigation requirements for RNP–RNAV equipment are an accuracy requirement, an integrity requirement, and a continuity of function requirement. For RNP-*X* airspace, the accuracy requirement limits the crosstrack and alongtrack error of aircraft position to less than *X* NM 95% of the time. For RNP-*X* airspace, the integrity requirement limits the undetected position error to less than 2 times *X* 99.999% of the time. The continuity of function requirement limits the failure of the system to meet RNP–RNAV standards to less than 0.01% of the time. Figure 2 illustrates the accuracy and integrity limits for the RNP-*X* route.

## AIRWAYS

Published airways provide defined paths for much of en route airspace. Generally, airways are defined by great-circle segments terminated by VOR stations. In remote areas, nondirectional beacons (NDBs) are used in the airway structure. Figure 3 shows an aeronautical chart of airways. In the United States the airways below 18,000 ft are designated as victor airways and have a prefix of V. Airways above 18,000 ft are designated as jet airways with a prefix of J. In other parts of the world, airways are prefixed with a letter (A1, G21, etc.) that is the first letter of a color (amber, green, etc.) Those airways are divided at different altitudes, and the upper airways are indicated with a prefix of U (UA1, for example). Airways have associated altitude restrictions to provide separation from terrain. In addition, published airways have certain conditional restrictions. The restrictions can be on the type of aircraft (only jet, for example) and on the direction of travel, and they can have restrictions that are effective for certain hours of the day.

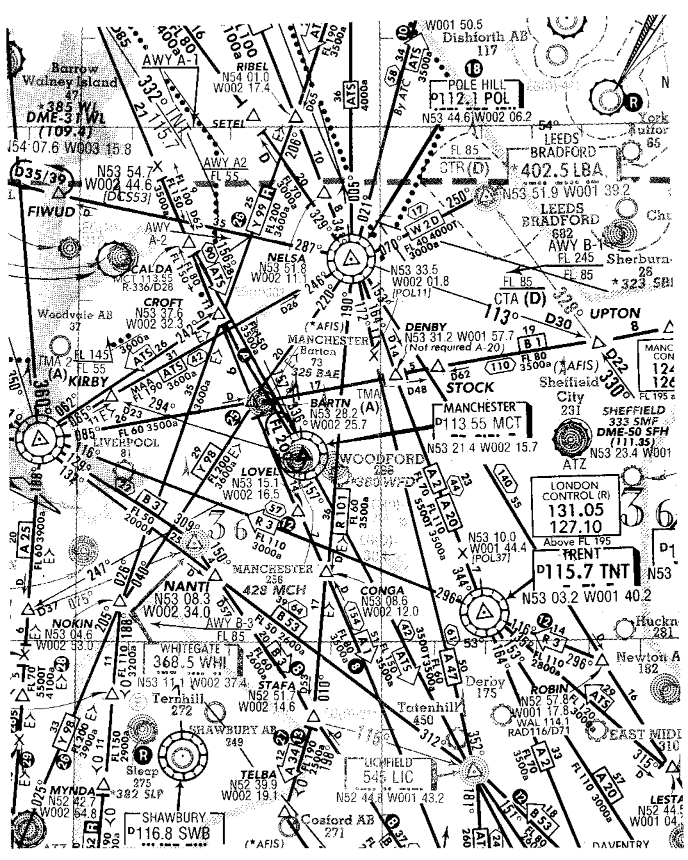

**Figure 3.** Example of an airway chart.

For purposes of transitioning from one airway to another, the intersections of airways are often defined by named fixes. Navigation equipment can store the network of airways and intersections for use by the pilot in defining the path. This allows the pilot to enter the intended flight path in terms of the airway identifiers. Airborne equipment generally does not store directional or other conditional airway restrictions.

For airways defined by VOR stations, the pilot is expected to navigate using the VOR at the closest end of the segment unless a changeover point (COP) is defined on the airway. The defined changeover point may not be at the midpoint of the airway segment to account for radio interference or other unique characteristics of the situation.

Some airways are designated as RNAV airways and are available only to aircraft operating with RNAV equipment. Such airways do not have the restriction that a receivable VOR or NDB be used to define the great-circle path. It is expected that the RNAV equipment uses available navigation stations or GPS to compute the aircraft position. Because conventional non-RNAV airways are defined by VOR or NDB stations, traffic becomes concentrated near those stations. RNAV airways offer a significant advantage by allowing the airspace planner the ability to spread the aircraft traffic over a greater area without the installation and support of additional navigation stations.

## TERMINAL AREA PROCEDURES

To provide a fixed structure to the departure and arrival of aircraft at an airport, published procedures are provided by the authorities. Such procedures are known as standard instrument departures (SIDs) and standard arrival routes (STARs). Figure 4 is an example of an SID chart. Generally, the instructions provided in SIDs and STARs are intended to be flown by the pilot without the aid of RNAV equipment. In order to incorporate the procedures into the RNAV equipment, the instructions must be reduced to a set of instructions that can be executed by the equipment. A subsequent section describes this process in more detail.

Standard approach procedures are issued by the authorities to assist pilots in safe and standardized landing operations. The generation of the approach procedures accounts for obstacles, local traffic flow, and noise abatement. Historically, the approach procedures are designed so that RNAV equipment is not required. That is, the pilot can execute the approach using basic sensors (VOR, DME, ADF) until landing visually. For operations in reduced visibility situations, there are Category II and III instrument landing system (ILS) approaches that require automatic landing equipment. In addition, there are RNAV and global positioning system (GPS) approaches that require RNAV equipment. Modern RNAV equipment is capable of storing the defined approach path and assist the pilot in flying all approaches. Figure 5 is an example of an approach chart.

## NAVIGATION SENSOR SYSTEMS

RNAV equipment receives information from one or more sensor systems and forms an estimate of the aircraft position. If more than one sensor type is available, the position estimation algorithm will account for the quality differences and automatically use the data to generate a best estimate of position. Complementary filters or Kalman filters are commonly used to smooth and blend the sensor data. The common sensors used for position estimation are GPS, DME, LORAN, VOR, and IRS. The data from each of the sensor types have unique characteristics of accuracy, integrity, and availability. In addition, each of the sensor types requires unique support functions.

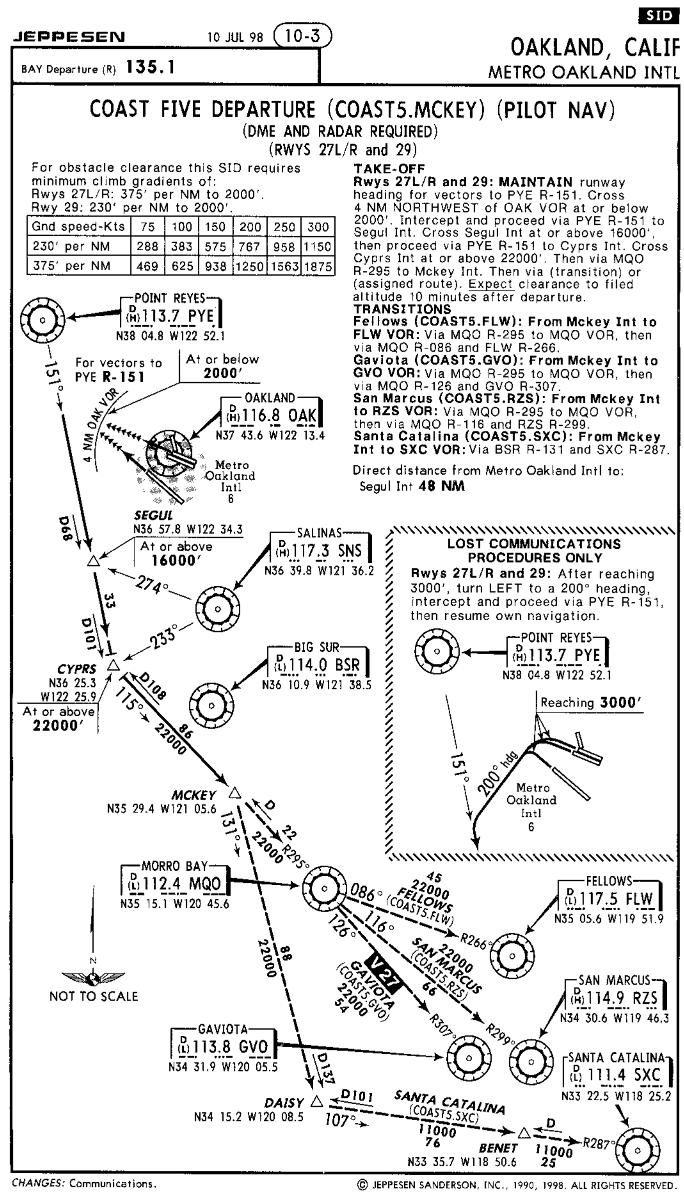


**Figure 4.** Example of an SID chart.

### Sensor Accuracy

The accuracy characteristic of a sensor can be expressed as the 95th percentile of normal performance. For any specific sensor, the wide variation in conditions in which it can be used makes it difficult to generalize the accuracy with specific numbers. The following data represent the accuracy under reasonable conditions.

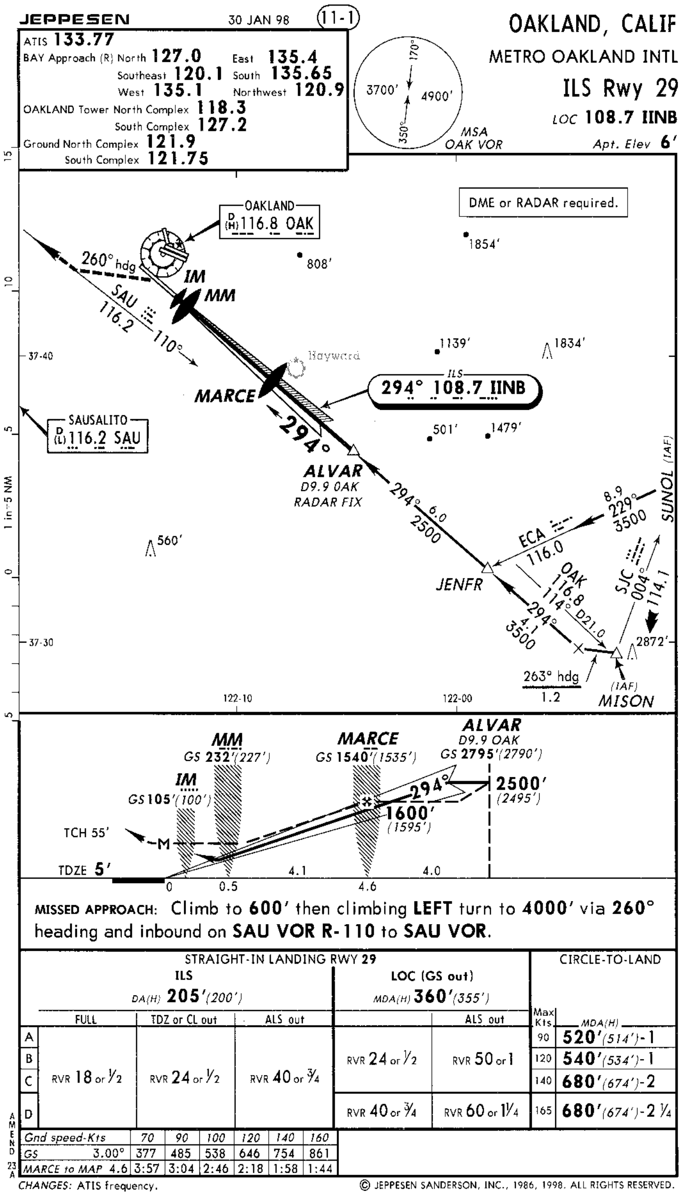


**Figure 5.** Example of an approach chart.

GPS has an accuracy of better than 0.056 NM in approach conditions, with some degradation allowed at higher speeds.

DME range is accurate to about 0.1 NM with some degradation for longer ranges. The accuracy of a position estimate based on two or more DME ranges will be dependent upon the geometry of the DME stations relative to the aircraft.

LORAN accuracy is about 0.25 NM when receiving a good ground wave signal.

VOR bearing is generally accurate to within 2°. When used as a position sensor, the position estimate accuracy is dependent upon the range to the VOR station.

IRS accuracy is dependent upon the time since alignment and the accuracy of the entry of the position at alignment. An accuracy of better than 2 NM/h since alignment is normal.

### Sensor Integrity

Integrity is the ability of the system to warn the pilot of significant errors in a timely manner. The most common way to provide integrity is with redundant measurements. By comparison of the redundant measurements, an error in one of the measurements can be detected and in some cases removed from consideration.

GPS has a function known as receiver autonomous integrity monitoring (RAIM), which provides integrity. This function can be used when sufficient signals of satellites are available. This is usually the case when the GPS receiver is receiving signals from five or more satellites. The status of RAIM is provided to the RNAV equipment and is important in approach operations using the GPS sensor.

For RNAV systems that use VOR and DME signals, if there are not redundant signals available, the position solution is vulnerable to the effects of radio signal multipath and to the navigation database integrity. The DME signal multipath problem occurs in situations where the local terrain supports the reflection of the radio signal to or from the DME station. The navigation database integrity is difficult to ensure, especially for DMEs that are associated with military TACANs. Military TACANs are sometimes moved, and the information does not get included in the navigation database in a timely fashion.

## NAVIGATION COORDINATE REFERENCE

The WGS-84 ellipsoid has become the standard for aeronautical navigation. This reference can be viewed as a surface of revolution defined by a specified ellipse rotated about the earth polar axis. The semimajor axis of the ellipse lies in the equatorial plane and has a length of 6378137.000 m. The semiminor axis is coincident with the earth polar axis and has a length of 6356752.314 m. Paths between two fixes on the WGS-84 spheroid are defined as the minimum distance path along the surface, known at the geodesic path between the two points. In general, the geodesic path does not lie on a plane but has a geometric characteristic of torsion. However, for reasonable distances, there is no significant error by approximating the path as a portion of a great circle of the appropriate radius.

Most of the fixes defined in the world were specified in a reference system other than WGS-84. An effort is under way to mathematically convert the data from the original survey coordinate system to that of the WGS-84 coordinate system. At the same time, when possible, the survey of the location is being improved.

## COURSE OF THE GREAT CIRCLE PATH

The basic path for airways is a direct path between two fixes, which may be a VOR station, an NDB station, or simply a geographical location. In terminal area procedures the most common path is defined by an inbound course to a fix. The RNAV equipment approximates such paths as segments of a great circle. Considering the case of a path defined as a radial of a VOR, the actual true course depends upon the alignment of the VOR transmitter antenna with respect to true north. The angular difference between the zero degree radial of the VOR and true north is called the VOR declination. When the VOR station is installed, the 0° VOR radial is aligned with the magnetic north so the VOR declination is the same as the magnetic variation at the station at the time of installation.

Magnetic variation is the difference between the direction of north as indicated by a magnetic compass and true north defined by the reference ellipsoid. As such, it is subject to the local anomalies of the magnetic field of the earth. The magnetic field of the earth varies in a systematic manner over the surface of the earth. It is much too complex to be defined as a simple bar magnet. The magnetic field is also slowly changing with time in a manner that has some random characteristics. Every 5 years a model, both spatial and temporal, is defined by international agreement using worldwide data. A drift of magnetic variation of 1° every 10 years is not uncommon on the earth. The model is defined in terms of spherical harmonic coefficients. Data from this model are used by sensors and RNAV systems to calculate the magnetic variation at any location on the earth. In particular, inertial navigation systems are references to true north and produce magnetically referenced data by including the local magnetic variation as computed from a magnetic variation model.

Because the magnetic variation of the earth is slowly changing, a VOR whose 0° radial is initially aligned with the magnetic north will lose this quality after a period of time. This discrepancy between the VOR declination and the local magnetic variation is one reason for ambiguity in course values.

As one progresses from along the great circle path, the desired track changes due to the convergence of the longitude lines and due to the magnetic variation. Figure 6 shows the effect of position on true and magnetic courses. The true course at the fix, $C_T$, is different from the true course, $C'_T$, at the aircraft because the longitude lines are not parallel. The difference in the magnetic courses is the result of the difference in the true courses together with the difference in magnetic variation at the two locations.

For the pilot, an important piece of information is the magnetic course to be flown to stay on the great circle path. With no wind, when on track, the current magnetic heading of the aircraft should agree with the displayed magnetic course. To achieve this goal, the RNAV equipment first computes the true course of the desired path and then adjusts it for local magnetic variation.

On the aeronautical charts, the magnetic course of the path is defined as the termination point of the path. When the aircraft is some distance from the termination point, both the true course and the magnetic variation are different. This causes the FMS to display a magnetic course at the aircraft that is different than that of the chart. As explained above,

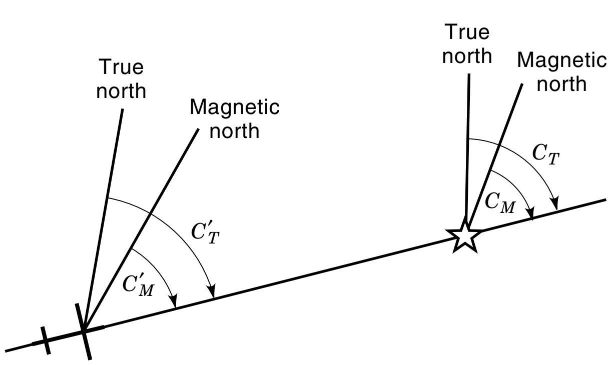


**Figure 6.** True and magnetic courses vary with position.

this difference is necessary to provide a display of course that is consistent with the magnetic heading of the aircraft as it progresses along the path.

## ARINC-424 NAVIGATION DATABASE

The navigation database installed in the RNAV system stores information about airways, SIDs, STARs, approaches, navigational aids, and so on. Such information changes continually as navigational aids are removed or installed, airports are improved, and so on. To ensure that the pilot has current data, new data become effective every 4 weeks by international convention. Because the aircraft may not be available for database update at the day the new data become effective, most RNAV systems have provisions to allow the new data to be loaded several days before it is to become effective. In effect, the RNAV system stores two databases, and the day of flight is used to determine the database that is effective for the flight.

An international standard for the interchange of navigational database information is encompassed in the ARINC specification 424 entitled Navigation System Data Base. This specification provides for standardized records of 132 ASCII characters. Record formats are provided to store a wide set of navigational information.

RNAV systems have packing programs that process ARINC-424 records into packed data that are loaded into the airborne equipment. The packing programs select only those records that are applicable to the RNAV system and are in the desired geographic area. It must also be ensured that the selected subset of data is consistent; that is, all references to other records are satisfied in the subset. Finally, the selected data are packed in the format required for the particular RNAV system.

The reduction of terminal area procedures to a set of instructions that can be automatically flown by the RNAV equipment is particularly complex. A considerable fraction of the ARINC-424 specification is devoted to this issue. A set of leg types have been established to encode terminal area procedures. Each leg type has a path definition and a termination definition. The intended flight path is encoded as a sequence of legs. The RNAV equipment will automatically fly the procedure by processing the sequence of leg types. As each leg becomes active, the path definition of that leg will form the current flight path intent, and the termination definition will provide information when the successor leg is to become active.

Table 1 lists the 23 leg types defined by the ARINC-424 specification. Note that generally the first letter of the leg type can be associated with the intended path and the second letter can be associated with the termination of the path.

Leg types CA, CD, CI, and CR are provided to handle instructions such as "fly 310° track until . . .," whereas leg types VA, VD, VI, VM, and VR will handle similar instructions such as "fly 310° heading until . . .." These leg types have no specified geographic path but will cause the aircraft to be steered to the proper track or heading from the current position of the aircraft whenever the leg becomes active. The other leg types are referenced to some geographic location.

### Limitation of ARINC-424 Coding

Using the ARINC-424 leg types, most terminal area procedures can be encoded in such a way that the RNAV equip-

**Table 1. ARINC-424 Leg Types**

| Leg Type | Path and Termination Description |
|---|---|
| AF | Fly a constant DME arc path to the fix |
| CA | Fly the specified course to the altitude |
| CD | Fly the specified course to a distance from a DME |
| CI | Fly the specified course to intercept the following leg |
| CR | Fly the specified course until crossing a specified VOR radial |
| CF | Fly the specified course into the fix |
| DF | Fly directly to the fix |
| FA | Fly the specified course from the fix to an altitude |
| FC | Fly the specified course from the fix for a specified distance |
| FD | Fly the specified course from the fix to a distance from a DME |
| FM | Fly the specified course from the fix until manually terminated |
| HA | Fly the holding pattern until terminated at an altitude |
| HF | Fly the holding pattern course reversal, terminated after entry maneuver |
| HM | Fly the holding pattern until terminated manually |
| IF | An initial fix (no path defined) |
| PI | Fly a procedure turn course reversal |
| TF | Fly the great circle path defined by two fixes |
| RF | Fly the arc defined by a constant radius to a fix |
| VA | Fly the specified heading to an altitude |
| VD | Fly the specified heading to a distance from a DME |
| VI | Fly the specified heading to intercept of following leg |
| VM | Fly the specified heading until terminated manually |
| VR | Fly the specified heading until crossing a VOR radial |

ment can generally fly the procedure in a fashion that is similar to the pilot navigation. However, there are significant limitations to this concept.

First, the concept assumes that the RNAV equipment has sufficient sensor data to accomplish the proper steering and leg terminations. Lower-end RNAV systems designed for smaller aircraft often do not have sensors providing heading or barometric altitude. Without a heading sensor, the system cannot fly the heading legs properly. Substituting track legs for heading legs is not always satisfactory. In the same way, legs that are terminated by an altitude (CA, FA, VA, and HA) require that the RNAV system have access to barometric altitude data. The use of geometric altitude determined by GPS data will introduce several errors. The geometric altitude ignores the nonstandard state of the pressure gradient of the atmosphere. The geometric altitude ignores the undulations of the mean sea level. Finally, the GPS sensor is accurate in the vertical axis to about 150 m, which is less accurate than altimeters.

A second limitation to the concept of using the ARINC-424 leg types has to do with the diversity of instructions that may

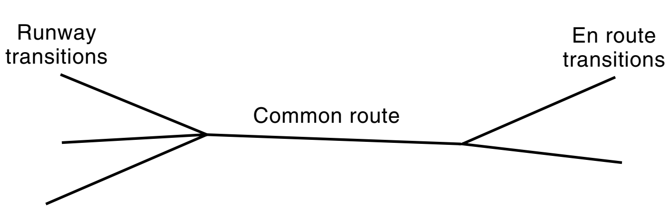


**Figure 7.** Data structure for SIDs and STARs.

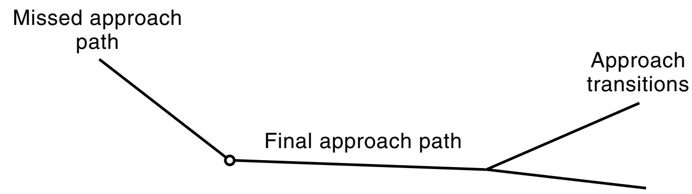


**Figure 8.** Data structure for approaches.

appear on the procedure chart. Because the chart is written with the pilot in mind, the chart may include logical instructions that cannot be coded with the 24 leg types of ARINC-424 specification. An instruction such as "fly to an altitude or DME distance, whichever occurs first" cannot be encoded as a sequence of ARINC-424 legs. Current charts exhibit a wide variety of logical instructions involving altitude, DME distance, aircraft category, landing direction, and the like. Many of these instructions cannot be directly encoded as a sequence of ARINC-424 legs.

## ARINC-424 Procedure Database Structures

SIDs can be defined in such a manner that a single identifier implies a single path. In other cases, a single identifier can be used to describe the departure paths from more than one runway. In such cases, the departure path specification must include the runway together with the SID identifier. In addition, the single identifier can further be used to describe the path to several en route terminations. The multiple optional paths are known as transitions. In the most general case, a runway transition path is linked to a common route and then linked to an en route transition path. The complete path is therefore specified by the SID identifier, the runway identifier, and the termination of the en route transition. To allow the encoding of the complete set of options, the ARINC-424 specification incorporates a database structure similar to that shown in Fig. 7.

STARs can have the same structure as SIDs, with the first leg of the star beginning at the first fix on the en route transition. With the complete SID or STAR encoded in the navigation database, the RNAV system allows the pilot to select the proper runway and en route transition and links a single path from the selection.

SIDs and STARs in the United States commonly use the branched structure. Outside the United States, this is generally not the case. That is, a single identifier is used to define the complete path from the runway to the final en route termination with no optional segments.

The general structure for approaches is a set of en route transitions followed by a common route. The common route includes both the final approach path and a single missed approach path. Virtually all approaches throughout the world have this structure (Fig. 8).

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**AIR DEFENSE.** See ELECTRONIC WARFARE.

**AIRPLANE MAINTENANCE.** See AIRCRAFT MAINTENANCE.