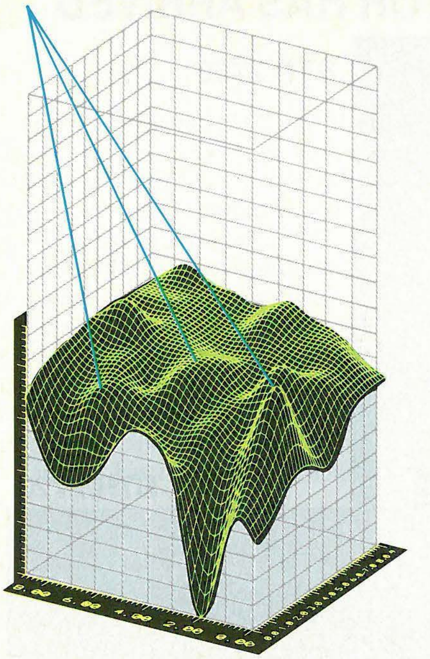

The Federal Radionavigation Plan

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"Innovation" is a regular column in GPS World *featuring discussions on recent advances in GPS technology and its applications as well as on the fundamentals of GPS positioning. Occasionally, we also discuss GPS policy. Central to GPS policy is the U.S. Federal Radionavigation Plan. In this month's column we'll take a look at this plan, its goals, and its effects on the GPS user.*

This column is coordinated by Richard Langley and Alfred Kleusberg of the Department of Surveying Engineering at the University of New Brunswick. We appreciate receiving your comments and suggestions of topics for future columns.

In the United States, as in most countries, the federal government is responsible for providing navigational services to the general public as well as to the military. The Department of Transportation (DoT), primarily through the United States Coast Guard (USCG) and the Federal Aviation Administration (FAA), operates navigation systems for both civil and military users, while the Department of Defense (DoD) operates systems specifically for national defense. Some of these DoD systems are common-use systems with large numbers of civil users.

By the late 1970s, the federal government was operating or developing no fewer than nine common-use radio-based navigation systems. In an effort to reduce the proliferation and overlap of these systems, Congress directed DoT and DoD to review their navigation needs and to select a mix of common-use systems that would meet requirements for accuracy, reliability, coverage, and cost while minimizing duplication of services.

In 1980, in response to Congress's request, DoT and DoD released the first edition of the Federal Radionavigation Plan (FRP). The FRP delineates policies and plans for federally operated common-use radionavigation systems, including consolidation of the systems. The plan is issued biennially, with the latest edition, the sixth, issued in December 1990.

The Global Positioning System (GPS) is a primary driving force of the FRP. Once fully deployed, GPS, with its continuous operation, global coverage, and high accuracy attributes, has the potential to supplant a number of the other common-use systems. However, a decision to phase out a particular system in favor of GPS will not be made until GPS is fully operational and can meet the civil requirements currently being met by the system to be phased out.

This article briefly looks at how these common-use radionavigation systems work, their accuracy, the size of their user communities, and their projected lifetimes. (For a more detailed history of the FRP and its relationship to these radionavigation systems, see "GPS and the U.S. Federal Radionavigation Plan," *GPS World*, February 1991.)

THE SYSTEMS

The nine systems considered in the FRP are Loran-C, Omega, Very High Frequency Omnidirectional Range/Distance Measuring Equipment (VOR/DME), Tactical Air Navigation (TACAN), the Instrument Landing System (ILS), the Microwave Landing System (MLS), Transit, radiobeacons, and GPS.

Loran-C. The present long-range navigation system, Loran-C, evolved from a system first developed during World War II for aircraft navigation. Loran-C's principle of operation is hyperbolic positioning. A receiver measures the difference in times of arrival of pulses transmitted at 100 kHz by a chain of three to five synchronized stations separated by hundreds of kilometers. The time-difference measurement derived from the signals of two stations, when multiplied by the speed of propagation of the signals, forms a line of position (LOP); the receiver could be anywhere on this line and give the same measurement. The geometrical form of this LOP is a hyperbola. Measurements using a third station provide another hyperbola, which intersects the first at the position of the receiver. (The hyperbolas may intersect at an additional point, but this spurious position fix will be located far from the desired fix and is easily discounted.)

The operation of Loran-C is the responsibility of the U.S. Coast Guard. Together with a number of host nations, the Coast Guard operates 17 chains of stations around the world, including one jointly operated with Russia. These stations provide coverage of the coastal areas of North America, Northern Europe, the Mediterranean Sea, the Far East, and the Hawaiian Islands. Additionally, as a result of a recent expansion, Loran-C provides complete mainland coverage of the conterminous 48 states. The Federal Aviation Administration sponsored this expansion, in part, in an effort to provide reliable, accurate, and economical en route and nonprecision approach navigation capability to improve accessibility to more airports for commercial and private aviation. In addition to the USCG chains, Russia, France, Saudi Arabia, and the People's Republic of China also operate loran stations. Several other countries, including Venezuela and India, are developing plans for loran chains.

Within the areas of coverage, Loran-C provides a predictable positioning accuracy of 0.25 nautical mile or about 460 meters (2 drms). The repeatable and relative accuracy of Loran-C is usually much higher — between 18 and 90 meters (2 drms).

Because the Loran-C signals are synchronized to Coordinated Universal Time (UTC), the system can be used for setting clocks accurately. Special "radio clocks" have been developed for this purpose.

According to the FRP, the projected number of maritime, aviation, and land users of Loran-C worldwide in 1992 is almost 600,000. About 80 percent of these users are in the civil maritime sector. DoD use of Loran-C is relatively limited, with about 500 users at present. The DoD requirement for Loran-C will terminate at the end of 1994.

USCG operations at the Hawaiian and overseas stations will be phased out, with closure of the Hawaiian stations possibly occurring as early as the end of 1992. The USCG is currently negotiating the continued operation of the overseas stations with the governments of the territories where they operate. The U.S. Loran-C chains in the conterminous states and Alaska will remain operational well into the next century.

Omega. Whereas Loran-C provides coverage of only selected areas of the earth's surface, another hyperbolic positioning system, Omega, provides worldwide coverage. Developed by the U.S. Navy and the Coast Guard and operated by the latter, Omega consists of eight stations transmitting time-shared carrier-wave signals on four frequencies between 10.2 and 13.6 kHz, in the "basement" of the electromagnetic spectrum. Each station also transmits a unique frequency to aid in identification and improve receiver performance.

An Omega receiver makes sequential phase-difference measurements between pairs of stations to establish an LOP. The intersection of LOPs determines the position fix. However, because the phase measurements are performed on carrier waves, the LOPs are ambiguous — points with the same phase difference recur throughout the coverage area. The area between lines of zero phase difference is called a *lane*. The width of a lane for 10.2-kHz measurements is about eight nautical miles. Single-frequency Omega receivers must keep careful track of lane crossings in the course of a voyage to provide accurate positions. By making measurements on multiple frequencies, a receiver can increase the lane width by up to 280 nautical miles, thereby reducing the potential for error.

The predictable accuracy of Omega is 2 to 4 nautical miles or 3.7 to 7.4 kilometers (2 drms). Accuracy depends on location, station pairs used, time of day, and propagation conditions. In some places, special beacon transmitters broadcast correction signals, which allow relative position accuracy of up to 0.25 nautical mile or about 460 meters (2 drms).

Omega is used by ships crossing the high seas, by aircraft operating in domestic and oceanic airspace, by weather balloons, and by weather reconnaissance dropsondes. Omega, like Loran-C, also is used for time transfer. The FRP projects about 27,000 users of Omega in 1992, more than 80 percent of whom are nonmilitary.

DoD requirements for Omega will terminate at the end of 1994. Because Omega is the sole means of air navigation in some oceanic areas, the Coast Guard will continue to operate the system until a suitable alternative is in place. No changes are anticipated until the mid-1990s, and Omega likely will remain part of the mix of navigation systems into the next century.

VOR/DME. Very High Frequency Omnidirectional Range and Distance Measuring Equipment are two systems that provide basic guidance for en route air navigation in the United States and in other countries. In the United States, FAA operates VOR and DME.

VOR stations transmit modulated signals in the 108- to 118-MHz band. A receiver on board an aircraft measures the relative phase of the signal modulations, from which it determines the azimuth of the aircraft relative to the transmitter.

The predictable accuracy of VOR, considering only ground station errors, is 1.4° (2 sigma). This angle implies a cross-track error of about 90 meters at a distance of two nautical miles (3.7 kilometers) from the station. The repeatable and relative errors are both 0.35° (2 sigma), resulting in a cross-track error of 23 meters at two nautical miles.

DME, often collocated with VOR, works on a two-way ranging principle. An interrogator in the aircraft sends out a pulsed signal that is picked up by the DME ground station. The station then replies with a similar signal. The DME instrument on board the aircraft computes the distance to the station from the round-trip travel time of the signals. This technique uses frequencies in the range of 960 to 1215 MHz.

The predictable, repeatable, and relative accuracies of DME are all 0.1 nautical mile or 185 meters (2 sigma).

Because they use signals in the very high frequency (VHF) and ultrahigh frequency (UHF) parts of the radio spectrum, VOR and DME operations are limited to line-of-sight. At ground level, this distance amounts to about 50 kilometers or less. For aircraft flying above 20,000 feet, the distance can be as much as 350 kilometers.

The FRP estimates that there are currently 196,000 civil users of VOR — about 80 percent of general aviation aircraft — and 89,000 users of DME. DoD users for both systems total about 12,500.

VOR/DME is the international standard for civil air navigation in controlled airspace and is protected until at least 1995 by international agreement. The systems likely will remain in the mix of radionavigation systems into the next century. However, both FAA and DoD are studying the feasibility of replacing VOR/DME with an alternate system, such as GPS. In fact, DoD is targeting the year 2000 for completion of its shift from VOR/DME use to GPS.

TACAN. The Tactical Air Navigation system is a military navigation system operated by DoD and FAA. The system provides both azimuth and range information through the use of ground transponder stations. In the United States, many TACAN stations are collocated with VOR stations. These facilities are called VORTACs.

The frequency bands used by TACAN and its coverage are similar to those of VOR/DME. The accuracies achievable with TACAN also are similar to those of VOR/DME: about 1° in azimuth and 0.1 nautical mile (185 meters), both 2 sigma.

Both FAA and DoD are studying the feasibility of replacing VOR/DME with an alternate system such as GPS.

According to the FRP, TACAN has 14,000 DoD users and fewer than 100 civil users. DoD will phase out land-based TACAN along with its use of VOR/DME. Some shipboard TACAN systems will continue in operation until a suitable replacement is found.

ILS. The Instrument Landing System is the standard civil landing system in the United States and abroad. It provides vertical and horizontal navigational information to aircraft approaching an airport. A localizer facility at the airport transmits a VHF signal to provide accurate horizontal guidance, and a glide slope facility transmits a UHF signal to provide vertical guidance. These signals ordinarily are supplemented by a marker beacon at 6 to 11 kilometers from the runway threshold and another about 1 kilometer from the threshold. A third beacon may be situated approximately 300 meters from the threshold.

The accuracy of ILS is sufficient for Category 1, 2, and 3 approaches, with 2-sigma horizontal accuracies at the decision height of 9.1, 4.6, and 4.1 meters, respectively. Vertical accuracies (2 sigma) are 3.0, 1.4, and 0.4 meters, respectively.

The FRP estimates 125,000 civil users of ILS and 10,500 DoD users.

Although ILS is adequate, it has limitations in siting, frequency allocation, cost, and performance. Microwave landing systems offer superior performance to ILS and eventually may replace it. However, an International Civil Aviation Organization agreement protects ILS until January 1, 1998, and the system will remain in use until an alternate system is in place. DoD-operated ILS facilities are expected to be replaced with microwave landing systems by 2004.

Some doubt the need for widely deployed MLS facilities given the improvements recently made to ILS and the potential of global navigation satellite systems.

MLS. DoT, DoD, and the National Aeronautics and Space Administration (NASA) are developing the Microwave Landing System to replace ILS. MLS facilities transmit signals over a wide area, permitting use by several aircraft flying along different approach paths throughout approach, flare, touchdown, and rollout maneuvers. Because the system permits curved and steep approaches, landing in mountainous terrain will be safer, and aircraft can conform more easily with noise-abatement requirements around airports in heavily populated areas.

MLS ground stations transmit multiple signals that permit the determination of the aircraft's azimuth, elevation angle, and range. The angles are determined using time-referenced scanning beams operating in the 5.0- to 5.25-GHz band. Range measurements are made on signals transmitted in the 960- to 1215-MHz band. The MLS signal format also accommodates special-purpose systems operating in the 15.4- to 15.7-GHz band.

As with ILS, the accuracies of MLS permit all three categories of approach.

FAA only recently has begun to phase in MLS. The transition to MLS will be slow, with simultaneous operation of ILS and MLS during the transition period.

FAA presently is proceeding with plans for fully implementing MLS. In March, the agency hopes to select two contractors to develop six prototype MLS ground systems for delivery in 1994. However, some segments of the aeronautics industry doubt the need for widely deployed MLS facilities given the improvements recently made to ILS and the potential of global navigation satellite systems (GNSS), the generic term for systems like GPS and the former Soviet Union's GLONASS. GNSS is currently unable to meet the accuracy and integrity requirements for precision instrument approaches. However, GNSS operated in a differential mode (see below) with suitable integrity monitoring, in combination with onboard inertial reference units and a flight management system, should be able to meet the requirements for Category 1 and 2 and some Category 3 landings. The Air Transport Association has stated that its member airlines believe that GNSS will be able to demonstrate Category 1 approach capability by 1994 and Category 3 capability by 1997.

Transit. Formally known as the Navy Navigation Satellite System, Transit is a satellite-based positioning system operated by DoD. Initially the system was classified because it was designed for updating the inertial navigation units of the Navy Fleet Ballistic Missile Submarines. However, DoD made Transit available to civil users in 1967.

The system consists of a constellation of satellites in circular, polar orbits at altitudes of roughly 1,100 kilometers with their nodes generally spaced evenly around the equator. Six or seven satellites are operational at all times. Each satellite transmits two harmonically related carrier frequencies, one at 400 MHz, the other at 150 MHz. Modulated onto both carriers is a broadcast message containing the orbit information uploaded to the satellite by the Naval Astronautics Group, which is responsible for maintaining the system.

The receiver compares satellite signals with the local oscillator frequency generated in the receiver, and the Doppler shift, or frequency difference, is integrated to yield the observable. By combining these Doppler counts with the satellite orbit data, the receiver can determine its coordinates. A single satellite pass yields the latitude and longitude of the receiver. If the receiver is stationary, data collected from multiple passes can provide very accurate three-dimensional position fixes. During the 1970s and 1980s, this approach was widely used to establish geodetic control.

For a single-frequency receiver observing a single satellite pass, predicted 2-sigma accuracy is around 500 meters. A dual-frequency receiver can eliminate most of the ionospheric delay on the signals, thereby achieving 25-meter accuracy. Exacting geodetic techniques have provided relative positioning accuracies of better than 1 meter.

The estimated number of civil Transit users worldwide is 90,000. There are currently only about 250 DoD users. DoD has no requirement for Transit after December 1996 and plans to shut down the system at that time.

Radiobeacons. Radiobeacons are nondirectional transmitters that operate in the low- and medium-frequency bands to provide navigation information for the aeronautical and marine communities. The signals are modulated to aid in station identification. A radio direction finder (RDF) is used to establish the bearing of a transmitter with respect to the heading of an aircraft or vessel. The bearing to a transmitter establishes an LOP, and bearings to additional stations can be used to obtain a position fix. RDF operation can be manual or automatic.

Many airports use aeronautical beacons for the transition from en route to precision terminal approach facilities and for nonprecision approach. Marine beacons provide a primary, low-cost navigation system for vessels with limited navigational capability, such as recreational craft. Navigators also use them as backup systems for more-sophisticated equipment.

The 2-sigma accuracy of aeronautical beacon bearings lies between 3° and 10°, whereas marine system accuracies are maintained to within 3°.

Of the almost 1,800 aeronautical radiobeacons in the United States, FAA operates 728, and DoD and nonfederal agencies operate the rest. The U.S. Coast Guard operates about 200 stations covering the Atlantic, Pacific, and Gulf coasts as well as the Great Lakes. USGS also operates a number of beacons that are triggered by a ship's radar. The estimated number of users of aeronautical and marine beacons is about 180,000 and 500,000, respectively.

Radiobeacons constitute a low-cost navigation method for the civil aeronautical and marine communities and will be maintained into the next century.

GPS. Previous Innovation columns have described various aspects of the Navstar Global Positioning System, but a brief summary here is in order. When fully deployed, this DoD-operated system will consist of a constellation of 21 satellites plus three operational spares. The satellites will be arrayed in six orbital planes inclined 55° to the equator. The orbits are circular with a nominal altitude of 20,183 kilometers. Each satellite transmits two radio frequencies for positioning purposes: L1 on 1575.42 MHz, and L2 on 1227.6 MHz. Two pseudorandom noise codes and a navigation message modulate the carrier frequencies.

By aligning a receiver-generated replica of the code with the arriving signal, a receiver can determine the clock-biased range (pseudorange) to the satellite. If the ranges to four satellites are combined with the orbit descriptions (the fourth range is required to account for the behavior of the receiver's clock), the receiver can determine its three-dimensional geocentric coordinates. Accurate velocity and time measurements also are possible. For precise navigation and surveying applications, the carrier phase is also measured.

Currently, 16 functioning satellites are in orbit: 11 operational (Block II) satellites and 5 prototype (Block I) satellites. DoD will declare GPS operational when 21 Block II satellites are in orbit and fully functioning. Until that time, the system remains under development, and DoD cautions users that signal availability and accuracy are subject to change without warning and that use of the system is completely at the user's own risk.

GPS initially was developed to serve the needs of DoD and the military forces of U.S. allies. In keeping with its national security mandate, DoD plans to limit the real-time absolute positioning capability of GPS afforded to most civil users. DoD will provide the Standard Positioning Service (SPS) to all GPS users on a continuous, worldwide basis without direct charge. SPS users will have access to the coarse acquisition (C/A) code and navigation message on the L1 frequency, but DoD will intentionally degrade the accuracy afforded through a process known as *selective availability* (see "The Issue of Selective Availability," *GPS World*, September/October 1990).

SPS will provide planned predictable horizontal positioning accuracy of 100 meters 2 drms at the 95 percent probability level, with a corresponding vertical accuracy of 156 meters (2 sigma). At the 99.99 percent probability level, the accuracy will be 300 meters.

During the buildup of the GPS constellation, the precision (P) code transmitted on both the L1 and L2 frequencies generally will be available to all users. However, when GPS is declared fully operational, use of an encryption technique known as *antispoofing* will deny most civil users access to the P-code.

A higher-accuracy service, the Precise Positioning Service (PPS), will be available to DoD-authorized users. The PPS provides access to the P-code on both the L1 and L2 frequencies and the undegraded navigation message. The PPS's predictable accuracy is 17.8 meters horizontal (2 drms) and 27.7 meters vertical (2 sigma).

The PPS community includes civil and military users in the U.S. federal and allied governments. A limited number of other users who can demonstrate to DoD that their use of the PPS is in the U.S. national interest, that certain security requirements can be met, and that a reasonable alternative to the use of the PPS is not available can also use the service.

Through differential techniques, SPS users can achieve positioning accuracies that are higher than those otherwise available. In differential GPS (DGPS), a monitor station operating at a known location provides range corrections to users' receivers via a communication link. Alternatively, the actual data collected by the monitor station could be transmitted instead of range corrections. The user's receiver combines the monitor station's data with its own to obtain a high-accuracy relative position (see "Precise, Real-Time Dredge Positioning," in Innovation, *GPS World*, February 1991). Surveyors using the GPS prototype constellation pioneered a non-real-time implementation of this technique in the early 1980s.

Figure 1 illustrates the expected growth in the number of GPS users between 1990 and 2003. These projections are based, in part, on figures from the FRP. Estimates of the number of civil land and maritime users in 1997 and beyond are highly speculative and are based on extrapolations of FRP estimates that are given only up to 1996. If GPS receivers eventually become as ubiquitous as quartz watches, as some pundits suggest, then the projected numbers of GPS users early in the next century may be far greater than those shown in the figure.

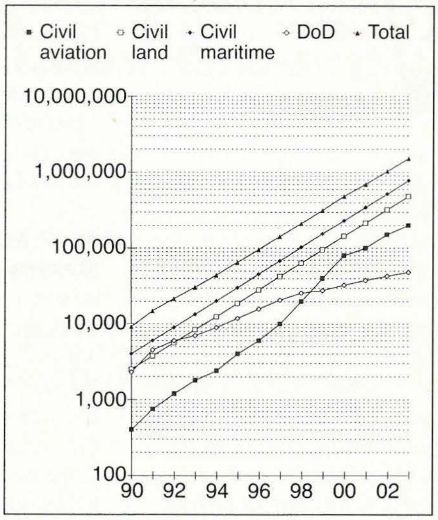

Figure 1. Projected growth in the number of GPS users

The Global Positioning System has the potential to meet or surpass the accuracy and coverage of other radionavigation systems. Consequently, DoT will consider phasing out some of the existing systems if the full civil potential of GPS is realized. However, any decision to discontinue the operation of a system will depend on many factors, including, according to the 1990 FRP, "resolution of GPS accuracy, coverage, integrity, and financial issues; determination that the systems mix meets civil and military needs currently met by existing systems; availability of civil user equipment at prices that would be economically acceptable to the civil community; establishment of a transition period of 10–15 years; and resolution of international commitments."

CONCLUSION

This article only briefly summarizes the contents of the Federal Radionavigation Plan. For more details and official policy statements, interested readers should consult the FRP directly. Copies of the 1990 edition are available at a nominal cost from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161, USA, (703) 487-4650, as document DOT-VNTSC-RSPA-90-3/DOD-4650.4. The FRP also is available from Navtech Information Service, 2775 South Quincy Street, Suite 610, Arlington, VA 22206-2204, USA, (800) 628-0885. ■