THE HOWS AND WHERES OF RADIONAVIGATION

MAPPING OUT THE TRANSPORTATION APPLICATIONS

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The Nationwide Differential Global Positioning System (NDGPS) determines real-time locations accurately within three meters, is available more than 99.9 percent of the time, and can detect data errors within five seconds. The NDGPS is an enabling technology, a foundation for many other applications.

Today the NDGPS is being used to develop and populate improved base maps of the transportation infrastructure; tomorrow it may guide snowplows and enhance vehicle safety by helping drivers stay on the road.

Base Maps

Location, location, location. The realtor's mantra is as apt today as it was 100 years ago and may be even more apt for the 21st century transportation network. Pressed to make the transportation network safer and more efficient, the nation must scrutinize the needs and the infrastructure to determine the optimal applications of limited resources.

Safe Truck is a system being developed to alert truck drivers who start to drift out of lanes or off the road.

Ensuring delivery of goods and services where and when needed and the availability and deployment of municipal services requires an understanding of the transportation network—its reach, its status, its bottlenecks, and how to move people and freight through it as efficiently and safely as possible.

Geographic information system (GIS) technology can be used to collect and make available much of this network information. GIS provides the tools to generate up-to-date maps of the transportation infrastructure and to evaluate many details, pinpointing areas for improvement.

The first step is to create accurate base maps—basic maps of the transportation infrastructure. Base maps typically are accurate to within one meter but offer few data beyond the location of a road's centerline. Developing and populating the base maps is key to their usefulness.

After integrating the base map into a GIS, other attribute data can be added in layers. One layer may include subsurface details such as underground utilities or culverts; another may include roadside infrastructure such as guardrails and warning signs. Anything on, under, or near the road can be layered onto the base map. Individual users then can overlay specific data onto the base map to analyze information critical to a project.

Collecting the data to generate and populate the base map can take days or weeks with traditional survey techniques. The NDGPS makes the task easier with radionavigation, which can work in a moving survey vehicle. The system is designed to provide accurate measurements, to be reliable and almost always available, and to assess its own health—that is, the integrity of the data supplied.

NDGPS Advantages

The NDGPS increases the accuracy, availability, and integrity of the Global Positioning System (GPS), the space-based system providing worldwide, all-

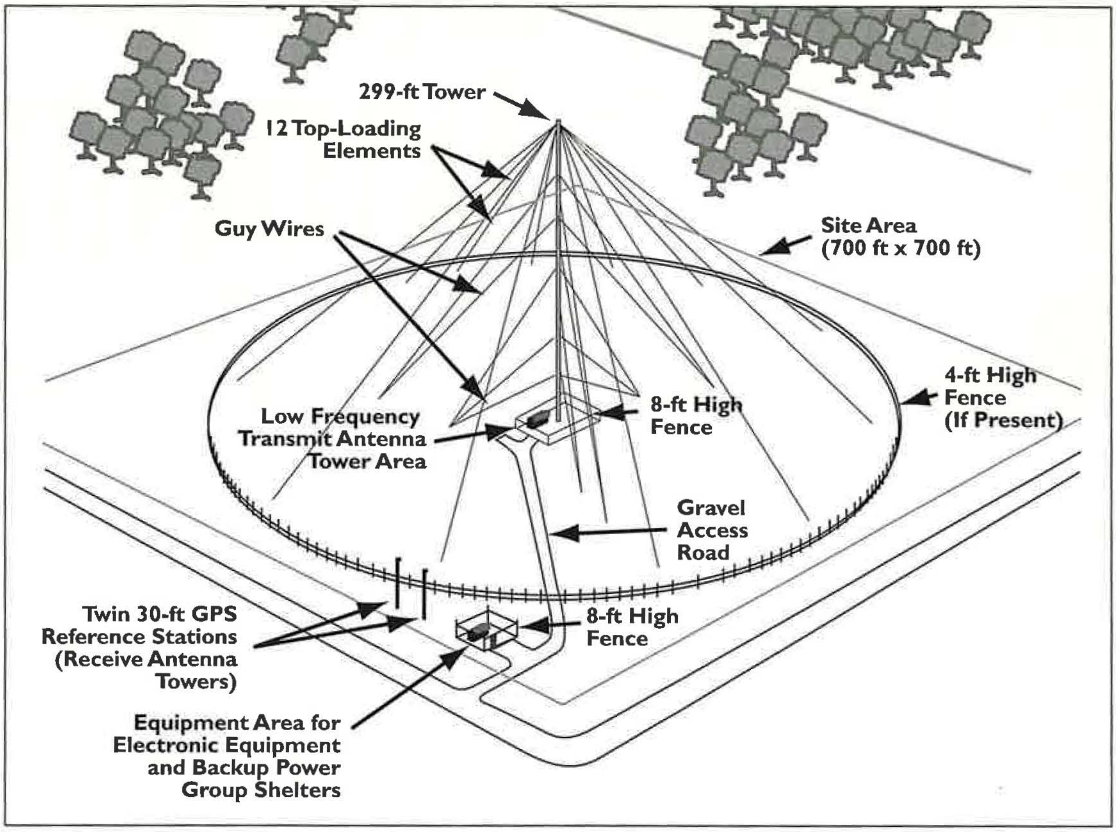


FIGURE 1 Nationwide Differential Global Positioning System (NDGPS) broadcast facility.

weather, passive, three-dimensional position, velocity, navigation, and time data to civilian and military users. The GPS deploys a constellation of at least 24 satellites, each continuously broadcasting a position and a timing signal.

Distance from the satellite is determined by measuring the time for a signal to travel from the satellite to the user's receiver. The receiver uses the distance from the satellite to form a sphere, with the satellite at the center and the receiver somewhere on the sphere. From a single satellite signal, the receiver can determine range, but not direction. From a second satellite, the receiver can describe a second sphere; the receiver's location is somewhere on the circular intersection of the two spheres. A third satellite defines a third sphere, reducing the receiver's possible location to two points. A fourth satellite then narrows the location to a single point. Combining the measurements from four different satellites determines the user's three-dimensional position.

GPS currently provides Standard Positioning Service (SPS) to civilian users. U.S. and allied military organizations have access to the Precise Positioning Service which offers increased jamming resistance and other functions not needed by civilian users.

Three parameters specify the quality of GPS service: accuracy, integrity, and availability.

Accuracy

Accuracy is the degree to which the estimated or measured position or velocity of a platform conforms with its true position or velocity. Radionavigation accuracy usually is presented as a statistical measure of system error, specified as

- **Predictable.** How accurate is the radionavigation system's position solution with respect to the charted solution? The position solution and the chart must be based on the same geodetic datum.
- **Repeatable.** With the same navigation system, how accurately can a user return to a position at previously measured coordinates?
- **Relative.** On the same navigation system, how accurately can a user measure position relative to measurements by another user at the same time?

Integrity and Availability

Integrity is the ability of a system to warn users in a timely way when not to use the system for navigation because the data may be flawed.

Availability is the percentage of time that the services of a navigation system are usable; it indicates the system's ability to provide usable service within a specified coverage area. Signal availability is the percentage of time that navigation signals transmitted from external sources are available for use. Availability is a function of the physical characteristics of the environment and the technical capabilities of the transmitter facilities.

Although the GPS offers many advantages over other navigation and positioning services, many emerging applications require greater accuracy, availability, and integrity than that of the GPS SPS (6 to 40 meters, 95 percent, and two hours respectively). To support these applications, the U.S. Department of Transportation (DOT) has begun to deploy the NDGPS to augment the SPS. The NDGPS provides an increased level of accuracy, availability, and integrity for the efficiency and safety enhancements identified by U.S. DOT for radionavigation services (*1*).

How NDGPS Works

Differential Correction

NDGPS improves radionavigation accuracy by providing a differential correction based on the known location of a GPS reference station antenna and the calculated position of the GPS receiver. Every NDGPS broadcast facility has two reference stations (see Figure 1), each with a precisely surveyed GPS antenna. The survey has an accuracy of a few centimeters, although newer sites measuring plate tectonic movement are surveyed even more accurately and employ more stable structures for the reference station antenna.

When a site is brought online, the GPS receiver calculates what is termed the pseudorange from the antenna to each of the satellites in view. The calculations are compared with those from the survey for the receiver's antenna. The difference between the two values is the correction factor or differential correction. The differential correction then is broadcast for users in the coverage area of the NDGPS facility.

In this way, a pseudorange correction can be generated and broadcast for each visible satellite, replacing a single value for the entire satellite constellation. This ensures that users can employ the optimal distribution of satellites for any location. Figure 2 illustrates the area for which the NDGPS will provide coverage by the end of 2001.

The technique for generating the differential corrections is termed a code phase correction, since it corrects for errors in the observed code ranges supplied by the satellites. The errors come from many sources, listed in Table 1, with magnitudes.

Cleaning Clocks

The NDGPS also can improve the availability of GPS by correcting for clock errors that make the satellite unusable and by providing an integrity function. If one of the cesium clocks on a satellite begins to drift, the message that the satellite broadcasts is designated as unhealthy as soon as the error goes beyond a pre-

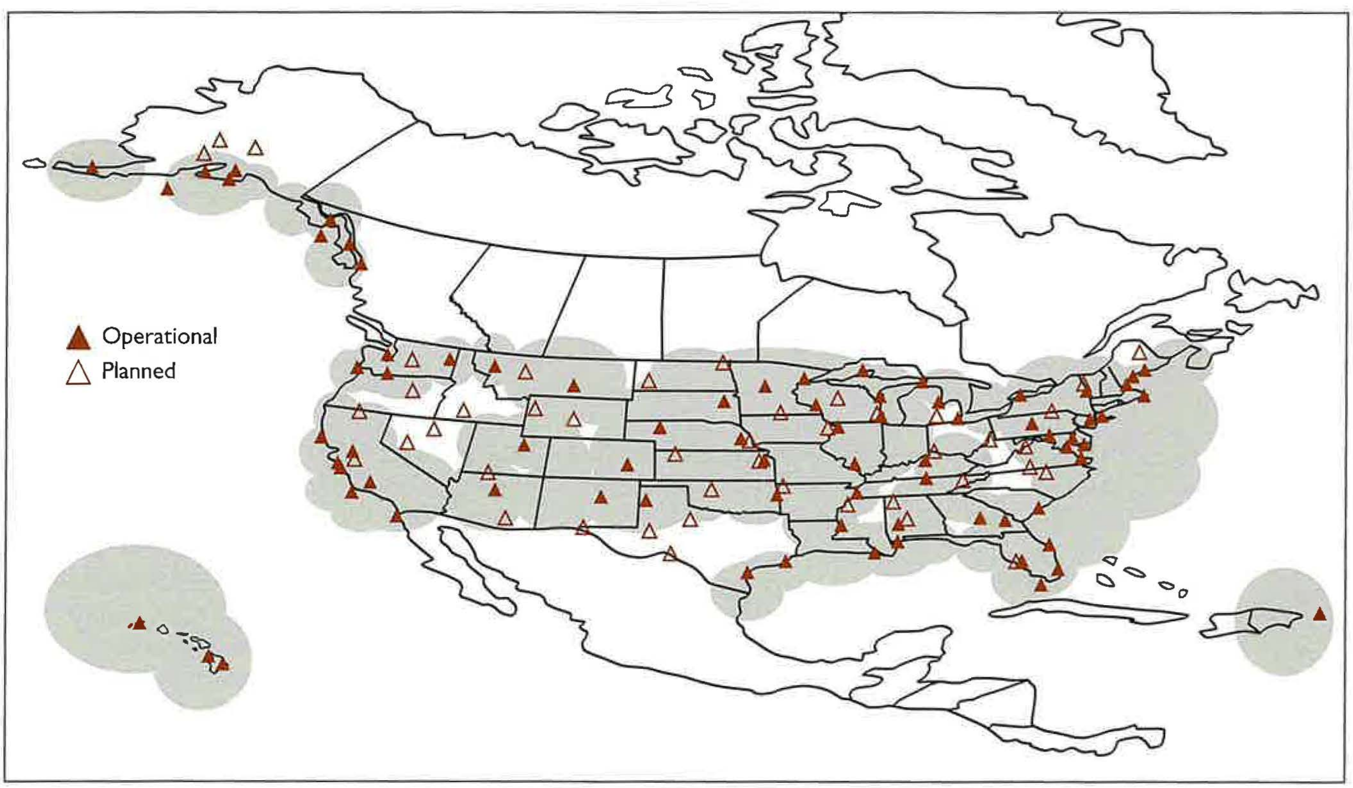


FIGURE 2 NDGPS coverage expected by the end of 2001.

TABLE 1 GPS Error Sources

Source	Typical Range Error Magnitude (meters, 1 sigma) SPS with II/IIA Satellites
Atmospheric Error	
Ionosphere	7.0
Troposphere	0.7
Clock and Ephemeris	3.6
Receiver Noise	1.5
Multipath	1.2
Total User Equivalent Range Errors	8.2

determined drift point or drift rate. However, the NDGPS service provides a correction for the error that is applied within the user's GPS receiver, allowing the satellite to remain in use for navigation.

Integrity is the ability of the service to notify users of a condition that makes a satellite unreliable for navigation. GPS satellites must pass over a satellite uplink station to set the broadcast to unhealthy—in some scenarios, this may not be possible for several hours. The NDGPS service can provide this integrity function within five seconds after the detection of a satellite anomaly.

Unblockable Performance

The NDGPS is designed to improve the accuracy, availability, and integrity of GPS to better than one to three meters, with a 99.9 percent availability and a five-second integrity. Additional research is under way to improve the accuracy to within 20 cm nationwide, maintaining availability and integrity.

Designed for surface applications, NDGPS broadcasts corrections for GPS using a low-frequency ground wave, which can work around and through man-made and natural obstructions; this increases the availability of a reliable navigation solution to better than 99 percent. The service can be received inside a closed building, so that wherever the GPS is available, the NDGPS also will be available, improving accuracy.

For example, in a recent test, corrections from the NDGPS broadcast facility in Chico, California, were received and applied in an automobile traveling on I-80 from Truckee, California, up to 50 miles east of Reno, Nevada. The received signal strength did not decline because of terrain blockage by the mountains between the Chico broadcast facility and the receiver but because of free space attenuation. Therefore, observed data—as well as knowledge of the propagation characteristics of low-frequency broadcasts—support the assertion that the NDGPS broadcast does not require a line of sight between the broadcast facility and the receiver.

Mapping Applications

Surveying and Maintenance

Mapping the transportation infrastructure has been time consuming and expensive. Many states resurvey the road network every three years, including everything on or above the road surface. Surveyors take many days to measure a segment of road at the current one-meter standard; a complete road inventory can take years.

With the NDGPS, the same road segment can be surveyed and all pertinent data recorded in hours. A van equipped with stereo cameras can record images for comparison. Traveling at or near highway speeds, the van can collect images, with each image linked to an NDGPS position. Combining the known location of the van with the offset available from the stereo image provides high-resolution locations for the visible roadside infrastructure. Links to road surface monitors that record the condition of the road surface allow maintenance personnel to identify and locate the worst sections of road easily and quickly for maintenance.

South Carolina Pioneers

Many states are using the NDGPS service to map infrastructure. South Carolina is a pioneer, using the NDGPS broadcast sites in Savannah; Macon, Georgia; New Bern, North Carolina; and Hartsville, Tennessee. With the NDGPS, South Carolina DOT has increased the rate of collecting and processing road survey data, saving thousands of dollars annually and improving the data. County governments also have invested in mapping grade receivers that use the NDGPS broadcasts.

The state is supporting applications to develop its 911 system—19 of South Carolina's 46 counties have used the NDGPS to develop 911 road maps, and 45 of the 46 counties are 911-certified. This could not have happened without the availability of the NDGPS. In addition, the counties are investing in more NDGPS equipment to map roadside infrastructure and other key aspects of the roadway. This information feeds into state tax maps, which now are referenced to the NDGPS sites.

Other states using the NDGPS for developing maps and populating GISs include Washington, South Dakota, Vermont, and Maryland. As more sites come online, other states are discovering the potential.

Beyond Base Maps

Although base maps form the core of transportation applications, other applications build on and increase the utility of the maps, as shown in the following examples.

Mapping the Infrastructure

South Dakota was one of the first states to receive NDGPS coverage, with installation of the sites in Clark, South Dakota, and in Whitney, Nebraska. South Dakota DOT has used the NDGPS to reduce the costs of GIS data collection. Previously, the DOT had been postprocessing data from state-operated reference stations; staff would spend as much time postprocessing as collecting the data. Eliminating the step has saved time and money. Other states, seeing the benefits, have invested in NDGPS mapping grade receivers for road survey data collection.

Highway–Rail Grade Crossing

Minnesota is using the NDGPS in an experimental highway–rail intersection warning system to alert drivers that trains are approaching. The NDGPS is well suited for this application because it can work around and through man-made and natural obstructions, is generally available nationwide at low cost, and offers high reliability and integrity.

The NDGPS receiver is mounted on the locomotive and uses a map of the track and road infrastructure to determine when the train will cross a roadway. The more accurate the calculations of the location, velocity, and direction of the locomotive, the fewer the false warnings that will be sent to vehicles on the roadway. However, drivers need assurance that the warnings are reliable.

Driver Characteristics

The NDGPS offers sufficient absolute and repeatable accuracy for collecting data about driver characteristics—such as determining driver reaction to various road hazards or geometric designs. NDGPS can collect 1 to 10 samples per second with a specially equipped vehicle, providing invaluable data on a driver's reaction—for example, when the vehicle began slowing for an obstruction, when a turning lane was entered, the vehicle's speed, and so on.

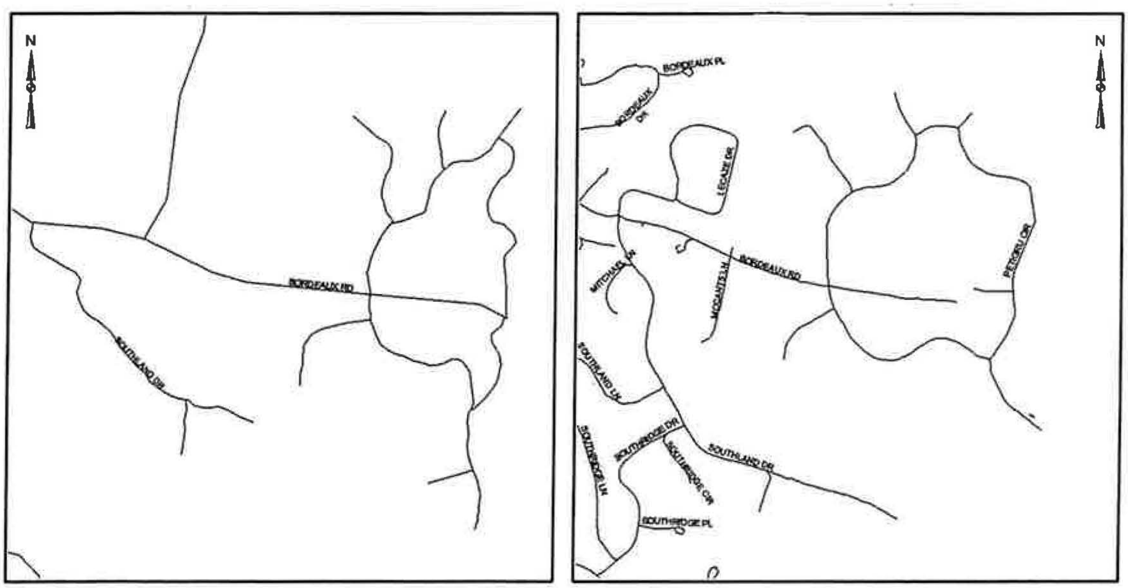
As with the highway–rail grade crossing, this application requires accurate readings of location, velocity, and direction; the vehicle's position must be known within one meter and errors cannot vary more than one-half meter from the area and time of data collection.

Precision Navigation

The combined use of the NDGPS with inertial sensors has achieved high reliability in critical applications. For example, laser gyros are accurate until abrupt changes in direction or speed introduce errors that can accumulate—the introduced error cannot be removed from the gyro's data. However, an alternate source of navigation information—such as the NDGPS—can bring the gyro data back in line with the vehicle's true location.

Railway Track Maintenance

Railroads are equipping track geometry and analysis cars with the NDGPS to identify the precise location of a track anomaly. Anomalies can take many forms; one of the most common is wear on the inside radius of the outer track of a curve—the train's pressure causes warping and wearing. Maintenance person-



Maps for 911 service in South Carolina counties, developed using the NDGPS.

Advanced snowplow employing NDGPS and other sensors.

nel, however, often have difficulty identifying the precise location of a problem, sometimes fixing something else instead—which can cause additional problems. The NDGPS can specify the location of a track defect within three meters, allowing a particular spot to be identified and repaired, saving railroads time and money and improving the safety of the rail infrastructure.

New Developments

With a signal structure and broadcast frequency that ensures availability when and where needed, the NDGPS is suitable for many additional applications. Research and development of applications continues.

U.S. DOT has set a research goal of achieving better than 20 cm accuracy on an NDGPS test network within the next year. The test signal will be broadcast from the Hagerstown, Maryland, facility and will be available for precoordinated testing for about one year, from November 2001 through October 2002.

The goal is to improve accuracy with the most efficient signal format. If made available nationwide, this service would enable many more applications.

Although the NDGPS has an availability of greater than 99.9 percent, supplements are needed for areas that the GPS cannot yet penetrate, such as tunnels and deep urban and natural canyons. Combining the NDGPS with other navigation services that are targeted to supplement the GPS will increase the availability of a navigation solution and keep overall system costs as low as possible.

The following applications may become available in the future. In many cases, the applications may not need greater accuracy but may require the resolution of other issues, including public acceptance.

Lane Keeping

The University of Minnesota, in cooperation with the Minnesota DOT, the Federal Highway Administration, and several other organizations, is developing Safe Truck. This program combines vehicular radar, magnetic lane markings, and high-accuracy DGPS to create a system for helping large trucks stay in lane by alerting drivers drifting into another lane or off the road.

Researchers hope to create an approach that is reliable and cost-effective. Current estimates from accident data suggest that advanced lane-keeping technologies could prevent as many as 19,000 crashes annually by vehicles running off the road in rural areas.

Intersection Collision Avoidance

Collision avoidance systems also must be highly reliable, inexpensive, and allow only gradual deterioration during a failure. To avoid collisions, the precise trajectory and position of each vehicle entering an intersection must be known and communicated to the other vehicles. The NDGPS offers the increased effectiveness of highly accurate readings, reducing system complexity and cost.

Semi-Autonomous Navigation

Semi-autonomous vehicle navigation is possible by combining lane keeping and collision avoidance systems. Although this may not be available for individual vehicles for many years, selected applications may produce beneficial and cost-effective results—for example, plowing snow during near-whiteout conditions (see photo of advanced snowplow on this page). Keeping the lanes open makes it possible to clear them quickly after a major snowfall, allowing emergency service personnel to reach where needed. This also reduces the economic impact of winter weather, allowing businesses to open sooner and customers to make purchases.

No Limits

The NDGPS offers many benefits for surface transportation—creating and populating base maps, providing cross-boundary links, and offering a versatile tool for monitoring the transportation infrastructure. The future transportation system will make greater use of computer and communication technologies—tasks will be automated, safety warning systems will notify drivers about potential accidents, and virtual rumble strips will alert drivers running off the road. The NDGPS can provide the fundamental radionavigation service to make these technologies possible.

What more the NDGPS will offer is limited only by the imagination—not by technology.

Reference

1. *Federal Radionavigation Plan.* U.S. Department of Transportation. 1999.