National Cooperative Highway Research Program

# NCHRP Synthesis 258

# Applications of GPS for Surveying and Other Positioning Needs in Departments of Transportation

A Synthesis of Highway Practice

Transportation Research Board
National Research Council

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National Cooperative Highway Research Program

# Synthesis of Highway Practice 258

# Applications of GPS for Surveying and Other Positioning Needs in Departments of Transportation

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communication and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration of the U.S. Department of Transportation.

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## PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

## FOREWORD

*By Staff*
*Transportation Research Board*

This synthesis will be of interest to both administrative and technical personnel in departments of transportation (DOTs), especially in the areas of surveying, mapping, transportation planning, environmental impact assessment, design, construction control, maintenance, operations, vehicle location, and other functions that require accurate location data. This report will be useful for intermodal transportation analyses and for measurement and positioning data for inventories and geographic information systems (GIS). It can also be useful to suppliers and developers of GPS equipment.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

This report of the Transportation Research Board presents a description of GPS, the major components, basic geodesy principles, how GPS functions, and how it can be applicable to the data and analysis requirements of transportation agencies. The anticipated cost effectiveness of GPS in terms of personnel, equipment, and time as related to the improved accuracies to be derived from GPS applications are described. Current and more advanced applications of GPS by DOTs to different transportation modes are presented. The report also includes a glossary of terms and a listing of GPS information sources.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the research in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

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Crawford F. Jencks, Manager, National Cooperative Highway Research Program, assisted the NCHRP 20-5 staff and the Topic Panel.

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# APPLICATIONS OF GPS FOR SURVEYING AND OTHER POSITIONING NEEDS IN DEPARTMENTS OF TRANSPORTATION

## SUMMARY

The development and maintenance of the nation's transportation infrastructure requires methods of locating facilities that are both effective and efficient. State departments of transportation (DOTs) use field surveying as a basic component of any project that requires location information. As the cost of doing surveys rises, DOTs search for more efficient methods to accomplish their work while providing more accurate levels of spatial measurement and location. DOTs are also becoming increasingly involved in other types of transportation planning and programming activities that require accurate location data. Two examples include 1) locating intermodal facilities and their connections to the National Highway System and 2) mapping and maintaining data inventories that meet the demands of environmental regulations. These additional DOT responsibilities require the ability to obtain and preserve accurate location information in geographic information systems (GIS).

The need for more accurate and cost-effective data-gathering techniques, as well as the increasing demand for spatial data, require that state DOTs use the latest and best technology available to measure and locate facilities. One technology that makes these tasks easier, cheaper, and more accurate is the Global Positioning System (GPS). This method of determining an accurate position on the face of the earth has revolutionized the way field observations are made. Using satellites, ground-based receiving stations, and computer post-processing, determining an X and Y location on the earth's surface has never been more accurate. Although not intended to measure elevation or a "Z position," GPS can, with post-processing, also provide this type of data.

The history of GPS begins in 1978 when the Department of Defense launched the first GPS satellites for testing. In 1983, the Texas Department of Transportation was one of the first states to use the new technology. Between 1989 and 1993 the constellation of GPS satellites was increased and in 1994 the system was declared fully operational.

Since the early 1990s DOTs across the nation, as well as other federal and state agencies, universities, and private companies have tested the technology in a variety of ways. Some examples include establishing survey baselines, increasing accuracy of traditional survey methods, control densification, project control, and mapping control. This advancing technology means that, in general, GPS survey methods can result in better accuracy, reduced time and staff requirements, and at less cost than conventional methods. For example, with one hour of satellite tracking, GPS can produce results with precision ratios that exceed 1:200,000. A new system, high-accuracy reference network, which will be available throughout the United States, allows DOT surveyors to use regional base stations as a continuously operating reference station. Such systems are in operation in Texas and Mexico.

In addition, some innovative applications have also been attempted, such as vehicle location and identification, tracking buses, assisting in photogrammetry, emergency response, and photo logging of highways with a GPS assist.

Other applications of GPS that state DOTs can find effective include using GPS differential positioning to locate, track, and navigate vehicles. This technique is in use in several

states—Iowa, Minnesota, and Michigan—to monitor maintenance vehicles and to efficiently dispatch appropriate vehicles in emergencies. This application, when linked to digital radio, can be used with the transmission of other digital data to describe the work activity of a maintenance party to automatically update a maintenance GIS system.

It is clear that GPS is not only a new technology, but a new way of locating features on the earth's surface and making earth-based measurements. It provides labor savings, increases positional accuracy, and is applicable to a wide range of modal needs. GPS supports the work of surveyors, civil engineers, planners, geographers, GIS technicians, and staff working in environmental studies.

CHAPTER ONE

# INTRODUCTION

## BACKGROUND

The development and maintenance of the nation's transportation system requires efficient methods of locating facilties within the infrastructure inventory. Three factors drive this growing need. First is the requirement to reduce costs for field surveys. Second is the need in state DOTs to develop or expand their Geographic Information Systems (GIS). The purpose of a GIS requires that "spatial location" be the basic attribute of each computer file within the system. A GIS containing descriptions of real property that are based on erroneous spatial relationships can have a devastating effect on projected costs. Many times the usefulness of information in a GIS data base is sacrificed because of the cost of acquiring a desired level of locational accuracy. The third factor is the need to acquire accurate information quickly and to provide this information in a way that is understandable by decision makers.

While present terrestrial based geodetic, cadastral, and construction survey technology is a vast improvement over historical methods, the associated personnel costs have been steadily increasing. The result is that the use of existing survey and positioning technology may not be cost effective in the future.

The degree of positional accuracy required in transportation related environments can vary from a few millimeters to hundreds of meters. What is needed, therefore, is an economical measuring and positioning system that can produce these accuracies in a cost-effective manner. The purpose of this synthesis is to describe the use of such a system—the Global Positioning System (GPS).

## GPS IMPLICATIONS FOR DOTs

GPS is a worldwide, earth-orbiting, all-weather satellite navigation system developed by the U.S. Department of Defense (DoD). Although it is primarily a military navigation system, federal policy permits limited civilian access. The limitations generally apply to "real-time" autonomous positioning capabilities of the system.

GPS, which is fully operational, is being used by many DOTs, federal agencies, commercial and private surveyors, and the military. This powerful tool has already proven its ability to:

- Measure baselines several kilometers long with millimeter accuracies using only a few minutes of satellite tracking data;
- Navigate land vehicles, aircraft, and ships with centimeter level precision in real time;
- Locate the position of an aerial photograph at the instant of exposure with centimeter accuracy;
- Measure baselines several thousand kilometers long with decimeter accuracies by tracking the satellites for a few hours;
- Determine the three-dimensional coordinate differences of terrestrial survey points with centimeter accuracies using less than 30 seconds of satellite observation time at each point; and
- Supplant spirit and trigonometric leveling to determine elevation differences when used in conjuntion with a good geoid model.

## BENEFITS

### General

GPS surveying is increasingly becoming the primary tool for making precise measurements on the earth's surface. GPS techniques have been used in a wide variety of surveying applications. Among these applications are:

- Primary and secondary engineering control surveys,
- Mapping surveys,
- Land, boundary, and right-of-way surveys,
- Hydrographic surveys,
- Geophysical surveys,
- Photogrammetric control surveys,
- Crustal motion surveys,
- Construction stakeout surveys, and
- Geodetic network control surveys.

The benefits of using GPS for surveying are associated with labor costs, time savings, and increased accuracies. For the most part, cost savings are a result of labor and time savings. Capital equipment investments, cost recovery methods, and personnel costs are different among organizations. Accordingly, cost savings in this review are considered to be the result of both personnel costs and time savings.

### Labor Savings

Personnel cost savings is most often measured in terms of person-hours, or some other personnel/time relationship. In any case, it is a measure of personnel time to complete a task.

The largest direct benefit experienced in GPS surveying is labor savings. If the survey project is suited to using GPS, it is almost certain that labor requirements for accomplishing the task with GPS will be less than what conventional methods would require. Labor reduction ratios reported for GPS are commonly near 6:1 for horizontal control surveys (*1*). The range usually falls between 3:1 and 20:1, depending on the variables involved. If elevations are derived from the GPS measurements, the ratios are nearer to 10:1 and higher.

There are additional labor savings with GPS that can be attributed to a decrease in return field trips to check angles or distances. Experience has shown that GPS methods generally have reduced demands for "field checking" original data. Unfortunately, the savings are difficult to quantify in practice.

A staff's level of expertise required for GPS is comparable to that required for conventional survey methods. Although considerable care is needed in site selection, antenna setup, and receiver operation, the average surveying technician acquires the skill with little effort. Field crews should have little trouble with typical GPS field work tasks. They may need some assistance in preparation and analysis of GPS results. In fact, more skill is required in the efficient operation of a theodolite, electronic distance meter, or total station than in the use of modern GPS hardware. Problems of personal errors in observing and recording conventional observations are minimized with GPS techniques.

GPS position calculation algorithms and processing are, on the average, foreign to the average DOT surveyor. GPS fundamentals and required knowledge can be readily acquired through a formal training program. Training is available from receiver manufacturers, universities and technical schools, and from private organizations, such as the Institute of Navigation (ION).

### Time Savings

Reduced project completion time is another major advantage of GPS surveys. Project surveys scheduled to take weeks can often take just a few days or hours with GPS. When applied to the installation of primary control for the average DOT project, GPS methods can show total project survey time reductions of 4:1. On some types of geodetic network surveys, GPS can reduce time requirements by a factor of 10.

Some of the time savings occur as a result of GPS being an all-weather system. Because it requires no line-of-sight between survey points, GPS can operate during most forms of precipitation or other restrictions to visibility. Successful GPS campaigns have been conducted in heavy snow, rain, and extreme high and low temperatures. Lightening during a thunderstorm is the one weather condition that restricts the use of a GPS for surveying. Because GPS is generally more efficient, it is good practice to review survey project schedules developed for conventional survey techniques to prevent over-committing personnel and time when using GPS methods.

### Accuracy

As a general rule, horizontal GPS accuracy can exceed that of conventional surveys by a factor of 5 or better (6). Elevations obtained from GPS can equal conventional methods, but not exceed them. If GPS and conventional survey costs are equal, GPS will deliver a much higher accuracy/cost ratio than conventional methods.

There is a tendency to "overdo" GPS accuracy when it comes to many DOT surveys. For the most part, DOT project surveys (engineering and cadastral) rarely require precision ratios exceeding 1:20,000. Today, 1:20,000 is generally the minimum accepted precision with GPS. All densification control in a local project area should require at least 1:100,000 or ppm 10.

With one hour of satellite tracking, GPS can produce results with precision ratios exceeding 1:200,000. With some of the newer, rapid static GPS methods, the same precision can be produced with just a few minutes of data. With the recent completion of high-accuracy reference networks (HARN) throughout the country, DOT surveyors will be able to use regional base stations as continuously operating reference stations (CORS).

It is important that the surveyor thoroughly understand the superior performance of GPS and adjust survey methods to meet real requirements. At the same time, the surveyor should realize that GPS offers the opportunity to upgrade the precision for many surveys without any appreciable increase in cost. However, the balance between increased productivity, accuracy, and reliability must be consistent with GPS surveying just as with any other method.

Future implications of GPS for DOTs can be illustrated by the following examples of GPS applications:

- One surveyor with two $20,000 GPS receivers can set a first-order survey point in just a few minutes, rain or shine.
- A photogrammetric map can be compiled at a scale of 1 in. to 50 ft with little or no ground control survey or targets.
- The real-time position of a moving vehicle can be continuously monitored at a remote site with centimeter level accuracy.
- One person with one low-cost GPS receiver can determine the coordinates of a highway mile marker from a moving vehicle traveling at 60 mph with meter-level accuracy.
- When properly applied to surveying tasks, GPS can produce labor and time savings on the order of 3:1 to 20:1.
- High-accuracy reference networks (HARNs) that provide a statewide reference system with accuracies better than one (1) ppm can be established economically.

GPS offers enormous opportunities for cost-effective application in many DOT operations. It is important that Executive, Administrative, Planning, Design, Construction, and Operational DOT personnel become familiar with the general capabilities of GPS. It can, and will, have a significant impact on the way DOTs conduct business. GPS has proven many of its capabilities and has already influenced surveying and GIS operations of several agencies and DOTs. When properly applied, GPS can provide benefits that far exceed its cost.

The following chapters in this synthesis describe the use of the GPS system for surveying; provide a general explanation of how it works; outline its limitations; present related costs and benefits; and describe the status of on-going development efforts. References are provided to assist DOT personnel in obtaining further information on the operation and application of GPS. Appendix A lists sources of publications and training sessions related to GPS. Appendix B is a National Security Council fact sheet issued by the White House on U.S. policy for GPS. A glossary of GPS terminology and a list of acronyms are also provided.

CHAPTER TWO

# THE GLOBAL POSITIONING SYSTEM

## BACKGROUND

Officially known as the NAVSTAR (Navigation System Using Time And Ranging) Global Positioning System, GPS is a full-time, all-weather, high-precision, earth-orbiting satellite positioning, navigation, and time transfer system. The primary function of GPS is to provide accurate navigation and positioning services for air-, sea-, and ground-based units of the U.S. Department of Defense (DoD) and other authorized nations. Present federal policy also permits civilian use of the system with some restrictions. These restrictions are generally directed at the accuracy of the real-time capabilities of the system.

The GPS concept was developed by the DoD in 1973 and the first prototype (Block I) satellite vehicle (SV) was launched in 1978. Additional Block I satellites were placed in orbit between 1978 and 1985. These prototype satellite vehicles were used to test and evaluate the system.

The potential use of GPS for geodetic surveying was recognized early and a few specialized, geodetic-quality GPS receivers appeared on the commercial market. Even though the early GPS satellite constellation was optimized for the western part of the United States, sufficient coverage was available to provide brief periods (3 to 6 hours) of useable availability in most areas of the country.

As early as 1982, at least one commercial surveying firm was offering GPS services. Almost simultaneously, a limited number of receivers were purchased in 1983 by the National Geodetic Survey (NGS) and the Texas State Department of Highways and Public Transportation (SDHPT) to support production geodetic survey operations.

The first of the production GPS satellites (Block II) were placed in orbit in 1989 and the buildup continued through 1993 when the constellation achieved initial operational capability. The system was declared fully operational in 1994. Three additional satellites were launched in 1996.

## GENERAL DESCRIPTION

### System Components

The GPS system comprises three major components: the control segment, the space segment, and the user segment. Each of these segments is critical to the overall operation of the system. To a large degree, they are interdependent. Figure 1 illustrates the three segments and their relation to each other.

The space segment consists of the satellite constellation and includes the development, production, and launching of the satellite vehicles. The constellation has 24 active satellites.

The control segment consists of five monitor tracking stations, and three ground antenna stations for uploading data to the satellites. A new station will be added at the launch site in Florida. Additional stations are available during launches and for back-up purposes. The Master Control Station is located at Falcon Air Force Base near Colorado Springs, Colorado. The locations of the tracking and upload stations are shown in Figure 2.

Operational control of the entire GPS system is the responsibility of the Air Force Space Command at Falcon Air Force Base. Information from the tracking stations is used to observe the condition of the satellites, determine their orbits, and monitor the behavior of the satellite clocks. The tracking information is also used to compute projected orbits (ephemeris), clock corrections, and other data for uploading into the satellite's memory. The satellite later broadcasts this information as part of its periodic navigation message transmission.

The ephemeris data broadcast by each satellite are used by GPS systems to compute the coordinates of the satellites within their respective orbits at the time measurements are made. The satellite positions are subsequently used by the GPS systems to compute the spatial coordinates of the receiver's antenna.

The user segment consists of GPS receiver hardware, software, and procedures for tracking the satellite signals for navigation, surveying, and other positioning needs in both military and civilian arenas.

## THE SATELLITES

Eleven prototype satellites (Block I) were constructed and launched between 1978 and 1985. Although their design life was 5 years, a few were still operational in 1997. The production satellite vehicles (Block II) are somewhat larger than the prototypes and weigh approximately 3,500 pounds. Figure 3 shows a typical Block II GPS satellite. Twenty-eight Block II vehicles were ordered and the first of these was launched (on McDonnell Douglas MLV Delta Rockets) in February of 1989.

Each satellite can be identified by one of several identification codes or numbers. Most common of these are the NAVSTAR and PRN (Pseudorandom Noise) code numbers. NAVSTAR 8, for example, is the same satellite as PRN 11. The PRN identification number system is used by geodetic survey systems and is also commonly used in other applications.

Aboard each satellite are several types of clocks. Two cesium, two rubidium, and at least one crystal oscillator are available. The cesium and rubidium clocks are "atomic clocks" and have extremely low drift rates to provide long-term frequency stability.

The satellites operate on batteries that are charged by solar panels. Among other things, these batteries power thruster engines used for orbit maneuvering.

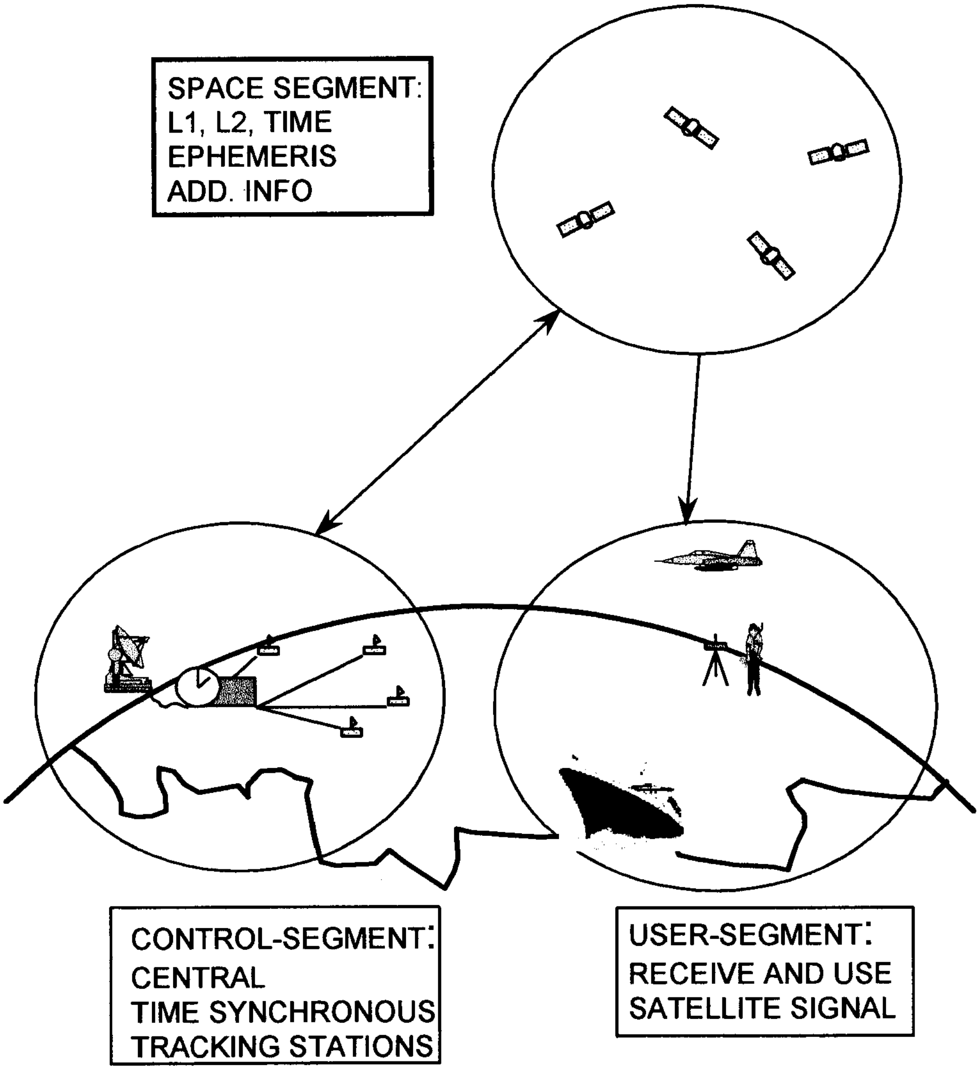


FIGURE 1 Three segments of GPS *(2)*.

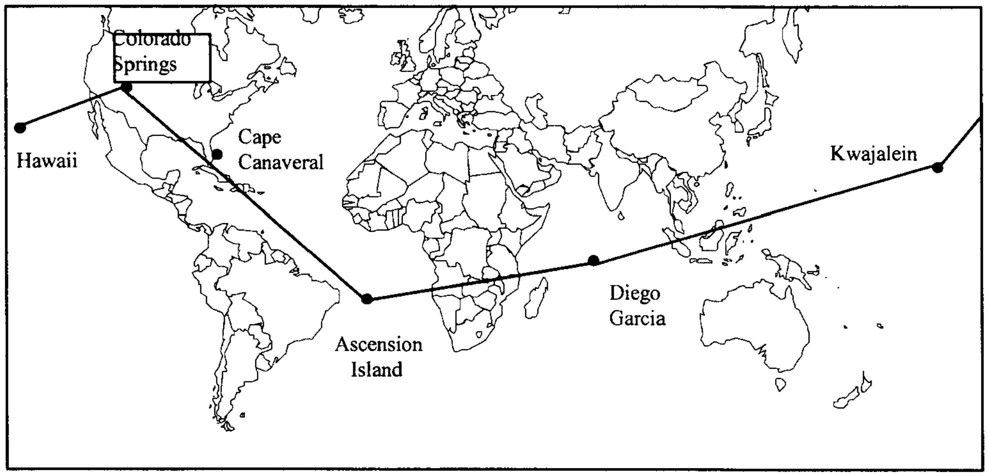


FIGURE 2 GPS monitor and upload stations *(3)*.

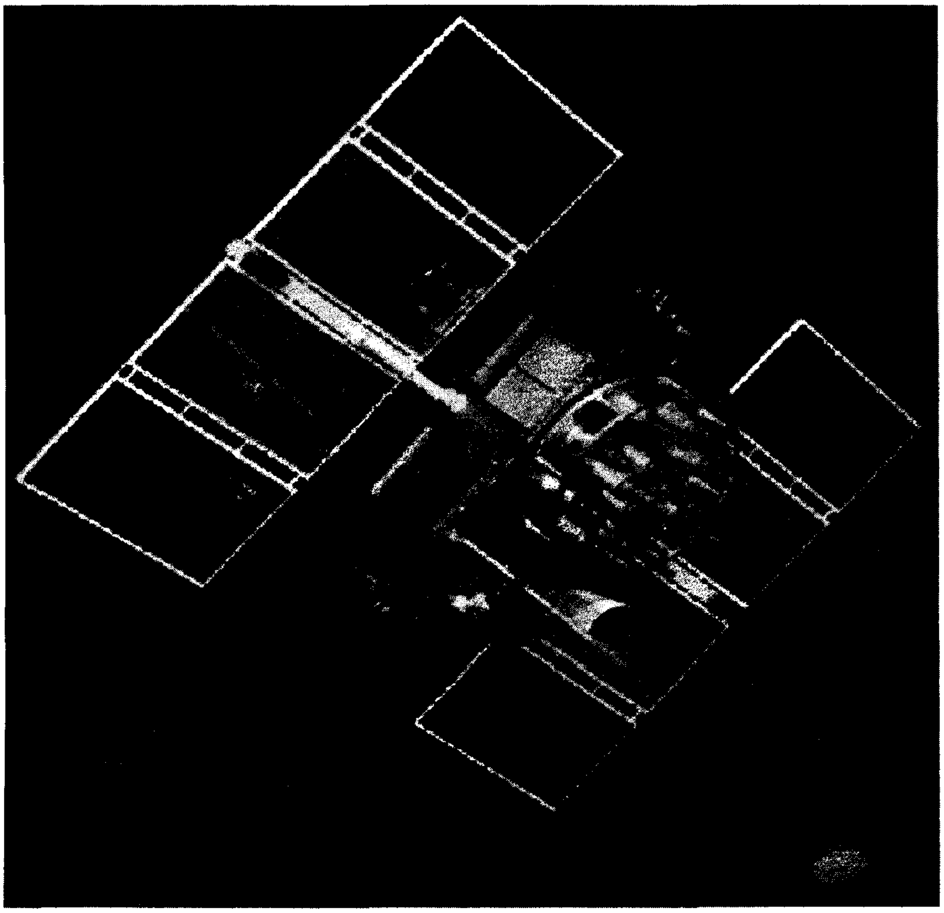


FIGURE 3 Block II GPS satellite.

## THE ORBITS

Figure 4 is a schematic diagram of the GPS satellite constellation. The satellites are in six orbital planes, equally spaced around the equator. Each orbital plane is inclined to the equatorial plane by 55 degrees. The orbits are nearly circular with an orbital height of approximately 20 200 kilometers above the earth's surface. The satellite rotation time (period) around the earth is $11^h\ 58^m$ solar-time, making two revolutions in 24 hours.

Orbital planes are identified by a letter in the range of A through F. Each orbit has four satellites that are assigned specific "slot" numbers within the orbit. The constellation is designed so that at least four satellites are visible all of the time, with good geometry (necessary for good position solutions), from just about everywhere in the world.

## THE SATELLITE SIGNALS

The GPS signal broadcast from each satellite is composed of two carrier frequencies, biphase modulated by pseudorandom binary code sequences. The complex modulation scheme, in addition to available carrier frequencies, provides several methods for determining the range (distance) between the satellite and a GPS receiver antenna at any given instant in time. The satellite-to-receiver antenna range is the fundamental measurement made for both geodetic surveying and navigation applications. This aspect of GPS positioning will be explored more thoroughly in chapter 3.

Table 1 gives a breakdown of GPS satellite frequencies and modulation details. The satellites continuously transmit synchronized signals on two carrier frequencies, L1 and L2, at 1575.42 MHZ and 1227.60 MHZ respectively. The fundamental frequency of 10.23 MHZ is multiplied by 154 to yield L1 and by 120 to yield L2. Three types of PRN binary codes are used to modulate the carriers:

1. The C/A-code (Coarse/Acquisition, low accuracy);
2. The P-code (Precise, high accuracy); and
3. The Y-code (Classified, high accuracy).

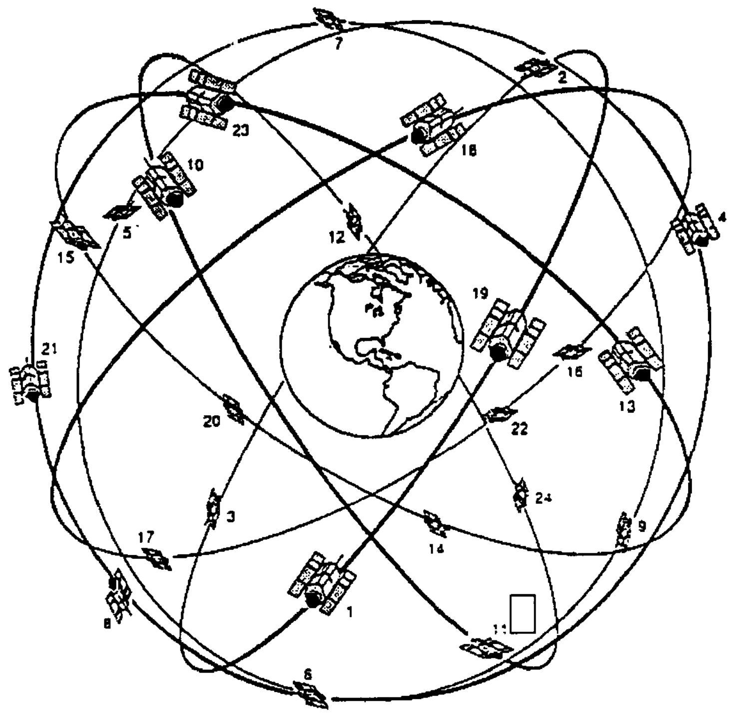


FIGURE 4 GPS satellite constellation.

TABLE 1

GPS TRANSMITTING AND MODULATION FREQUENCIES *(3)*

- Fundamental Frequency = 10.23 MHz
  L1 = 154 F = 1575.42 MHz
  L2 = 120 F = 1227.60 MHz
- Pseudorandom codes are added to carrier as binary biphase modulation
  P code: 10.23 MHz = F
  CA code 1.023 MHz = F/10
- Navigation message is added to carrier as binary biphase modulation at 50 bits per second
- Binary biphase modulation
  Phase change of 0 deg: binary -1
  Phase change of 189 deg: binary 1

TABLE 2

CARRIER AND CODE TRACKING ACCURACIES

| Code Type | Frequency (MHz) | Wavelength (Meters) | 1% of Wavelength (Meters) |
|---|---|---|---|
| C/A | 1.023 | 300 | 3 |
| P | 10.23 | 30 | 0.3 |
| Carrier (L2) | 1227.6 | 0.24 | 0.0024 |
| Carrier (L1) | 1575.42 | 0.19 | 0.0019 |

The PRN codes are called pseudorandom because they have the general characteristic of random noise even though they are generated by a mathematical algorithm. In addition to the PRN codes, a Navigation Message is added to the carrier as binary biphase modulation at 50 bits-per-second.

PRN binary codes are a series of positive ones (+1) and negative ones (-1) that modulate the carrier. The wavelengths of these modulating frequencies are important because they help determine the accuracy of range measurements.

An acceptable GPS receiver can measure the frequency to about one percent of the code and carrier frequency. Accuracy's available when tracking PRN codes and carrier frequencies are shown in Table 2.

Table 2 reflects that a well-designed GPS receiver can track the C/A-code to within 3 meters. On the other hand, it can track the L1 carrier-phase to within 2 millimeters, a significant precision level. It is the ability of a good GPS receiver to precisely track the carrier frequency and measure its phase that makes GPS so useful for accomplishing high-accuracy geodetic surveys.

The sequence of positive ones and negative ones that form the C/A-code repeats itself every millisecond and modulates the L1 carrier frequency at 1.023 MHZ. At the same time, L1 is also modulated by the P-code at a frequency of 10.23 MHZ with a different sequence of positive ones and negative ones that repeats itself every 267 days. Each satellite carries a one-week-long portion of the P-code.

Currently, L2 is only modulated by the P-code at 10.23 MHz. The equations that generate the C/A- and P-codes are known. The Y-code, which (for classified uses) replaces the P-code on all Block II satellites when Anti-Spoof (AS) is enabled, is classified and not published.

L1 and L2 are also modulated by a 50-Hz Navigation message. This contains information concerning the health of the satellites, orbit parameters for the broadcasting satellite (ephemeris), satellite clock correction information, and system time. The message also contains a signal that alerts specially equipped receivers that the Y-code is active.

## ERROR SOURCES

GPS is a complex technology. Its application in determining locations and for surveys must be done with considerable care and a thorough understanding of the potential sources of error. An experienced user of GPS knows that each of the error sources should be given attention because the accuracy and precision of survey data are only as good as the techniques used to collect them. In the following section, a number of error sources are identified and briefly discussed.

### Selective Availability

Through a process called Selective Availability (SA) the DoD can deliberately degrade the accuracy of GPS using a variety of techniques. The purpose of SA is to reduce the accuracy available to unauthorized users. SA is a process of deliberately introducing errors into the satellite signals to affect a desired amount of reduced accuracy. The methods are dithering of the satellite clock, and offsetting the orbit data (degraded broadcast ephemeris parameters). Encrypted information for correcting degraded clock and/or orbit information is made available as part of the satellite navigation message to authorized users.

### Range Errors

The fundamental measurement in GPS positioning is the range (or distance) between the receiver antenna and the satellite(s) at the time of measurement (epoch). Since this measurement is not error free, it is normally referred to as 'pseudorange.' Accounting for and correcting this error improves positioning accuracy. A general term used to express the accuracy of the range measurement is the "User Equivalent Range Error" (UERE).

#### *Clock Errors*

In general there are two sources of clock errors: the satellite(s) clock error (or bias) with respect to a standard "GPS time" and the receiver clock bias with respect to the satellite(s) clock. The satellite clock bias is included in the satellite navigation message and is available immediately. The receiver-to-satellite clock bias can only be determined by tracking four satellites and solving for the time bias. For example, a one micro-second clock bias can induce position errors at the 300-meter level. For the most part, satellite clock biases cancel out when using relative positioning techniques because they appear on both sides of the solution equation.

#### *Orbital Errors*

The position of the receiving antenna is dependent upon the length of the range vector and the coordinates of the satellite at the instant of measurement. Accordingly, orbital errors (ephemeris errors) affect the computed position of the antenna. Orbital errors can have several components: radial error (or distance from the mass center of the earth); along track error (or displacement along the orbital track); and out of plane error (or lateral displacement from the orbital plane). Under normal operational conditions, ephemeris errors affect the range measurement by 5 meters or so. In relative positioning, orbital errors tend to cancel out.

#### *Ionospheric Errors*

The ionosphere is generally defined as that portion of the atmosphere between 50 km (31 mi) and 1000 km (621.4 mi) above the earth. Radiation from the sun ionizes the gasses within the ionosphere to varying intensities depending upon the state of sun spot activity. Signals from GPS satellites are "bent" or delayed, while traveling through ionized gasses. Ionospheric delay is inversely proportional to the frequency, so the two GPS frequencies are affected differently. The ionospheric error increases as the elevation angle of the satellite above the horizon decreases. Tracking satellites at elevation angles less than 15 degrees is not recommended for geodetic survey purposes.

Typical errors due to ionospheric delay are between 4 meters (13 ft) and 10 meters (33 ft) but can be as large as 30 meters (98 ft). The ionospheric effect is greater during daylight hours. Single-frequency receivers must rely on using ionospheric modeling parameters contained in the satellite navigation message to correct for signal delay. Dual-frequency receivers can measure the ionospheric delay by comparing L1 and L2 frequencies directly. The ionospheric delay tends to cancel out when using relative positioning techniques for short baselines, because the delay is considered to be the same at both locations. However, ionospheric conditions can vary considerably as the baseline length increases. The use of dual-frequency receivers for baseline measurements in excess of 30 km (19 mi) is recommended.

#### *Tropospheric Errors*

Like ionospheric error sources, tropospheric refraction affects on GPS signals can be significant, especially at low satellite tracking angles. There are two tropospheric components that contribute to the error: the wet component and the dry component. The wet component is associated with the amount of water vapor present along the signal path and is the most difficult to determine. The dry component can be derived from ambient atmospheric pressure readings at the surface.

The magnitude of the range errors due to the troposphere before correction can be as high as 30 meters. Fortunately, there are tropospheric models available that can reduce this error to a range of 1-3 meters (3-10 ft). Tropospheric errors tend to cancel under relative positioning measurements when baselines are short. In geodetic survey applications involving baselines more than 30 km (19 mi) long, local temperature, humidity, and pressure readings to improve standard tropospheric models will help reduce the magnitude of the error. This practice should be required on long baseline measurements and when weather conditions at each end of the baseline are significantly different.

### *Multipath Errors*

Multipath errors are caused by reflections of the GPS signal from nearby objects. Since a reflected signal path is longer than the direct signal path, a false range measurement will be obtained. A television picture with one or more ghost images is an illustration of multipath. The magnitude of the range error-caused multipath is dependent upon which PRN code or carrier frequency is used. The error can range from a few centimeters to several meters. Range errors of 1-6 meters (3-20 ft) are not uncommon when tracking the C/A-code.

Antennas used for geodetic survey purposes are generally designed to minimize multipath affects, especially at low reflective angles. Unlike most other error sources, multipath errors do not tend to cancel since the errors are sensitive to location of the antenna with respect to local reflective surfaces.

## Geometry Errors

The relative positions of the satellites with respect to the observer's position is vital to obtaining accurate positions with GPS. The problem is analogous to "strength of figure" in classical triangulation or trilateration surveys. The term used in GPS is "Dilution Of Precision" (DOP). DOP is a number (without dimensions) that expresses the geometrical strength of the positions of the satellites with respect to the observer's position. DOP numbers range from one to infinity. An estimate of position error can be obtained by multiplying the DOP number by the UERE. Useable DOP numbers range between one and 10 with five or less being preferred. Positioning accuracys begin to degrade when DOP numbers exceed five.

### *Miscellaneous Errors*

There are several other error sources that are not necessarily significant in navigation applications but are important to geodetic carrier-phase tracking surveys.

### *Obstructions*

The presence of obstructions that can block the satellite signal is a major concern. The proximity of large buildings that can block the signals from several satellites at the same time can completely negate a survey mission. This is especially true when only tracking four satellites (the minimum). Selection of antenna sites for geodetic surveys must consider the magnitude of the signal blockage potential.

### *Antenna Phase Center*

Significant variation in the location of the antenna phase center can cause errors in geodetic survey results, especially in the vertical coordinate component. The antenna phase center is the focus of received signals and the reference point for all signal measurements. It is especially important for geodetic survey applications that the location of the antenna's phase center be accurately known and accounted for in subsequent position calculations. The phase center of some antennas changes considerably as the satellite elevation changes. For this reason, an antenna designed for navigation purposes may not suffice for geodetic survey use.

CHAPTER THREE

# HOW GPS WORKS

## BASIC MEASUREMENT

The fundamental measurement in GPS positioning is the distance (range) between the satellite(s) and the phase center of the antenna of a GPS receiver at a particular instant in time (epoch). Figure 5 illustrates this basic measurement in schematic form. For purposes of illustration in the following paragraphs, it is expedient to temporarily ignore several error sources that are present in the process of determining the satellite-to-antenna range. These errors will be reviewed in later chapters.

## A QUICK LOOK AT GPS RECEIVERS

Figure 6 is a functional diagram of a basic GPS receiver. In a general sense, GPS receivers are classified by their ability to track the various codes and carrier frequencies broadcast by the satellites. C/A-code, single-frequency receivers can track the C/A-code and the L1 carrier frequency. Dual-frequency C/A-and P-code receivers can track both codes and the L1 and L2 carrier frequencies. In the following illustration however, it is assumed that a single frequency (L1) C/A-code receiver is being used.

### Code Tracking

As shown in Figure 6, the receiver has separate circuitry that tracks the carrier frequency(s) and PRN codes present on the satellite signal. To track the C/A-code, the receiver generates a replica of the C/A-code sequence being sent by the satellite, using the same algorithm that is employed by the satellite. The function of the receiver code-tracking loop is to shift the receiver-generated code sequence in time to match the identical code sequence received from the satellite, as shown in Figure 7.

Assuming the clocks in the satellite and receiver are perfectly synchronized, the time shift (Dt) required to align the two code sequences is the time required for the signal to travel from the satellite to the receiver. Multiplying this time shift by the speed of light gives the distance (or range) between the satellite and the receiver antenna. As it is not likely that the clock in the receiver is perfectly synchronized with the clock in the satellite, the range measurement is biased by the difference in the clocks. These biased distance measurements are called pseudoranges.

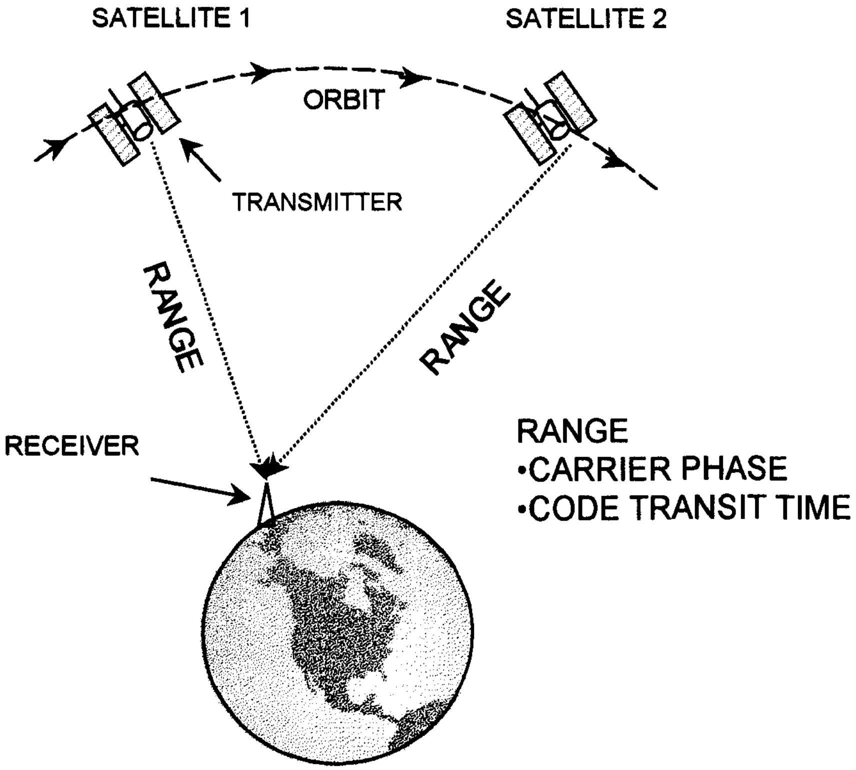


FIGURE 5 Basic measurement—range.

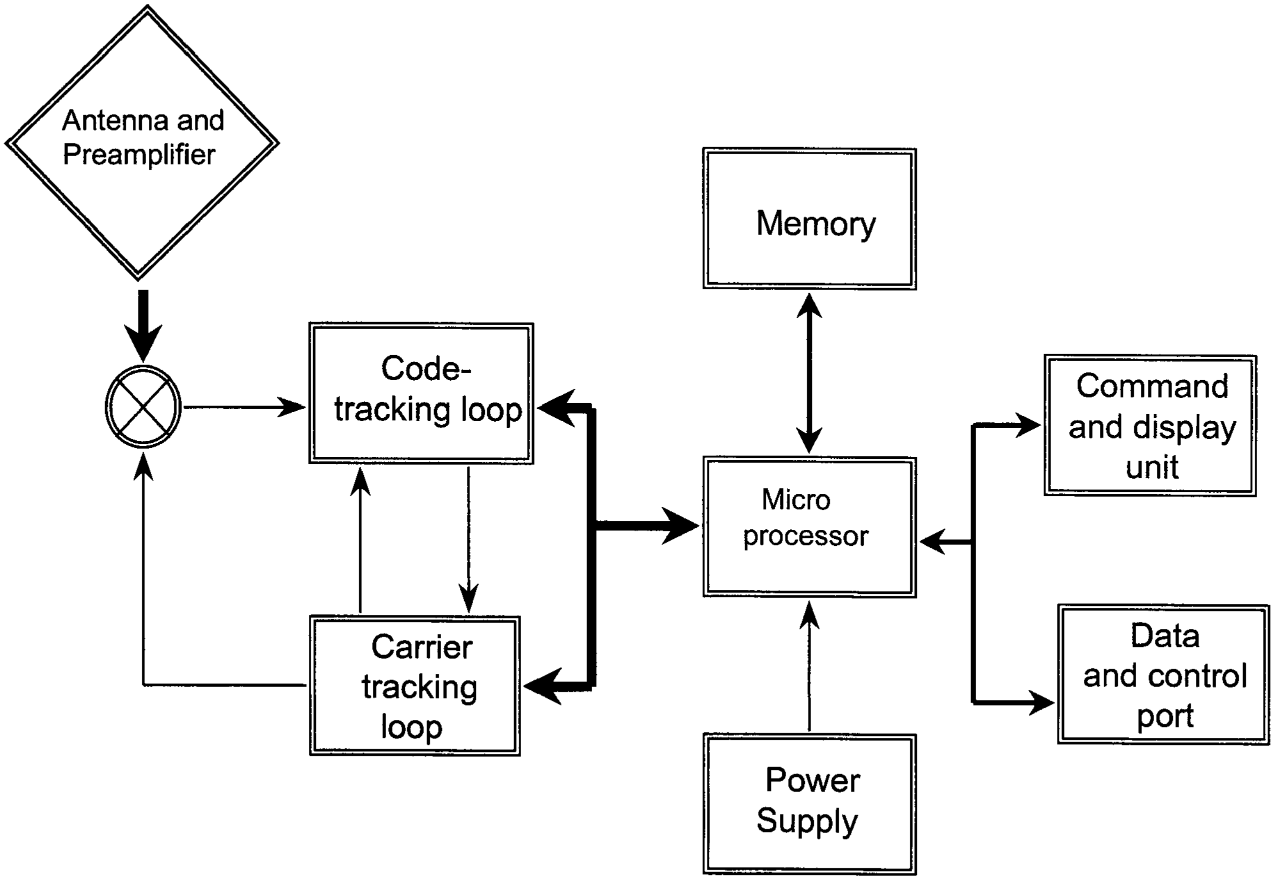
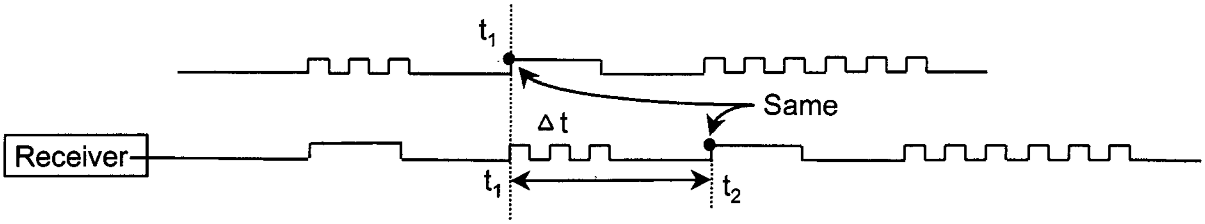


FIGURE 6 Basic receiver functions *(4)*.

- To determine range to SV
- Code receivers generate replica of SV code and compares



$t_1$ = time signal left SV
$t_2$ = time signal received
c = speed of light
Distance to SV = C × Δ t
Distance = "Range" if clocks the same
Distance = "Pseudorange" if clock bias is present

FIGURE 7 Using code to determine range.

### Carrier Tracking

Along with PRN-code tracking, geodetic quality GPS receivers can also track the carrier frequency(s). This capability leads to another, more precise, range measurement technique called "carrier beat phase" tracking. Because a geodetic GPS receiver can track the carrier to within one percent of the wavelength (2 mm at the L1 frequency), the carrier-beat technique is considerably more precise than pseudorange methods.

Because of the relative motion of the satellite with respect to the receiving antenna, the frequency of the received carrier has been shifted due to doppler effects. The "carrier beat phase" is the phase of a new frequency obtained from beating the received carrier frequency (doppler shifted) against a fixed frequency internally generated by the receiver itself. This technique provides a method of measuring the fractional wavelength portion of the wavelengths (cycles) between the satellite and the antenna. What is not known, however, is the total number of wavelengths between the satellite and the antenna (Figure 8). Geodetic receivers can maintain a running account of the number of whole (integer) cycles received once the measurement process begins. The problem of determining the number of integer cycles between the satellite and the antenna before the receiver count began is more commonly referred to as the "ambiguity" problem.

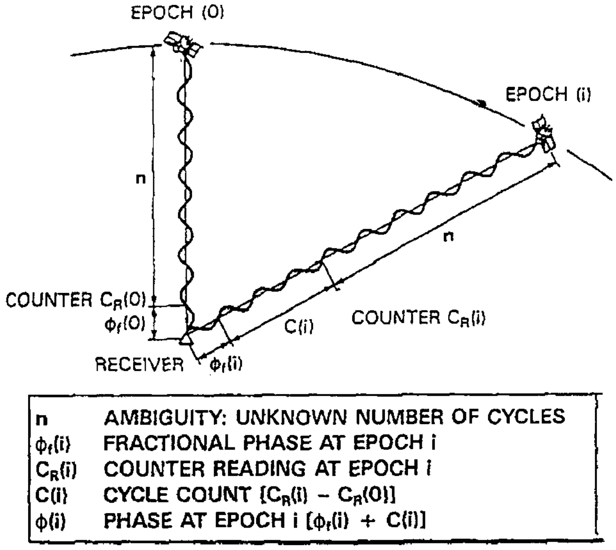


FIGURE 8 Definition of carrier phase "ambiguity" *(8)*.

A problem with carrier tracking is the possibility that the receiver will lose its cycle count because of signal blockage. This is referred to as the "cycle slip" problem. Post processing of the tracking data (as in the case of most surveying applications) permits some opportunity for detecting and fixing cycle slips provided they are not severe.

### THE NAVIGATION SOLUTION

The reason for measuring the range between the satellite(s) and a GPS receiver antenna is to determine the location of the antenna. The process of locating a position with a single GPS receiver is similar to the classical "trilateration" surveying technique where distance measurements are made between the unknown position and three or more other positions whose coordinates are frequent.

Figure 9 is a two-dimensional illustration of the general solution process. The diagram shows range measurements made to a satellite at two different times. Coordinates of the satellite position at times T1 and T2 are obtained from the satellite ephemeris information contained in the navigation message broadcast by the satellite. The position of the antenna can be obtained by intersecting circles drawn about two satellite positions with their respective range measurements as radii.

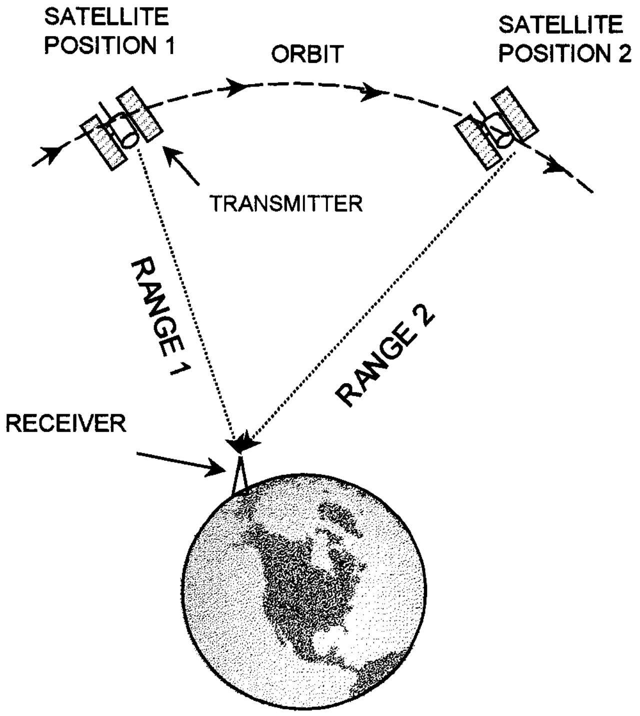


FIGURE 9 Using range to determine position.

In reality, the problem is three-dimensional and requires simultaneous range values from three satellites to obtain the position of the antenna. In this case, the antenna is located at the intersection of three spheres.

A more precise position can be obtained by tracking four satellites. The addition of the fourth satellite eliminates the error caused by the difference in time (and drift rates) between the satellite clocks and the receiver clock.

In practice, GPS receivers measure the range to four (or more) satellites every few seconds (sometimes much faster) and compute a solution about as frequently. Sometimes the solutions are processed through a filtering algorithm to smooth results. It should be noted that the positioning capabilities of the receiver are applicable whether the receiver is at rest (static) or in motion (kinematic). Many receivers output a complete real-time navigation solution including position, ground track (the course over ground), velocity, and course and distance to the next waypoint (if waypoint coordinates are entered).

## POSITIONING METHODS

The navigation positioning scenario described in the preceding paragraphs is not the only positioning method available to the GPS user. The navigation solution makes use of a single receiver and obtains an autonomous solution. This process is sometimes referred to as "absolute positioning" or "point positioning" (if the receiver is stationary).

Another method of GPS positioning, called "relative positioning," uses two or more receivers tracking the same satellites at the same time. This method, shown in Figure 10, is the preferred technique for performing high-accuracy geodetic surveys.

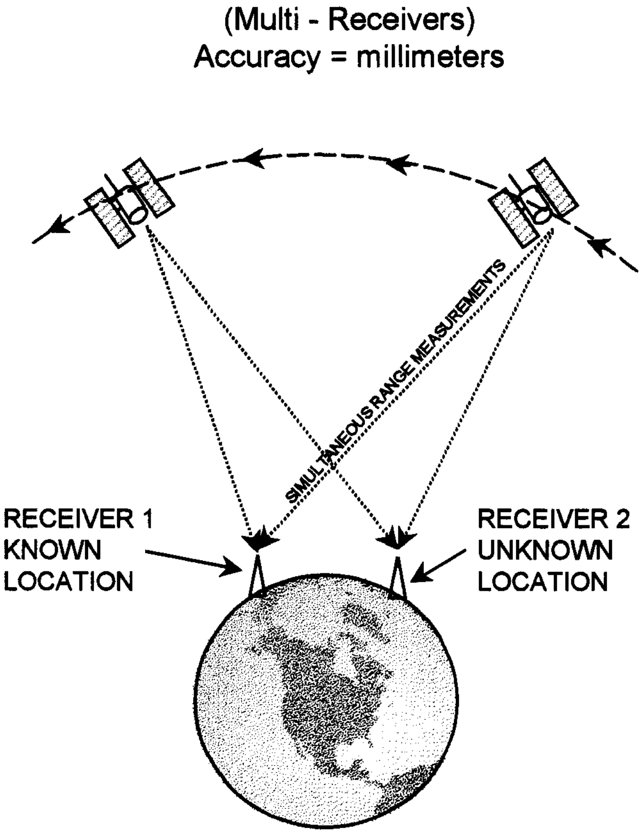


FIGURE 10 Differential or relative positioning.

Relative positioning requires that a reference receiver be located at a point whose coordinates are known. The other receiver(s) are located on unknown points. In conducting geodetic surveys, for example, the reference receiver is often placed over a National Geodetic Survey Reference Marker whose coordinates are well known. After a period of satellite tracking, the observation data recorded by each of the receivers are collected and processed together to solve for the positions of the other receivers relative to the reference receiver.

Relative positioning is not limited to static measurements. The technique is also applicable to receivers that are in motion, as shown in Figure 11. As a general rule, the reference receiver remains stationary during these kinematic applications.

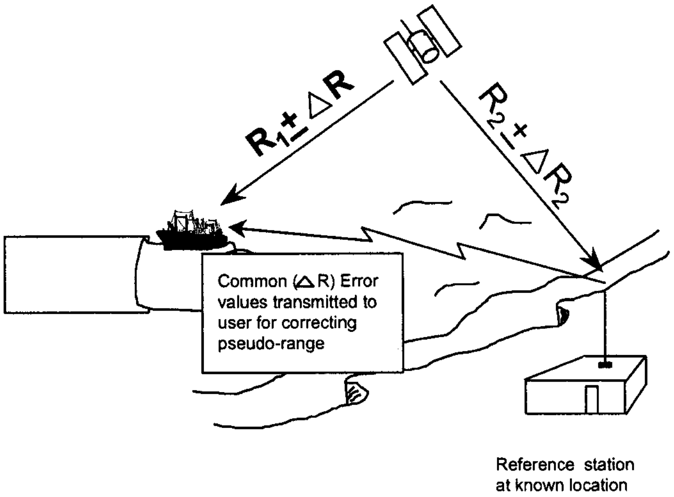


FIGURE 11 Differential positioning for mobile vehicles *(3)*.

The benefit of relative positioning is increased accuracy. For example, under certain conditions a single C/A-code receiver operating by itself can determine its position to within 100 meters. Operating in conjunction with another receiver using differential carrier-phase tracking methods can produce a position with centimeter accuracies. In real-time navigation applications, differential methods can produce positions at the submeter or centimeter level by broadcasting differential correction data from the reference receiver to mobile a receiver(s).

CHAPTER FOUR

# BASIC GEODESY PRINCIPLES

## GEODESY FUNDAMENTALS

### Background

Geodesy is the branch of applied mathematics concerned with calculating the size and shape of the earth and the exact position of points on its surface. It also pertains to the description of variations of the earth's gravity field.

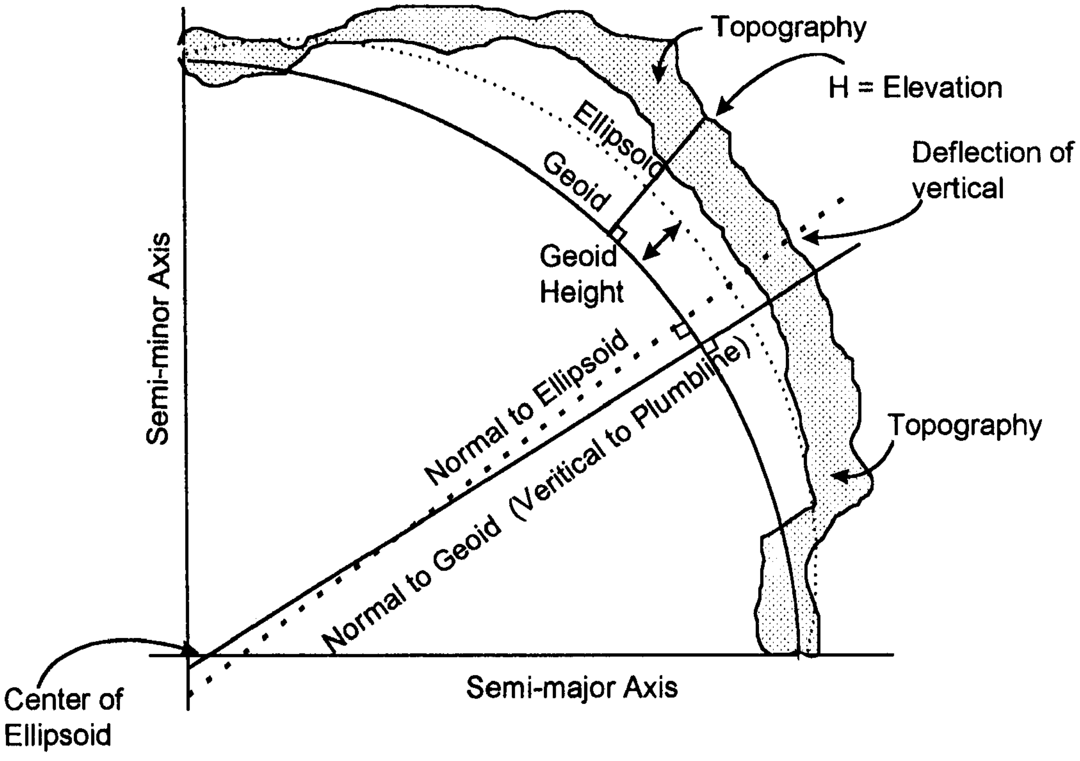
Geodesy is a complex science and this synthesis does not attempt to investigate the concepts in any detail. However, it is important that surveyors using GPS become aware of certain geodetic principles to better understand the results obtained with this measuring tool. An understanding of the relationship between the GPS system and the surfaces on which measurements are made is useful in applying GPS methodology.

There are three surfaces to consider when making measurements on the earth, as shown in Figure 12:

1. The topography—the physical surface of the earth;
2. The geoid—the equipotential (gravity) surface that best approximates mean sea level; and
3. The ellipsoid—a mathematical reference surface that approximates the shape and size of the earth.

While these surfaces can be individually defined, they are used in an interactive sense when applied to geodetic surveying, especially in GPS surveying and navigation.

Classical surveying instruments (theodolites, levels, etc.) use gravity, as indicated by a level bubble, for defining a local level surface to which horizontal and vertical measurements



- Geoid and Ellipsoid not the same
- Geodetic coordinates (Latitude and Longitude are referenced to the ellipsoid)
- Elevations are referenced to the geoid
- Deflection of vertical is an indication of the difference in slopes between geoid and ellipsoid

FIGURE 12 Relation of three measurement surfaces.

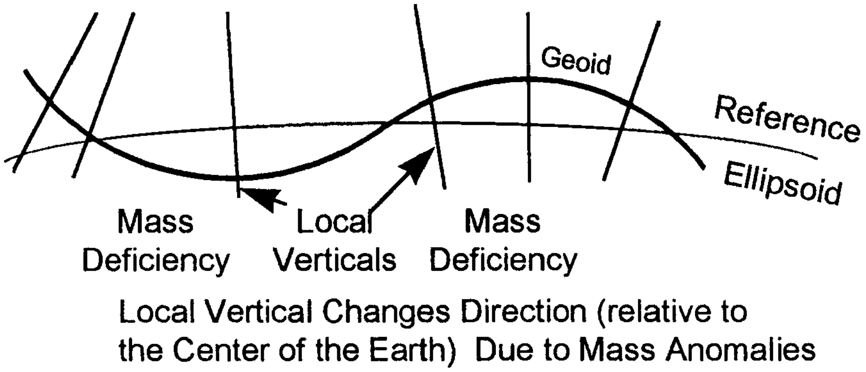


FIGURE 13 Variations in geoid with respect to the ellipsoid *(5)*.

are referenced. The result is that classical surveying measurements are referenced to the geoid, a surface based on gravity.

GPS measurements, on the other hand, are referenced to an ellipsoid, a mathematical surface centered at the mass center of the earth. This distinction will become clearer in the discussions of the geoid and ellipsoid in the following paragraphs. It is well to note here, however, that for surveying purposes, these reference surfaces can be related to each other. The differences in these reference surfaces are also considered in the solution of GPS navigation problems, but the severity of their effect is less than in geodetic surveying.

### The Topography

Topography is the actual surface of the earth on which both navigation and geodetic surveying GPS applications are accomplished. The earth's topography is by no means uniform and considerable variation in shape, height, and density can occur over very short distances. Unfortunately, it is on this ever-changing environment that most geodetic measurements and navigation occur.

The topography and the geoid are closely related, and one can influence the other. In addition, the topography is not static, but is constantly changing. Because of its irregularity and tendency to move about, the topographic surface does not readily lend itself to exact mathematical computation. The general shape of the earth's surface approximates that of an oblate ellipsoid.

### The Geoid

The geoid is, perhaps, one of the more difficult concepts for the average surveyor (and navigator) to visualize. The geoid is defined as the equipotential surface which more nearly conforms best to mean sea level. Accordingly, the geoid can be loosely described as coincident with mean sea level over the entire surface of the earth. If one envisions land masses covered by a network of canals through which waters of the oceans were freely allowed to flow under the influence of gravity, water surface in the oceans and canals would form the geoid (neglecting tides and other currents) (*4*).

If the earth were of uniform density and its topography did not exist, the geoid would have the shape of a smooth oblate ellipsoid (*4*). However, since the earth's surface (topography) is not of uniform density, variations and distortions occur in the gravity field causing the shape of the geoid to distort. These variations are called "geoidal undulations." When compared to a mathematical ellipsoid that approximates the shape and size of the earth, the geoidal variations are referred to as "geoidal separations," or "geoidal heights." Figure 13 depicts variations in the geoid with respect to a reference ellipsoid. The geoid can vary above and below a selected reference ellipsoid due to undulations, and the mathematical shape and size of the chosen ellipsoid. For example, in nearly all of the United States, the geoid is below the elipsoid.

Knowledge of geoid characteristics is helpful in conducting GPS surveys, and necessary when determining elevations using GPS methods. Information describing characteristics of the geoid is available in the form of geoid "models." Geoid models are derived from analysis of gravity observation information and from precisely measuring ellipsoid heights (by GPS) and geoid heights (by precise leveling) at the same geodetic control monument.

### The Ellipsoid

The topography and geoid are not suitable surfaces for precise mathematical computations. Their irregularity and constant change make them too difficult to define and use for this purpose. Since the shape of the earth approximates that of an oblate ellipsoid (also erroneously called a spheroid), it is convenient to use the ellipsoid as a computational base.

An ellipsoid is formed by rotating an ellipse about its minor axis. Figure 14 shows the fundamental elements that define an ellipse. In geodesy, the ellipse is generally defined by stating the length of its semi-major axis (a), and a flattening ratio (f), which is derived from the relationship between the semi-major and semi-minor axes (b).

An ellipsoid that approximates the shape and scale of the geoid is called a "reference ellipsoid" and is used as the primary reference surface for computing position on the earth. The expression of position on the ellipsoid is given in angular measurements called latitude and longitude. When combined

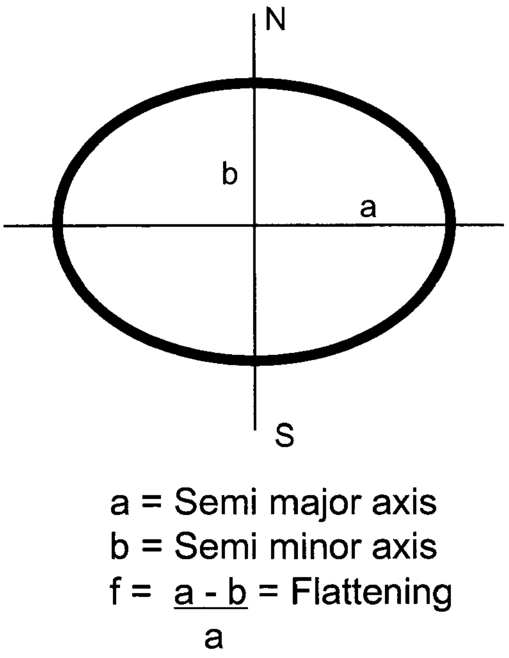


FIGURE 14 Defining parameters of an ellipse.

with gravity and other geodetic constants, the reference ellipsoid becomes a "Geodetic Reference System (GRS)."

Over the years, numerous ellipsoids have been defined and used for navigation and surveying. Most are special purpose ellipsoids designed to best fit the geoid in a local area, but have limited value elsewhere in the world. Several reference ellipsoids for global use have been defined by international agreement. Table 3 is summary of a few of the more popular reference ellipsoids.

With the introduction of satellite positioning techniques, it was important to define ellipsoids that not only provided the best geoid fit on a worldwide basis, but also to assure that the center of the ellipsoid coincided with the mass center of the earth (or as closely as possible). This is important because the satellites orbit about the mass center of the earth and a geocentric (center of mass) ellipsoid correlates best with the GPS satellite orbit.

The reference ellipsoid used with GPS positioning is the "Geodetic Reference System 1980." More commonly called "GRS 80," this ellipsoid was defined by the International Union of Geodesy and Geophysics in 1979.

The actual ellipsoid, World Geodetic System 1984 (WGS 84), used by the GPS system is insignificantly different from the GRS 80 ellipsoid. The difference is between the flattening of the two ellipsoids and does not materially affect practical results (*7*).

### Relationship of Surfaces

The topography, geoid, and ellipsoid are three distinct surfaces that affect our ability to determine positions and make measurements on the earth. Each is individually defined and must be accounted for, with varying degrees of precision, for both navigation and surveying applications of GPS. Figure 15 shows the general relationship of these surfaces. Notice that for traditional surveying instruments (level, theodolite, etc.), the level line of sight is set perpendicular to the direction of gravity at that point through the use of the level bubble. The level line of sight is, therefore, parallel to the slope of the geoid at that location. Accordingly, traditional surveying observations are made relative to the geoid. GPS measurements, however, are referenced to the ellipsoid through a three-axis Cartesian coordinate system. Essentially, GPS measurements do not involve the geoid.

Figure 15 also shows that a line perpendicular to the ellipsoid through the center of the survey instrument does not coincide with the gravity based "plumb line." The angular difference between these two lines is known as the "deflection, or deviation, of the vertical." It is also interesting to note that the horizontal position of the survey instrument (latitude and longitude) is referenced to the ellipsoid while the elevation of the instrument is measured from the geoid (sea level). The effect of the vertical relationship of these surfaces with regard to determining elevations with GPS will be discussed further on in the chapter.

## COORDINATE SYSTEMS

### Global Cartesian Coordinate Systems

The topography and geoid do not lend themselves as foundations for precise positioning and measurement purposes on a global scale. The ellipsoid is the only surface capable of supporting rigorous mathematical computations required by high-precision horizontal control geodetic surveys.

TABLE 3
REFERENCE ELLIPSOIDS USED FOR VARIOUS DATUMS *(6)*

| Coordinate System (Datum) | Reference Ellipsoid Used | Size (a) (Meters) | Shape (1/f) |
|---|---|---|---|
| NAD 27* | Clarke 1866 | 6378206.4 | 1/294.9786982 |
| WGS 72 | WGS 72 | 6378137 | 1/298.26 |
| NAD 83 | GRS 80 | 6378137 | 1/298.257222101 |
| WGS 84 | WGS 84 | 6378137 | 1/298.257223563 |

Note: NAD) North American Datum, WGS) World Geodetic System, GRS) Geodetic Reference System.
*NAD 27 is not for global use.

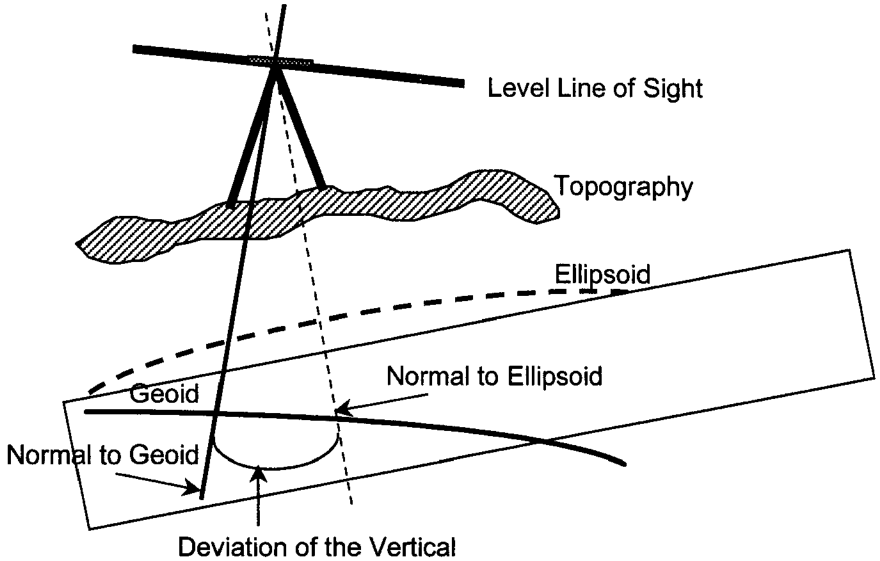
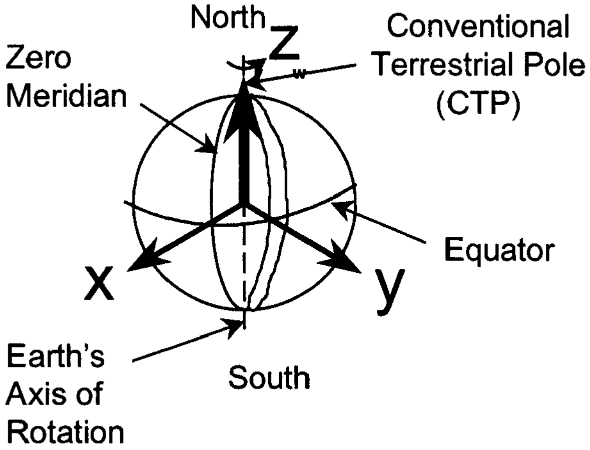


FIGURE 15 Relationship of surfaces *(5).*



"Nominally" WGS–84 and NAD–83 Coordinate System

FIGURE 16 CTRS—Cartesian Coordinate System *(6).*

GPS satellite orbits are not governed by the size or shape of an ellipsoid. Satellite orbits are related to the mass center of the earth, and positions of the satellites are referenced to a three-axis global Cartesian coordinate system. Fortunately, there is a precise mathematical relationship between the global Cartesian coordinate system used by the satellite system and the reference ellipsoid. The origin of the Cartesian system and the center of the reference ellipsoid are defined to be at the mass center of the earth.

GPS uses a global Cartesian coordinate system called the Conventional Terrestrial Reference System (CTRS). The origin of the CTRS is at the mass center of the earth (geocentric) with the X- and Y-axes in the plane of the equator. The X-axis is aligned with the prime meridian (zero-degrees longitude) located at Greenwich, England. The Z-axis coincides with the earth's mean rotational axis. The three axes are mutually perpendicular and form a right-handed system that rotates with the earth. Figure 16 shows the Cartesian coordinate system in relation to the reference ellipsoid.

It is instructional at this point to note that the fundamental position information derived from GPS measurements is expressed in terms of CTRS X, Y, and Z coordinates. These coordinates define the position of a point in space without regard to the topography, the geoid, or the ellipsoid.

#### Geodetic Coordinate System

It is necessary for surveying (and most navigation) that the position obtained from GPS be related to the earth (or more precisely the reference ellipsoid) rather than just an X, Y, Z coordinate somewhere in space.

A convenient coordinate system for the reference ellipsoid is the familiar latitude, longitude, and height above (or below) the ellipsoid. Because latitude and longitude are related to the ellipsoid, they are referred to as "geodetic latitude and geodetic longitude."

Latitude is the angle measured north or south from the equator (zero latitude). The earth's poles are located at latitude 90 degrees north and south. Longitude is an angular measurement on the equatorial plane from zero longitude at Greenwich, England (prime meridian) to the point in question. Longitude ranges from 0-360 degrees measured counterclockwise looking at the equator from the north pole. Longitude is more commonly expressed as an angle from 0–180 degrees east or west from the prime meridian.

The concept of height above (or below) the ellipsoid is generally foreign to the average surveyor. It is an essential concept, however, in dealing with GPS. An understanding of ellipsoidal heights is fundamental to the process of determining elevations (or elevation differences) with GPS.

### ELEVATIONS AND GPS

The relationship between the topography, the geoid, and the reference ellipsoid has to be considered when attempting to determine elevations with GPS. It is necessary to define two terms that represent "heights": *elevation* and *ellipsoidal height.*

In Figure 17, elevation (H) is the vertical distance to a point as measured with respect to mean sea level (or geoid). Ellipsoidal height (h) is a vertical distance above (or below) the reference ellipsoid. Figure 17 diagrams three surfaces involved and shows the various height relationships. Figure 17 also shows geoidal height, N. Geoidal height (or geoid height) is the vertical distance from the ellipsoid to the geoid. Geoid height cannot be measured directly, but can be approximated from gravity models. It can also be determined by obtaining the ellipsoidal height of the point (using GPS) and subtracting the elevation of the point. GPS computational techniques for determining elevation generally rely on gravity models (or geoid height contour charts) for computing the geoid height and subtracting it from the GPS-derived ellipsoidal height. The gravity model currently used to convert ellipsoid heights to geoid elevations is GEOID 96. The model is available through the Internet from the National Geodetic Survey.

GPS provides excellent ellipsoidal height differences. Accuracies of a few centimeters over distances of 50 km (30 miles) are common. The conversion of GPS ellipsoidal height differences to elevation differences will depend on how well geoid height differences can be determined. It is important to realize that the difference in ellipsoidal heights between two points is not necessarily the elevation difference.

### DATUMS

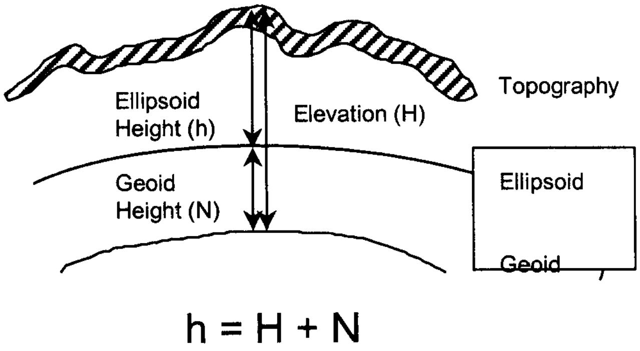
#### General

A datum is "Any quantity or set of such quantities that may serve as a reference or basis for calculation of other quantities" (*3*). In making measurements and determining positions on the earth, we are concerned with two types of datums: horizontal control datums, and vertical (or elevation) datums.

#### Horizontal Control Datums

The National Geodetic Survey (NGS) is responsible for establishing and maintaining a National Geodetic Reference System (NGRS). NGRS is a network of geodetic horizontal control stations covering the entire United States.

There are more than 250,000 NGRS stations in the United States used by surveyors as primary reference points for subsequent surveys. The position of each NGRS station is published in terms of latitude and longitude in two different geodetic horizontal control datums. These datums are: the North American Datum of 1927 (NAD 27), and the North American Datum of 1983 (NAD 83).



$$h = H + N$$

FIGURE 17 Illustration of geoidal height *(5).*

Numerous horizontal control datums are defined throughout the world, but NAD 27 and NAD 83 are, by far, the most widely used in the United States for both surveying and navigation.

Table 4 is a summary of parameters that define NAD 27 and NAD 83 horizontal control datums. NAD 83 is the latest datum, being implemented in 1986. Accordingly, NAD 83 is a geocentric, global, geodetic horizontal control datum completely compatible with GPS. NAD 83 was a complete readjustment of all NGRS stations utilizing a combination of original terrestrial measurements and new satellite doppler measurements. The positional relationship of the NGRS stations in the NAD 83 datum was greatly improved over the relationship expressed by older NAD 27 coordinates for the stations.

TABLE 4

DATUM ELEMENTS FOR NAD 27 AND NAD 83 *(6)*

| | NAD-27 | NAD-83 |
|---|---|---|
| Reference Ellipsoid | Clarke ellipsoid 1866<br>a = 6,378,206.4 M<br>f = 1/294.9786982 | GRS 80<br>a = 6,378,137 M<br>f = 1/298.257222101 |
| Datum Point | Triangulation Station "Meades Ranch" | "IERS" Zero Meridian |
| Longitude Origin | Greenwich Meridian (BIH Zero Meridian) | |
| Azimuth Orientation | From "South" | From "North" |
| Adjustment | 25,000 points<br>Several hundred base lines<br>Several hundred astro. azi. | 250,000 points<br>approx. 30,000 EDMI baselines<br>5,000 astro. azi.<br>600 doppler point positions<br>12+ VLBI baseline vectors<br>"NO" GPS vectors |
| Best Fitting | North America | World-Wide |

Until 1986, the NAD 27 system was the standard horizontal control datum used in the United States, Canada, and parts of South America. Contrary to the NAD 83, NAD 27 is not a global datum but is considered a local datum. The center of the Clarke ellipsoid of 1866, used by NAD 27, does not coincide with the mass center of the earth (geocentric) and is, therefore, less compatible with GPS.

### Datum Transformations

The results of a GPS measurement will generally be given in terms of X, Y, and Z coordinates in the CTRS Cartesian coordinate system. If elevations are required, GPS ellipsoidal heights must be transformed into elevation by one of the methods described previously.

Transformation formulas are available for converting NAD 83 coordinates into NAD 27 coordinates. Although there are universal constants for relating the two systems, it is better to use locally derived constants for surveying purposes. An in-depth analysis of this process is beyond the intent of this synthesis and the reader is directed to work by Hoar (5), and similar material, for additional information.

### Vertical Control Datum

Just as it is necessary to relate horizontal position to some reference system, or datum, it also necessary to relate measurements of elevation to a standard datum. In the United States, the standard vertical control datum was, until recently, the National Geodetic Vertical Datum of 1929 (NGVD 29). That datum was defined using observed heights of mean sea level at 21 tide gauges in the United States and 5 gauges in Canada, and by the elevations of all bench marks resulting from a related adjustment (*8*). The datum does not coincide with the geoid or any other equipotential surface (*8*).

NGS has recently defined and implemented a new vertical datum called the North American Vertical Datum of 1988 (NAVD 88.) This is *not* a sea level datum. The origin is station Father Point, on the St. Lawrence River at Rimouski, Quebec, Canada, one of the original International Great Lakes Datum water-level stations. Using this point as the origin satisfies the requirement of shifting the datum vertically to minimize the impact of NAVD 88 on the Great Lakes Dynamic Height System.

## GEODETIC CONTROL NETWORKS

### General

The increasing application of GPS to high-precision geodetic surveying tasks has revealed a need for geodetic control networks with higher precision than existing NGRS. The capability of GPS to measure baselines hundreds of kilometers long with centimeter accuracies far exceeds the accuracy of the existing NAD 83 NGRS. NAD 83, for example, has an accuracy range between 3 ppm and 1 ppm. GPS, on the other hand, can perform at the 1 ppm to 0.1 ppm precision level. Often times, the results of GPS surveys were (and are) degraded to match lower precision control networks.

The ability of GPS to make high-precision measurements over long distances is an asset to many scientific endeavors, such as monitoring the earth's crustal motion. NGS has nearly completed efforts to develop a national high-accuracy reference network (HARN) to support the growing demand. In cooperation with the efforts at the federal level, many states have implemented similar systems in support of long-range integration of state Geographic Information Systems (GIS) and improved cadastral relationships. Three of these special networks are described below.

### VLBI Network

While not specifically developed for GPS purposes, the Very Long Baseline Interferometry (VLBI) network has become an important space and terrestrial reference frame. The network consists of radio telescope tracking stations located at several sites, shown in Figure 18, such as Westford, Mojave, and Yellow Knife.

Simultaneous recordings of radio frequency noise emitted by stars (quasars) is used with an analysis technique called Radio Interferometry to establish absolute and relative positions of the stations. The positional accuracy of the network points is centimeter level (a feat almost equaled using GPS methods). The VLBI network is used extensively by the scientific community as a primary geodetic reference frame in a multitude of spaceborne and terrestrial applications.

### CIGNET GPS Tracking Network

The Cooperative International GPS Tracking Network (CIGNET) is an internationally supported, civilian operated, GPS tracking network designed to fill the need for GPS satellite tracking data for use in both scientific and commercial applications.

All tracking stations are located at VLBI sites and use off-the-shelf civilian GPS receivers. Figure 18 shows the locations of the CIGNET stations. CIGNET stations operate in an automatic mode and tracking data is downloaded via communication lines to offices of the National Geodetic Survey. Tracking data is checked, catalogued, then made available to subscribers over dial-up computer facilities.

The CIGNET network is oriented with the VLBI reference frame and is rapidly becoming a standard source for high-precision GPS tracking information for the user community. Data from the CIGNET network is also used by GPS to generate a GPS satellite "Precise Ephemeris" that is also available to the civilian user.

CIGNET tracking data is used as a reference system for orienting other high-precision GPS networks, such as those being developed by some states.

FIGURE 18 CIGNET tracking stations *(6).*

**State GPS Networks**

In cooperation with the NGS, many states have established high-precision networks (1 ppm and better) to improve the status of existing geodetic control networks and to support growing GPS applications. One of the most significant reasons for establishing these high-precision networks is the growing development and implementation of state GIS systems. High-precision networks provide improved database correlation and increased positional integrity of GIS data over the long term. They will also improve the usability of data exchange between governmental and commercial GIS information.

These networks, for the most part, use existing network stations (such as NGRS stations) supplemented by new stations. Two examples of such networks are GPS high-precision networks in Florida (Figure 19) and Texas (Figure 20).

These two examples show the diversity of long-term GPS requirements envisioned by each state and methods of meeting those needs. The Florida network consists of more than 100 reference stations spaced at approximately 50 km. The Texas network consists of 10 stations. The primary difference is that the Texas system is designed to have full-time GPS tracking receivers that are used as permanent reference receivers for relative positioning applications (this concept is discussed in a later chapter). Other states have systems similar to the Florida network and all states have a high-precision network.

For the most part, high-accuracy state networks become the foundation for readjusting all existing NAD 83 network station coordinates throughout the state. Several state high-precision networks are cooperative undertakings between states, counties, and cities. Additionally, several networks have been established in cooperation with the NGS.

Revised NAD 83 coordinates derived from these new networks are published separately to distinguish them from standard NAD 83 coordinate values. It is expected that, in time, the high-precision GPS state networks will become the standard geodetic reference.

*Fitting to Existing Networks*

GPS surveys generally have excellent internal accuracy; that is, accuracy without regard to external networks or reference points. Sometimes referred to as geometric accuracy, this accuracy is a reflection of the precision of GPS techniques (if properly conducted).

In most cases, GPS surveys have higher internal accuracies and consistencies than available geodetic networks to which they are attached. It is not uncommon to see the results of a GPS survey with superior internal accuracy "degraded" to conform to a less precise geodetic reference system. This is particularly true when adjusting a GPS survey to the NAD 27 network. Better results are obtained when using the NAD 83 reference network. States have established HARNS to overcome this problem; they are more compatible with GPS-derived survey results (see chapter 6).

Because GPS is not a real proportionate system, common adjustment methods, such as compass rule, transit rule, or Crandall method for adjusting conventional surveys, do not adequately apply to a GPS survey. A least-squares adjustment process is more commonly used. The majority of available software statistics packages contain adjustment routines of this nature.

It is important that accuracy requirements for a typical DOT engineering survey be kept in mind when using these software packages. Most adjustment routines are intended for high-precision geodetic network surveys where accuracy requirements of 1:100,000 or better are common. A good portion of DOT surveys, however, are engineering related where accuracy requirements are generally less than 1:20,000 and,

FIGURE 19 Florida HARN points *(9)*.

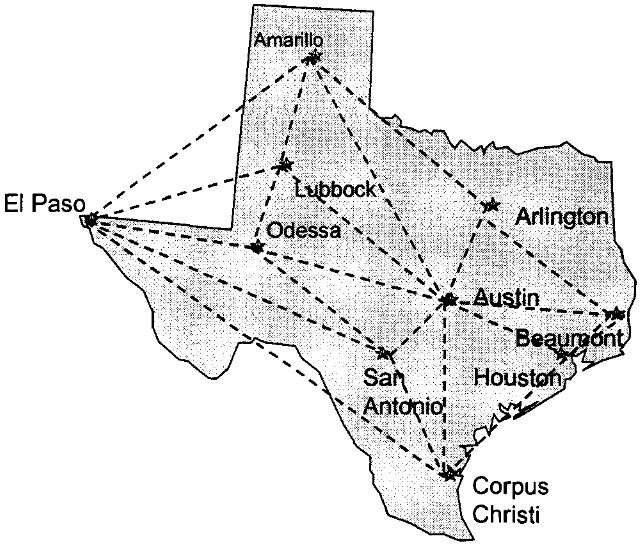


FIGURE 20 Texas HARN points.

therefore, may not require a rigorous level of analysis. With implementation of the HARNs, more and more engineering surveys will be completed using GPS base stations (CORS) as the control, this will require base line measurements of 1:1,000,000 (1 ppm).

Existing adjustment methodologies should be examined and understood before applying them to GPS surveys. For the most part, adjustment processes for surveys accomplished using classical survey techniques assume that the network to which it ties is superior in precision than the survey itself. This is not necessarily true for surveys accomplished with GPS.

### *Project-to-Project Fitting*

Reliable project-to-project coordinate fitting has always presented a problem for DOT surveys. This is especially true on projects such as highways where short pieces of control surveys are placed to control individual projects. Some time later, an intersecting project is laid out requiring continuity of control between the two surveys. There are several reasons for this problem: distortion in the primary geodetic reference system, excessive survey adjustments on individual projects, and the tendency to "push" project-to-project tie problems to an area outside the immediate project area.

GPS can provide assistance in resolving these difficulties through its ability to make additional ties and checks between projects that would be too costly or impossible to make using conventional techniques. For the same reason, GPS measurements can also reveal problems in fit that may not be obvious using other methods. The fact that GPS can produce high precision over any distance makes it an excellent tool for detecting, measuring, and fixing project-to-project problems rapidly and economically.

CHAPTER FIVE

# GENERAL DOT APPLICATIONS

## INTRODUCTION

GPS is steadily developing into a versatile and cost-effective measurement and positioning tool for DOT operations. Even during its early test stage in the 1980s, GPS was being used for surveying by a limited number of state DOTs, commercial firms, and several federal agencies. These early applications were generally associated with high-precision geodetic surveying tasks.

Although early use of GPS concentrated on survey operations, it soon became apparent that GPS had the capability of providing positioning information for other DOT operations requiring less precision. The Tennessee DOT, for example, conducted early experiments that used real-time GPS positioning for affirming and correcting roadway maps and obtaining positions of roadway inventory items as related to GIS systems.

GPS applications are rapidly expanding. It is beyond the scope of this synthesis to report on all variations and benefits associated with each. Most applications fall into one or more general positioning techniques offered by GPS. These categories pertain to whether the positioning (or measuring) is done in a static mode or while in motion (kinematic). Additionally, applications can be classified by accuracy requirements. Surveying applications (either static or kinematic) generally infer centimeter accuracy. GIS or small-scale mapping operations most often require only meter-level accuracy.

To provide an understanding of where and how GPS can be used in DOT operations, the remainder of this chapter concentrates on presenting a potpourri of applications broadly categorized as: surveying applications, GIS applications, and vehicle-positioning applications. A glance at two sample GPS receiver types is given to provide a basic understanding for the relative size and costs of the hardware involved in some of the applications described below. Detailed information on GPS static and kinematic survey applications and processes are covered in chapter 6, and additional details on selected kinematic applications are given in subsequent chapters.

## GPS RECEIVERS AT A GLANCE

For purposes of this chapter, GPS receivers fall into two broad categories: Geodetic high-precision with centimeter accuracies and general purpose units capable of meter- and submeter-level accuracies. In 1997, a typical high-precision, geodetic-quality, GPS receiver cost between $5,000 and $40,000 depending on configuration. These receivers are about the size of a large book, weigh about 10 lbs (or less), track eight or more satellites simultaneously, consume less than 4 watts of power, operate on 12 VDC, and function in most weather conditions. Geodetic-quality receivers are capable of tracking and recording carrier-phase information required for survey work. In addition to their use for precision surveys, these receivers can also accomplish almost all navigation functions, including real-time differential operation.

A hand-held, general-purpose GPS receiver used in a variety of positioning applications including real-time navigation, typically costs between $300 and $10,000. Some require a laptop computer for recording position information and may need an additional I/O display unit. Others have built-in navigation software and display units. A few can also track carrier-phase and use it to produce an improved pseudorange position in real-time. Variations of these receivers are available as complete systems for marine, land, and airborne vehicle navigation applications.

Geodetic-quality receivers are used for surveying applications while other applications can take advantage of the less-expensive general-purpose receivers. It should be pointed out that geodetic-quality receivers are versatile and can be used for most other applications.

## SURVEYING APPLICATIONS

### Introduction

No other area of DOT operations lends itself more readily to GPS technology than surveying. When properly applied, GPS methods can produce labor cost savings ratios of 6:1 or more, and improve accuracies by a factor of four (*10*). Surveying applications take advantage of both static and kinematic capabilities of GPS. The following paragraphs briefly outline current (and future) surveying tasks that can take advantage of GPS methods (*1*).

### Control Densification

Densification of existing geodetic control networks is an excellent application of GPS. The idea of having network reference stations closer together and more readily available for use at the local level has been a pervasive concept in the surveying community. National Geodetic Reference Stations vary in density throughout the country. Highly urbanized areas often have reference stations spaced at 10 km or so, while in some rural areas, spacing of 25 km and more are common. Some regions of the country have very few reference stations while others are adequately served.

The cost of traversing distances of 5 to 25 km to tie a project survey to the NGRS system can increase a project's costs significantly. Using classical surveying techniques (electronic distance measuring units, total stations, and theodolites) to densify the network is extremely costly since line-of-sight between adjacent stations is necessary for proper measurement. This often requires erection of expensive observation towers, night observations, and good weather.

By comparison, GPS does not require line-of-sight between adjacent points, and measurements can be made in nearly any weather in about 30 minutes (or less in some kinematic methods). Many cities, counties, and states have taken advantage of the relatively low cost of GPS surveys to densify network control stations in their local area.

Cost effectiveness of GPS techniques for this application is high when compared with classical survey methods. While true-cost comparative figures are rare at this time, estimates of effectiveness over classical methods can range from 6:1 to 20:1 (and in some cases much higher) over standard survey methods. Improved accuracy is almost always an additional benefit when using GPS for densification work.

### Corridor and Project Control

Installing primary geodetic control within a project corridor, or area, is almost always accomplished early in the life of a project. This primary control becomes the backbone for subsequent cadastral, design, and construction surveys. Corridor and project control surveys almost always have higher precision requirements than subsequent engineering surveys. Although point spacing varies considerably, spacings between 1 and 6 km (0.6 and 4 mi) are not unusual. Consequently, a high-cost factor is associated with corridor surveys. One significant source of the high cost can sometimes be attributed to the task of tying project control to a national or state geodetic reference system.

The application of GPS surveying methods for corridor and project control surveys were among the earliest DOT applications. At the present time, it is not unreasonable to speculate that the purchase cost of GPS hardware to do these surveys can be recovered in just one or two projects when compared with classical survey methods.

### Mapping Control

As in primary corridor and project control, geodetic surveys for installing ground control for mapping have a high-cost factor. For the most part, these surveys have higher precision requirements than nominal engineering surveys. Maps compiled at scales of 1/600 using photogrammetric techniques require ground control surveys that have precision ratios of 1/20,000 or so. Most surveys for cadastral and engineering rarely have ratio of precision requirements in excess of 1/10,000.

Map control surveys are also done early in the project life, complicating ground survey operations. For the most part, these surveys are in the same general class as corridor surveys, depending on the accuracy required by the mapping process.

Although distances between points used for map control may be closer than corridor control points, static GPS methods are still cost effective. Kinematic GPS methods are of particular interest in this application when the project provides overhead access to the satellites, such as along an existing highway or railroad right-of-way.

### Construction Reference Control

The placement of preconstruction reference control points using GPS can be cost effective, particularly when project clearing has not occurred and control is required in separated areas (such as initial control for highway interchange construction). The ability of GPS to set points without the need for a clear line-of-sight between points can be an asset in meeting the need for placing isolated construction reference points. Much time and cost can be added to projects because reference control did not include existing right-of-way and baseline monuments.

GPS is extremely precise over short distances (up to 24 km, 15 mi), and the installation of construction reference points using corridor reference points can minimize the need for line clearing and traverse surveys. As long as satellite visibility requirements are met, GPS techniques can compete quite favorably with classical methods.

Real-time kinematics (RTK) is the latest GPS innovation. On-the-fly ambiguity resolution is available with dual-frequency receivers. The concept of having one person (with one book-size GPS receiver operating in the relative positioning mode) setting a construction reference point in a few seconds is a reality.

Although static GPS methods have been used for setting basic construction reference points, RTK techniques are also applicable, particularly when project clearing has occurred to provide easy access on the construction site.

### Structure Control

Application of GPS for structure related surveys has, for the present, been limited to basic control surveys and independent checking of critical measurements. GPS techniques are ideal for establishing construction control over long, open water projects such as causeways, or high-level bridges with long buildup approach roadways. GPS is also useful for installing primary reference points over large expanses of water. An example of this is the tunnel project between France and England beneath the English Channel where GPS was used to establish a unified control reference network for each end of the tunnel.

Some efforts are underway to adapt GPS precise kinematic capabilities for monitoring the movements of large structures. It may be possible to use GPS as a real-time structural displacement monitoring system, particularly when used in connection with other monitoring systems, such as strain gauges and accelerometers. This application has the advantage of providing independently determined movement information for correlation with other systems.

### Cadastral Surveys

There are a variety of cost-effective applications of GPS pertaining to the location and measurement of right-of-way and other property lines or points. GPS is especially effective for surveys of large tracts of land, particularly in rugged terrain (*5*).

Where access to property corners is unobstructed, RTK methods can be applied effectively. Practical results verify that RTK methods can produce results in several hours that would have taken 3 days to accomplish using conventional methods (*6*).

GPS can be used to assist in the recovery of lost property monuments, section corners, and right-of-way markers by taking advantage of real-time relative positioning and navigation techniques.

### Airborne GPS/Photogrammetry Control

Recent tests by NGS and others in production mode for small-scale maps have shown that GPS can determine the coordinates of an aerial photograph at the instant of exposure with sufficient accuracy to eliminate (or greatly reduce) the need for aerial ground control targets and accompanying field surveys to produce photogrammetric maps. This application is described in more detail in chapter 6.

## GIS APPLICATIONS

### Background

The need for improved quality and spatial accuracy of Geographic Information Systems (GIS) is becoming more of an issue as the data in these systems become increasingly integrated. One of the major advantages of a GIS is the ability to integrate information from a variety of data base sources to identify and isolate problems and to present, analyze, solve, and plan corrective infrastructure programs.

Data used to develop a GIS are often derived from a variety of sources whose real spatial accuracy may be unknown. Much information comes from maps whose original accuracy may have been known, but are subsequently distorted by continuous applications of "rubber sheeting" techniques through the magic of computer-aided drafting systems. As the demands for spatial integrity of GIS information increases, map-fitting and redigitizing will not suffice over the long term.

GPS technology provides a cost-effective method for increasing the spatial integrity of GIS information by offering accuracy capabilities to match the needs required by any GIS element. GPS technology can be used to upgrade the spatial integrity of existing data bases and provide the vehicle for building the spatial foundation of new GIS's.

The following paragraphs describe a typical application of GPS technology to solve a GIS related problem.

### Verifying Spatial Accuracy

In 1986, the Environmental Protection Agency (EPA) conducted a GIS demonstration project involving groundwater contamination in the San Gabriel Basin in California. An extensive network of groundwater monitoring stations, water supply wells, and groundwater flow models was used to determine the extent of contamination and to identify the parties responsible (*12*).

Because well locations were commonly plotted on maps with reference to specific streets or intersections, it was decided to verify the location of the streets themselves before entry into the data base. This was accomplished by driving the streets in a vehicle equipped with a GPS receiver. Selected wellheads were then located through a GPS survey and the well locations indicated in the data base rectified accordingly (*12*).

The results of the project assisted in determining that GPS can be successfully used to assess the spatial quality of GIS thematic data layers, especially if those layers are not related to any common geodetic reference frame.

## DOT MAINTENANCE AND INVENTORY APPLICATIONS

Typical GPS applications for maintenance management systems are aptly described in NCHRP Report 334 (*13*). This report of the National Cooperative Highway Research Program (NCHRP) describes maintenance applications for GPS and demonstrates the integrated use of GPS with other technologies, such as data collection systems and telecommunications. Of particular interest is the description of a prototype roadway feature data collection system similar to one being developed under the American Association of State Highway and Transportation Officials (AASHTO) 38-state GPS/GIS project. The fundamentals described in this system can be used in various degrees to meet specific DOT needs.

GPS hardware is getting smaller, more rugged, and less expensive, making the cost for installation in maintenance vehicles about the same as the cost of the high-frequency radios already installed in most of these vehicles.

The Montana Department of Highways (MDH) used a pilot project to demonstrate the combined value of GPS and GIS technology for highway inventory and location purposes (*14*). In addition to recording the location and attributes of some 25 roadway items, the system also produced digital maps of the roadway alignment.

A similar, but more comprehensive, system was demonstrated by The Center for Mapping of the Ohio State University (OSU). The objective of this project was to design and construct a prototype vehicle that could simultaneously determine horizontal and vertical roadway alignments and record images of roadway features. Contributors to the project included the FHWA, National Aeronautics and Space Administration (NASA), 38 states, the Defense Mapping Agency, a variety of corporate firms, and Canada.

The final product was a van (called the GPSVan) containing an integrated system of technologies including GPS, video

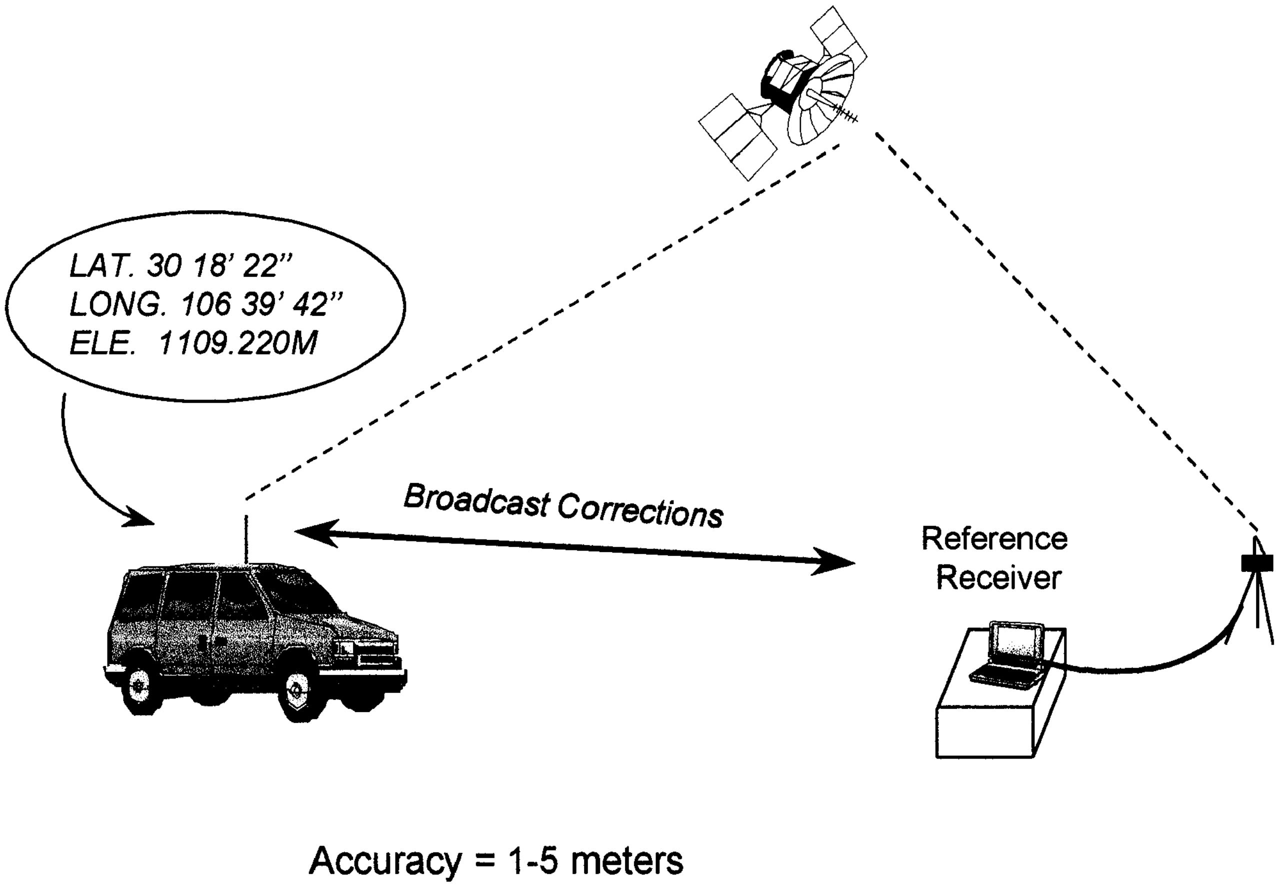


FIGURE 21 Vehicle location and navigation using GPS real-time GPS relative positioning.

cameras, computers, and data-recording devices. Using GPS differential techniques, a gyro-assisted heading and attitude sensor, and a precision wheel revolution counter, the GPSVan was successfully demonstrated in a number of states (*10*). The functions and accuracy of the project demonstrated the viability of integrating GPS with other technologies to perform transportation related mapping and inventory tasks.

By intergrating multiple cameras to provide stereo imaging of highway features, objects may be positioned to 1-meter accuracy. By digitizing their positions from the image on the computer screen, spatial measurements of the relative distances and directions between objects on the same video image can be made at the decimeter-level of accuracy.

## VEHICLE LOCATION AND NAVIGATION APPLICATIONS

Figure 21 shows the fundamentals involved in using GPS differential positioning to locate, track, and/or navigate vehicles. The basic concept shown in Figure 21 applies to any vehicle, whether on land, water, or in the air. The technique works for all velocity and acceleration factors likely to be encountered in DOT applications. When combined with communication links, the location of the vehicle can be recorded and displayed in real-time at a central site. This technique is being used in Iowa, Minnesota, and Michigan to monitor DOT maintenance vehicles and for efficient dispatching of appropriate vehicles in emergencies. When used with appropriate digital radio links, the position of the vehicle could be included with the transmission of other digital data that describe the work activity of a maintenance party to automatically update a maintenance GIS system. The accuracy of differential GPS techniques is sufficient, in most cases, to delineate roadway lane widths.

The meter-level accuracy of real-time GPS navigation could be used, for instance, to navigate emergency vehicles to individual locations on roadways, provided maps used as reference were of equal accuracy. Chapter 6 describes several GPS vehicle location and navigation projects that are either in operation or being planned.

CHAPTER SIX

# ADVANCED APPLICATIONS

## GENERAL

The use of GPS for DOT surveys is a cost-effective methodology for accomplishing geodetic positioning with centimeter accuracies. Some fundamental GPS techniques used to accomplish surveying can be amplified and enhanced to accommodate other applications as well.

Relative positioning techniques used in surveying are equally effective for navigation where meter-level position is required. Some employ carrier-phase tracking methods and can be considered as enhanced survey applications. Some applications use pseudorange solutions for meter-level accuracies, and still others use pseudorange solutions smoothed with carrier-phase. These are not necessarily new GPS techniques, but rather enhancements or modifications of GPS processes already described.

## ACTIVE CONTROL STATIONS

### Descriptions

GPS Active Control Stations (ACS) are also called Continuously Operated Reference Stations (CORS), Active Control Points, Continuous Trackers, Regional Reference Points, and a variety of other names. ACSs are automated, full-time, GPS tracking stations designed to track all visible GPS satellites. The stations are controlled by a small computer that stores the tracking data and monitors the station's related systems and environmental conditions. The small computer also provides a communication capability for remote station monitoring and data transfer. Some installations also contain high-precision clocks that drive the GPS receiver. Typically, cesium or rubidium oscillators are used because of their low long-term drift characteristics. Figure 22 is a functional block diagram of an ACS developed by the Texas Department of Transportation.

National Geodetic Survey (NGS) has CORS located at VLBI sites that are primarily used for developing the precise satellite ephemerides computed by that agency. In addition to Texas and New Mexico, several other states are considering implementing the ACS concept. One CORS network designed to support high-precision geophysical research is currently in operation in southern California. Operated by the Scripps Institute of Oceanography, the network has five stations primarily used to monitor deformation of the earth's crust in that area.

The Geodetic Survey of Canada has a nationwide system of CORS to serve all surveying and navigation users, both public and private. The Canadian system proposes to use satellite data communication links for data transfer, operation, and for broadcasting real-time differential corrections. Figure 23 shows operation of the proposed ACS, and Figure 24 is a data-flow diagram for the Canadian system.

### Concept

As it applies to the average DOT operation, the function of CORS is to provide a continuously operating reference point for GPS relative positioning surveys and navigation. The area served by the typical station is a function of the accuracy required.

CORS continually collects both pseudorange and carrier-phase data and acts as the known point for relative positioning surveys surrounding the station. For geodetic surveying, the nominal useful radius of the station is about 100 km (may not be true in areas of crustal motion e.g., California), but new position calculation algorithms can extend the useful radius of the station to several hundred kilometers for surveying purposes. This is especially true when several CORS act as a fiducial network *(16)*.

### Operation

CORS continuously track the satellites and store the tracking data (either locally or at some central site). Roving receivers in the field either transmit their data to a central site or receive tracking data from CORS that coincides with the roving receivers' observation times. The data is brought together for post-processing.

In operation, there can be any number of roving receivers operating at the same time from different agencies, all using CORS as their reference receiver for relative positioning. If the station broadcasts pseudorange corrections, that is, Differential GPS (DGPS), the station can be used for real-time submeter-level positioning by vehicles and other applications.

### Costs

The cost of a CORS varies considerably depending on the sophistication of the receiver, support hardware, and operational software. A CORS for DOT use can cost between $50,000 and $200,000, not including support personnel and operating costs. It should be noted that CORS systems for DGPS requirements are available from receiver manufacturers at costs less than those stated above.

### Benefits

Major benefits derived from a CORS are reduction of labor and reduced costs for GPS receivers. The system eliminates the need for a survey field party. The operator and receiver are

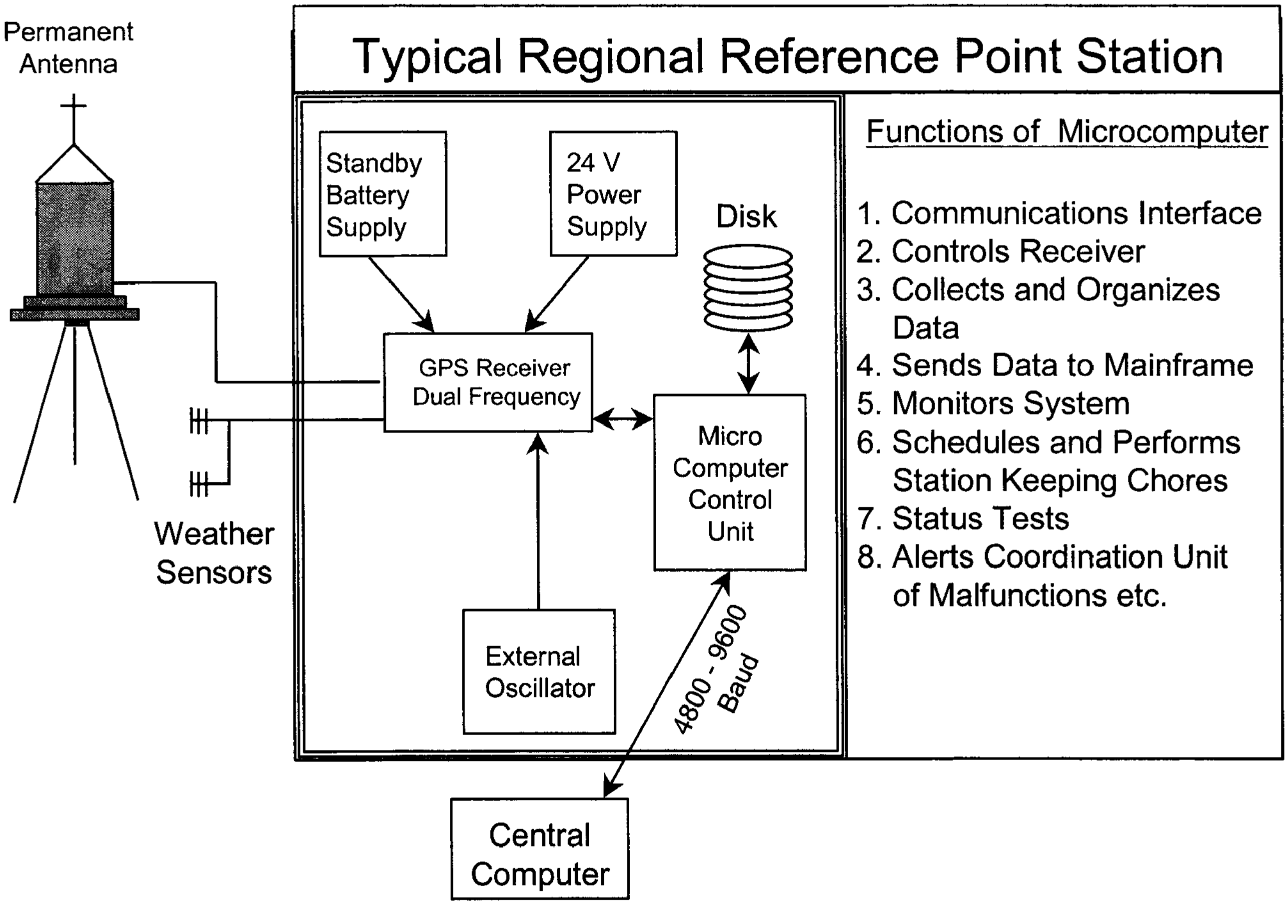


FIGURE 22 Function diagram of TXDOT ACS stations.

assigned to occupy only unknown points, increasing production for a fixed number of receivers.

Other benefits include reduced field party time devoted to traveling to and from reference points, and reduced receiver requirements for surveying operations.

When used for less-accurate positioning associated with roadway inventory items, GIS, and pavement management systems, an ACS can significantly reduce hardware costs. A single CORS centrally located in most states can serve the meter-level positioning needs of the entire state unless crustal motion is a factor.

## AIRBORNE GPS/PHOTOGRAMMETRY CONTROL

### Background

Aerial photography used to produce accurate maps requires ground-reference points visible on the photography. Normally these reference points are made visible by physically placing prominent markers, or targets, over each point before the photograph is exposed. Coordinates of these reference points are determined by ground-based surveys using either classical or GPS field techniques. Coordinates and photo images of the targets are used for precise scaling and orientation of the photography in preparation for the map compilation phase.

The process of targeting and surveying ground reference points is a major cost in producing photogrammetric maps. This is especially true for most large-scale DOT maps produced for engineering purposes where target positions must be determined to accuracies of just a few centimeters.

If spatial coordinates of aerial photographs can be determined at the instant of exposure, the need for placing ground control targets and performing required precision field surveys is negated, or at least, greatly reduced.

In the early 1980s, NGS experimented with the concept of using GPS kinematic carrier-phase differential techniques to determine the position of an aircraft for controlling high-level aerial photography. Earlier computer modeling showed that positioning accuracies of just a few centimeters were possible *(18)*. Subsequent tests conducted jointly between the NGS, Texas Department of Transportation, and the Washington Department of Transportation, confirmed earlier accuracy estimates. Results in the Texas and Washington tests confirmed that GPS kinematic techniques can determine the spatial position of the aircraft GPS antenna to better than 5 cm (0.16 ft); sufficiently accurate for DOT photogrammetric engineering map compilation.

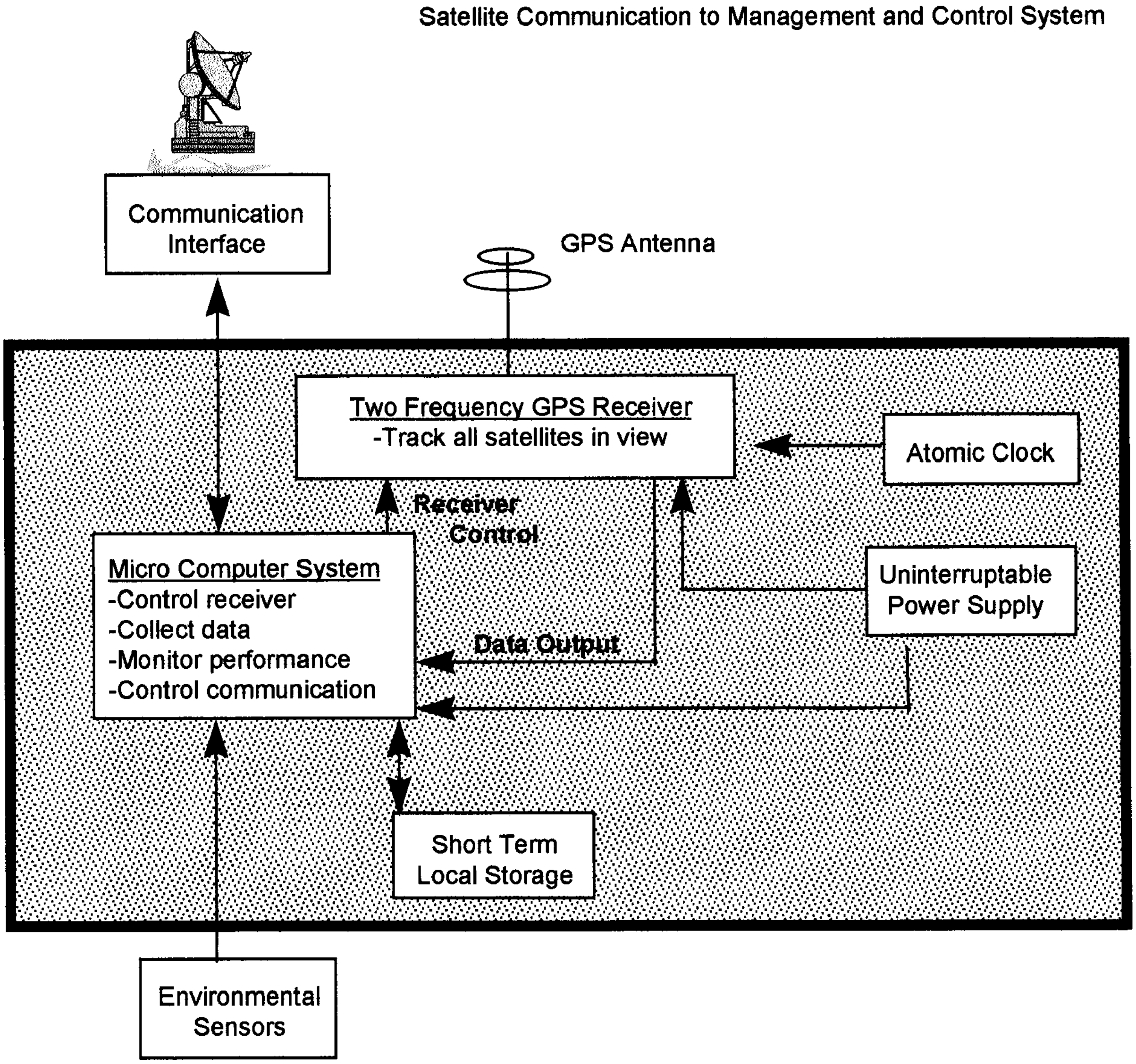


FIGURE 23 Function diagram for Canadian ACS station *(17)*.

### Concept and Operation

The general concept of using airborne GPS for controlling aerial photography is described below. A geodetic-quality GPS receiver installed in the aircraft works in conjunction with a ground-based receiver in the relative positioning mode. At the conclusion of the aerial photography flight, the receiver data sets are brought together and processed using kinematic relative positioning methods. As a result of the processing, the aircraft antenna is positioned at each epoch. For low-altitude photography associated with engineering map compilation, the epoch interval is normally one second or less.

An electronic pulse generated by the camera at the center of picture exposure duration is compared to GPS time generated by the GPS receiver to compute the exact time of exposure (event). The computed time of exposure is tagged with the exposure number generated by the camera. Both pieces of data are either filed in the GPS receiver along with the satellite tracking data or transmitted to an external computer for storage. A few geodetic GPS receivers have photogrammetric options that allow for camera pulse input and for computing the event times.

Using kinematic data processing methods, antenna positions at each epoch are computed and used to derive the position of the antenna at each recorded event time. A polynominal fit across several epochs provides a good estimate of antenna position at the time of exposure.

It is important that the exact time relationship between the center of the camera shutter opening and the shutter output pulse be known in order to account for any time biases that

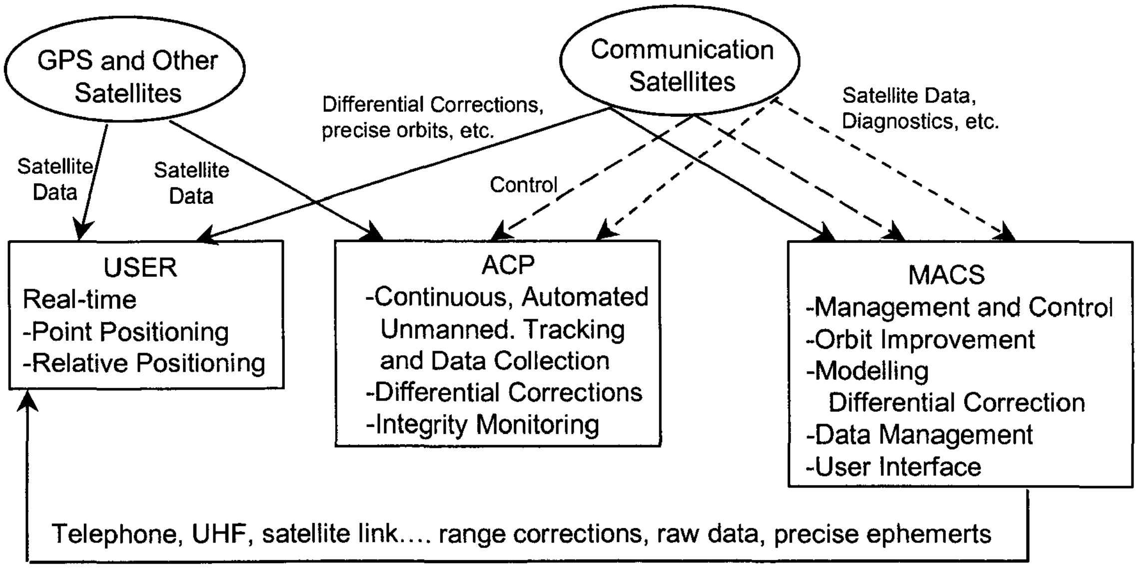


FIGURE 24 Data flow for Canadian ACS system *(17)*.

may be present. Knowing the time offsets (both random and systematic) within 100-micro-seconds is generally acceptable. Systematic biases are easily accounted for, but if the random component is excessive, accuracy will suffer. A one-millisecond error can translate into a 5-cm error in position at aircraft velocities of 50 meters per second. Most modern aerial mapping cameras have pulse outputs that are within a few micro-seconds of the actual center of the shutter opening.

It is also important that the relationship between the aircraft GPS antenna axis and the camera axis be determined as accurately as possible. This information is used in subsequent computations to translate coordinate positions from the GPS antenna to the camera axis.

Present procedures call for indexing the aircraft over a known point on the airport before takeoff and re-indexing it when it returns. With "on-the-fly" ambiguity resolution, the aircraft will take off, fly one or more projects, and return to any convenient airport.

Once the GPS camera positions are computed, they are combined with the normal output of the photogrammetric analytical bridge process and used in a photogrammetric block adjustment system to compute photo orientation and scaling parameters used in subsequent map compilation steps.

### Results

Several organizations have tested and evaluated the GPS/photogrammetry control technique, including NGS, USGS, state DOTs in Texas, Washington, North Carolina, and Ohio, as well as private firms. GPS methods can produce coordinates of ground points within 4 to 7 cm (0.13 to 0.23 ft) in all three axes of the coordinates determined by terrestrial survey techniques. This is satisfactory for compiling large-scale engineering maps used by many DOTs. The results are more than satisfactory for compiling planning maps generated from photography taken at higher altitudes.

### Benefits

Airborne GPS control of aerial photography has an extremely high benefit-to-cost ratio. Field surveys for photogrammetric ground control often comprise half the costs involved in producing photogrammetric maps. Problems associated with scheduling limited field party resources are compounded by bad weather and more pressing survey demands. The airborne GPS method also eliminates the need for survey party access to private land and the placement of ground targets. Practical application will probably dictate that one or two ground reference points be targeted and used for checking and later reference by subsequent project surveys.

Using GPS to navigate the aircraft during the time aerial photography is being taken also minimizes the need for return flights caused by flight tangent misalignments and gaps in the photography. GPS is much better than Loran and visual methods for this task. Complete GPS-based flight management systems for aerial photography aircraft are available.

## REAL-TIME VEHICLE POSITIONING

### Location and Navigation Systems

The versatility of GPS is emerging in a variety of applications where locations at meter-level accuracies are required, especially in real-time. The ability to locate and navigate land, sea, and air vehicles is rapidly becoming an issue with many DOTs. When combined with new technology permitting onboard vehicle real-time map displays, GPS can provide real-time positioning with 15 to 100 meter (49 to 328 ft) accuracy from a single receiver acting autonomously (depending on selective availability and antispoofing status—see Glossary). Submeter accuracy operating in a real-time relative positioning mode is readily available. The recent emphasis on Intelligent Transportation Systems (ITS) has put renewed emphasis on the capabilities of GPS for vehicle location and navigation.

GPS receivers for these applications are inexpensive compared to geodetic-quality receivers used for surveying. Six-channel GPS receivers on small computer boards (sometimes called GPS engines) can be inserted into a personal computer. Costing $500 to $4,000, these engines and small receivers can operate in the differential mode. The low cost of new receivers is making their installation in vehicles attractive, especially when combined with automated map systems.

### Automatic Vehicle Location and Navigation Systems

Automatic Vehicle and Location and Navigation systems, more commonly known as AVLNs, allow the user to position a vehicle by using satellite signals; display a digitized map of the area of interest; plot the position of the vehicle on the map display in real-time; and obtain routing, traffic, and other information in real-time over a communications link *(19)*.

#### TravTek

TravTek is an ITS related test in the Orlando, Florida area, of 100 vehicles equipped with GPS receivers, map display units, communications links, and dead-reckoning systems. The GPS receivers provide positioning information for a vehicle and provide continuous updating of the dead-reckoning system. The vehicles transmit their position every minute to a Traffic Management Center located in Orlando. The Center tracks the vehicles to develop patterns of use by short-term rental drivers and to monitor the patterns of long-term drivers. Seventy-five of the vehicles were tested by Avis rental company and the remaining 25 were operated by Orlando area drivers *(20)*. Partners in the test are General Motors, the Federal Highway Administration, the Florida Department of Transportation, and the City of Orlando.

#### ADVANCE

The Advanced Driver and Vehicle Advisory Navigation Concept (ADVANCE) is a 5-year demonstration project that tracks and navigates 5,000 vehicles in the Chicago, Illinois area. GPS receivers in each vehicle work in conjunction with on-board map display units and dead-reckoning systems to display the vehicle position in real-time *(20)*. The system is designed to provide motorists with the best routes to a destination and up-to-date traffic information via a communications link to a centralized Traffic Information Center. Based on the latest traffic conditions and other information, an on-board computer computes the best route to the destination and displays it on the vehicle map system along with the vehicle's present position.

The ADVANCE project is under the management of the Illinois Department of Transportation with the participation of other private and public organizations. ADVANCE is one of the largest field evaluations of ITS, costing $35 to $40 million *(21)*.

#### MAYDAY

The Colorado DOT is working on a GPS project that advances AVLN. The Colorado MAYDAY system's purpose is to allow drivers of private vehicles to possess emergency and nonemergency communication and location identification *(22)*. The MAYDAY system combines GPS and cellular phone technology. The system test involves more than 2,000 vehicles over a 12,000 square mile area in northern Colorado. The GPS unit will automatically identify the location of a vehicle. The use of the cellular phone allows the occupants of the vehicle to communicate the problem to a centralized response center.

#### MAYDAY+

The concept of using emergency response has been taken a step farther by the Minnesota DOT. Just as in the Colorado project, discussed above, the Minnesota MAYDAY+ project locates a vehicle using GPS *(personal communication, Troy Schmidt, Minnesota DOT, 1997)*. In addition, sensors in the car will be able to automatically provide data about the severity of an impact and where on the vehicle that impact occurred. The data gives staff in the response center information to determine the location of an accident, the severity of the incident, and the appropriate emergency response procedures. If funding allows, the system will also store medical information about vehicle occupants that can also be transmitted back to the response center. This project will be tested by the Minnesota DOT Rochester District. A similar system is also being considered by the New York State DOT.

#### SAFETRUCK

The SAFETRUCK research project is sponsored by Minnesota DOT and the University of Minnesota *(23)*. The purpose of the project "is investigating means for reducing road departure incidents." The experimental approach uses a sleeper cab equipped with controlled throttle, steering, and brake subsystems. In addition to measuring lateral vehicle dynamics, the vehicle systems take into account X and Y coordinates with respect to an inertial coordinate system. Two sensory systems are employed—a second generation differential global positioning system (DGPS) and an inertial measurement unit. "The truck's position and velocity are checked in real-time against the roadway's lane geometry as stored in a digital map." The accuracy of the DGPS is impressive. With the vehicle traveling at 20–35 mph, and with the GPS receiver's latency removed, the DGPS determined position displayed a mean offset error of -17.3 cm or -6.82 in. (the minus indicates the error was ahead of the vehicle's actual position).

### Benefits

Benefits for motorists using AVLN systems are reduced travel time, fuel savings, route assistance, and improved emergency assistance. It is estimated that vehicle system cost for these applications will be less than $500 when in full production, about the cost of an automobile stereo-radio system. Field tests of AVLN systems such as ADVANCE and TravTek should provide information necessary to ascertain the real benefits of AVLN.

## DATA COLLECTION FOR HIGHWAYS AND TRAVEL SURVEYS

A practical application of GPS technology for state DOTs is the identification and classification of highway inventory elements. In this role, GPS provides the means to accurately locate each element. The GPS calculated position takes the place of locating elements through the use of mile markers, which are often incorrect and subject to change.

The Virginia Transportation Research Council, a division of the Virginia DOT, undertook a development project to test the feasibility of and to develop procedures for using GPS to inventory highway elements *(24)*. A mapping-quality GPS unit was used as a datalogger for the project. Three applications from the DOT's GIS Strategic Plan were addressed. They included the identification of point data for railroad crossings, line data for Adopt-a-Highway Program links, and polygon data for wetland delineation for compliance with NEPA.

The results of the project were impressive. The accuracy of the data points whether for point, line, or polygon data were within 2 meters of their real world locations. According to the study's authors, this level of accuracy was acceptable for most of VDOT's GIS applications, but the level of accuracy was not acceptable for design projects. The general conclusion of the project was that differential GPS is a viable method to collect highway spatial data and their attributes. The project also identified problems with the use of GPS, such as the need to recollect data if the GPS receiver could not keep constant contact with a satellite because of an obstruction.

One of the most interesting applications of GPS is as a tool for collecting information about personal travel surveys. The FHWA and Battelle have employed GPS as part of a project that makes collecting data for travel surveys easier and more accurate *(21)*. The driver of a vehicle is mailed a personal digital assistant (PDA), which is placed in the vehicle. The PDA is preprogrammed with questions about who is traveling, the number of travelers, and the purpose of the trip. The driver, using a touch screen, enters data into the unit at the beginning of each trip. The PDA with its GPS unit locates the vehicle (latitude and longitude) and records the time of day.

As the vehicle begins to move, the GPS unit records the location of the vehicle at discrete time intervals and records the trip end time (Figure 25). The data from the PDA is transferred to a desktop computer that can differentially correct the raw GPS location data. According to the authors, "Absolute data locations were found to always be within approximately 150 feet left or right of the US Census Tiger file roadway center lines and often much closer" *(25)*. The differentially corrected data ranged from no error to 75 ft from the centerline.

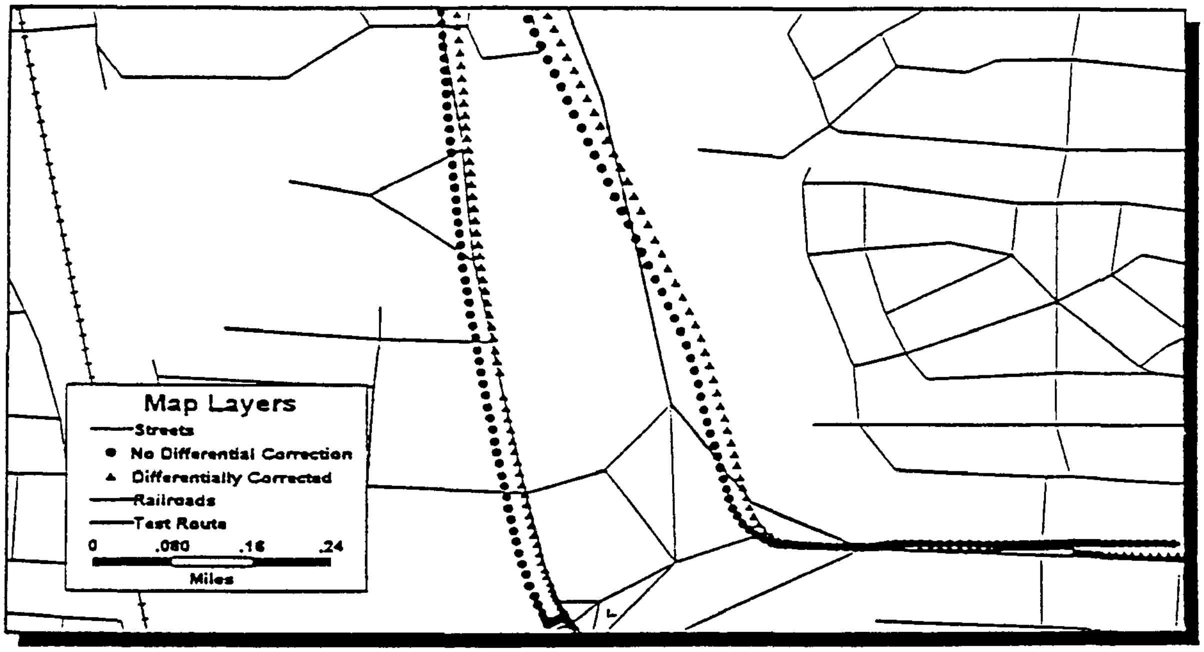


FIGURE 25 Comparison of absolute and differential GPS test data for travel surveys *(25)*.

## OTHER APPLICATIONS

### Transit Applications

Transit agencies across the United States are testing GPS for vehicle location. The ability to automatically track the location of buses and paratransit units in real-time introduces a level of scheduling flexibility that was difficult before the introduction of GPS technology.

The Caltrans Santa Clara County Smart Vehicle Program is a good example of this GPS application. The GPS location of a bus is used in combination with computerized dispatch to optimize the daily route structure of the bus system. In addition, disabled travelers can call and request service. The dispatcher can determine which bus can most efficiently pick up the rider even if it requires a route deviation. This program has increased overall system efficiency by 30 to 40 percent. It has also allowed for real-time scheduling of buses and more satisfied customers. There are similar programs at the Potomac and Rappahannock Transportation Commission in northern Virginia, as well as New York City's MTA.

### Hydrographic Applications

Another ideal GPS application is hydrographic surveying. For the most part, these surveys are done in relatively open spaces: lakes, rivers, and oceans. While there are some river and lake areas that preclude satellite tracking because of foliage or other obstructions, GPS hydrographic surveys can be successfully accomplished on the majority of these bodies of water.

Several federal and state agencies use GPS for hydrographic surveys because of its simplicity (compared to other positioning methods) and accuracy. DGPS is used as the prime positioning method for recording location/depth information and for navigating the hydrographic survey vessel over predetermined survey track lines. The 1 to 5 meters (3.2 to 16 ft) accuracy of real-time differential GPS is adequate for most hydrographic applications.

GPS positioning methods were chosen for some applications because of restricted geometry available for the range-range systems commonly employed *(26)*, or because of the difficulty and costs to set range lines using conventional terrestrial techniques.

The U.S. Army Corps of Engineers is experimenting with using real-time GPS positioning of dredging operations, and the USGS is planning GPS positioning for shoreline hydrographic surveys in association with monitoring shifting shorelines.

It is doubtful that other positioning systems can economically compete with GPS in accuracy and cost if satellite tracking is possible. GPS receivers capable of differential positioning and adequate for this application are available for less than $3,000 each, including positioning software.

### Marine Applications

GPS is being used by commercial and private marine vessels for navigation on the high seas and inland waterways *(27)*. Most promising is the combination of GPS and the emerging technology of Electronic Chart Display and Information Systems (ECDIS). This combination superimposes the ship's exact location, determined with GPS in real-time, onto a map display generated by the ECDIS *(18)*. At present, however, much of the existing mapping data base is not as accurate as the real-time positioning capabilities of GPS, which limits the full potential of the combined technologies.

The United States Coast Guard (USCG) has DGPS stations located along the U.S. coast line, the Great Lakes, and the Mississippi River that are broadcasting GPS differential corrections. The stations are part of a program for upgrading marine coastal navigation accuracies and for locating buoys *(28)*. In 1997, the US DOT proposed to expand the system for nationwide transportation applications. The stations are CORs with positional accuracy of approximately 1 meter. The Radio Technical Commission for Maritime Services, Special Committee 104, has prepared standards for transmission of these corrections, see Appendix A.

### Railroad Applications

The Burlington Northern Railroad (BN) is developing a GPS-based Advanced Railroad Electronics System (ARES). GPS data on the location and speed of all trains will feed into a command and control system for scheduling and monitoring purposes. The company believes that GPS will solve many of the problems existing with land-based navigation systems. The railroad is also using DGPS methods to map its track structure including mileposts, signal masts, switches, and road crossings with accuracies to a fraction of a meter *(29)*.

### Airborne Applications

In addition to the use of GPS in photogrammetric aircraft to establish ground control for mapping, there are several other airborne applications for GPS.

In the scientific arena, airborne GPS techniques are opening up opportunities for geophysical exploration and data gathering that have been difficult to obtain otherwise. Two specific areas are airborne gravity measurements and altimetery for terrain profiling. Airborne GPS techniques were successfully used to obtain airborne gravity, magnetic, and ice-surface profiles along 95 000 km (59,000 mi) of traverses in Greenland in the summer of 1991 *(30)*.

The Federal Aviation Administration (FAA) has approved the use of GPS for navigation within U.S. airspace. Approval includes the use of GPS for landing at 2,500 small airports not equipped with precision landing systems. Approval for precision approaches is expected in later phases of GPS implementation by the FAA *(31)*. Additional applications at airports include the control of aircraft and other vehicular ground movements, and runway incursion.

CHAPTER SEVEN

# CONCLUSIONS

Earth-orbiting satellites have been used for navigation since the early 1960s. The use of satellites for geodetic surveying purposes started with satellite doppler-positioning using the Navy TRANSIT satellite system made operational in 1964. Orbit heights for TRANSIT satellites are approximately 1000 km, and their orbital period is 107 minutes.

Geodetic use of TRANSIT is generally limited to large network development and long-baseline measurements. To attain precision levels of 1/100,000 for example, baselines on the order of 50 km or more are generally required. Application to surveys of a type useful to DOTs is limited. At least one state DOT (Texas) experimented with TRANSIT and found it lacking with regard to nominal engineering surveys. Consequently, the application of satellite surveying for DOTs really began with GPS.

Several other issues are associated with the use of GPS in state DOTs. They are presented here as a matter of information and no attempt is made to resolve them.

The legal status of GPS with regard to federal and state surveying laws is rather uncertain. State laws vary considerably when survey results are involved in legal proceedings.

Federal and most state policies on maintenance of "original" survey documents are well established; for example, the length of time that original project documents are to be kept on file is stated. Although each state is different, there are guidelines that define what original documents are and rules for maintaining them. For federal-aid projects, that time frame may be 7 years. In some states, the original document is considered to be surveyors' field notes, which record measurements at the time of the survey. One could ask the question here "what is to be considered the original document in a GPS survey?" Is it the original satellite tracking data tape or disk; the first digital file made after extracting data from the GPS receiver; or the printed results produced by a vendor's position calculation software package?

Just what are the legal liabilities of the various players in a GPS survey? Involved are: the GPS Joint Program Office, the receiver manufacturer, the developer of the calculation software, the receiver operator, the surveyor who processes the data, and perhaps the National Geodetic Survey, if their published precise orbit information and geodetic control were used.

Unlike nominal classical surveying, the original data collected in a GPS survey is essentially unseen. One legal author states that from a strictly legal viewpoint, the U.S. Government is under no legal obligation to provide GPS services to the civil user (*32*). If this is correct, then what are its real liabilities concerning GPS integrity? The same author suggests that it will be incumbent upon civil GPS users to match the capabilities and limitations of GPS against the risks associated with the activity being undertaken (*32*), in this case surveying.

In summary, it appears that GPS surveying methodology has not yet been subject to examination in the courts. In essence, there may be no real difference in the ultimate responsibilities of surveyors concerning the integrity of the surveys accomplished with GPS and those accomplished with classical methods (see Appendix B–Presidential Policy, March 29,1996).

The process of monumentation as it applies to GPS has also elicited varying opinions. The first position contends that no changes in existing monumentation guidelines are necessary. Whatever guidelines are used for conventional survey techniques apply equally to GPS methods. The other position results from increased surveying productivity and reduced costs for setting points generally associated with GPS methods. The driving force behind the controversy is the ability of GPS to set first-order survey points just about anywhere, at any time, at costs that are equal to or less than those required to install a sophisticated first-order monument. The argument revolves around geodetic control for projects rather than primary networks.

A second controversy is the need for reference point densification. GPS surveying makes network densification projects less costly while increasing accuracies. Many states, counties, and cities have embarked on large-network densification projects. The other side of the discussion asks the question, "If one surveyor with one GPS receiver can set a first-order point anywhere, at anytime, over distances of 1 to 100 km (1 to 62 mi), what is the need for densification?" The controversy hinges on the economics involved for a surveyor to tie a survey project to a certified monument. The question that arises now is, "Has GPS changed the economics involved in tying a survey to a certified monument?" Evidence to date shows that GPS has favorably changed the economics of surveying.

Another associated controversy is the practice of submitting local GPS survey data to NGS for "acceptance" and inclusion in the National Geodetic Reference System (NGRS). One school believes that with the prolific production rates capable with GPS, NGRS (and NGS) will be overburdened with coordinate information that is of interest to the local community. The other school of thought sees no reason to change the practice. As long as survey specifications for local densification (and other surveys) contain requirements for submitting data to NGS, the practice should continue.

Selective availability (SA) and anti-spoofing (AS) are not threats to normal DOT GPS survey operations; the carrier-phase differential processing techniques used by surveyors eliminates the degradation caused by SA.

SA is the name of the process employed by the Department of Defense (DoD) to deny the full accuracy of GPS to unauthorized users. Present DoD policy is that SA is in effect for all Block II satellites. The policy also states that accuracy levels for the

Standard Positioning Service (SPS) will be no worse than 100 meters 2drms (95 percent of the time). The problem is that there is no statement of accuracy on the remaining 5 percent of the time. SPS uses the C/A-code.

While SA is not a threat to DOT surveying, it is a problem with other uses of GPS for positioning purposes, such as GIS, where a single receiver is being used for position determination. Post-processed pseudorange solutions using DGPS techniques negate the SA problem. Real-time DGPS methods will also eliminate the SA effect if baselines are kept less than 200 to 300 km.

Anti-spoofing is a method employed to deny access to the P-code. The process encrypts the P-code into a new code called the Y-code. Use of the P-code for surveying is a "plus" in that improved tracking and ambiguity resolution problems can be more readily solved by tracking the P-code. AS will not affect nominal DOT surveys for baselines less than 50 km. Baselines more than 40 km long will require ionospheric correction through dual-frequency receivers. Equipment manufacturers have developed receiver technology that can overcome AS. Neither SA nor AS is any real threat to DOT GPS surveying. Differential GPS methods essentially negate SA effects in both post-processed and real-time applications.

GLONASS is the former Soviet Union's counter-part to GPS. The systems are similar in many ways, yet different enough that GPS receivers will not track GLONASS satellites. In May 1996, a GPS manufacturer offered for sale a combination GPS/GLONASS receiver. Until recently, detailed information concerning GLONASS was not freely available. Better international relations have improved the information flow from Russia; they are cooperating fully in international efforts to exchange information on the system (*33*).

The obvious benefit from joint use of GPS and GLONASS is that the number of satellites available will double. Station occupation times could be reduced significantly because of the increased number of solutions available. Another benefit is that the redundant position determination from the two independent systems can act as an integrity monitor (*33*).

The accuracy of GPS for surveying and navigation has been demonstrated. GPS requires that an adequate portion of the sky is clear of obstructions in order to track the required number of satellites. If a GPS receiver cannot "see" the required number of satellites for a minimum amount of time, it cannot provide a position solution.

For terrestrial surveys and navigation on land, there are ample opportunities for blockage of satellite signals. Even with new ambiguity-resolution techniques, where continuous lock on the satellites is not required, the receiver cannot obtain sufficient tracking data for a solution if overhead conditions preclude the receiver from "seeing" the satellites. Dense trees, overpasses, bridges, and tall buildings all contribute to the possibility of not being able to use GPS in certain areas.

Combining GPS with inertial positioning systems provides opportunities to bridge gaps in GPS positioning. A major effort to integrate GPS with inertial navigation systems is the $163 million effort by the Defense Advanced Research Projects Agency (DARPA). This effort, involving several commercial firms, has a goal of developing a small, low-cost guidance system for aircraft with a circular error of 20 meters (using GPS autonomous positioning) (*34*).

Within the past 20 years, inertial measuring units have improved considerably, using such technology as fiber optic gyros. Some new inertial navigation systems have gyro drift rates small enough to be considered for use in aiding terrestrial meter-level surveying to span GPS signal-blockage periods lasting several minutes.

Inertial units for conducting geodetic surveys have been used for several decades on special projects. Costing from $500,000 to $1 million, these systems required considerable preventive maintenance and had to be stopped each 2 to 4 minutes to conduct a zero velocity update (ZUP). The ZUP allowed the system to calibrate its accelerometers to known accelerations (namely zero). For the most part, the systems cost precluded their use by DOTs to any significant degree. However, they have been used on many surveys (even DOT work) with satisfactory results.

New gyro technology combined with more powerful field computers and improved data-filtering algorithms (Kalman filters) is producing inertial systems with gyro drift rates of 0.001 degree/hour for less than $100,000. When combined with special software, these units hold some promise of being capable of centimeter-level accuracies over short GPS signal outages (a few minutes).

The United States Geological Survey conducted an investigation (through the Applied Research Laboratories of The University of Texas) to determine the feasibility of developing a low-cost, robust, portable GPS/INS system. System specifications required accuracies suitable for meter-level surveys during GPS outages lasting several minutes. Results of the study indicate that the technology is available to meet these goals.

Considering the many signal blockage environments encountered by survey operations, it is important that DOTs be aware of the potential benefits of emerging GPS/INS technology. It is important not to confuse true inertial systems with "dead reckoning" systems also being used with GPS in a variety of navigation applications.

There is no question that, where applicable, GPS methods can significantly reduce labor and time requirements for geodetic surveying, as well as other positioning needs with less precise accuracy requirements. Although GPS equipment costs are still high when compared with the average "total station," the benefit/cost ratio for GPS is often also high.

GPS surveying is no longer a technology that needs to be "evaluated." The process has been successfully used by numerous federal and state agencies, cities, counties, and commercial and private surveying firms, on a multitude of survey project types and sizes.

Where there is an abundance of applicable survey work to be done, cost recovery on GPS hardware is rapid. In most DOTs, the cost of GPS hardware can often be recovered after just a few survey projects. The added value of the improved accuracy offered by GPS is difficult to quantify, but it is significant over the long term.

It is especially important that DOT survey managers realize that *GPS is a new surveying method, not just another surveying* *tool.* There are fundamental concepts of error sources, measures of precision, and geodesy that need to be understood by the surveyor in order to obtain maximum benefits from GPS. It is a natural tendency of surveyors new to GPS to put the technology in the same category with EDMs and total stations. The inclination to use GPS as a "super" total station has a negative effect on obtaining the productivity and accuracy increases readily available from the technology.

Because GPS surveying is a different method of surveying, it requires different project personnel planning and time frames. It is for this reason that survey managers need to know the capabilities of GPS and be prepared to implement new procedures, different project specifications, and perhaps, organizational revisions.

DOT applications for GPS in areas other than surveying are numerous and beneficial. The ability to locate and track vehicles in real-time opens up new applications in DOT maintenance and traffic operations. Submeter-level positioning offers improved spatial relationships for DOT Geographic Information Systems (GIS) data, and economical methods for determining those relationships.

GPS technology is growing and improving rapidly, and new developments promise more accuracy, in less time, at lower cost. In terms of surveying history, GPS is undoubtedly one of the most significant technological developments to influence the surveying profession for some time. It is certain that GPS will continue to have a beneficial impact on the way DOTs conduct surveys. As with most new methods, new capabilities foster new applications, and new applications reveal new needs.

If GPS is used to its potential, DOTs will possess more accurate locational data for the positioning requirements of their infrastructure inventory. In addition, they will have a more effective and efficient way to address old and new problems concerning the nation's transportation system.

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# APPENDIX A

## GPS Information Sources

This appendix contains a brief list of sources of information on GPS of interest to those who wish to learn more about GPS or to use it in practice. These sources include information on the current and future status of GPS, orbital data, publications, and training programs.

### GPS STATUS, ORBIT DATA, AND EQUIPMENT PERFORMANCE

#### CPSIC (GPS Information Center)
#### Electronic BBS and other service

Sponsored by the U.S. Coast Guard. Offers constellation status, scheduled outages, almanac data, electronic mail, downloadable files, and user advisories, DGPS, Loran-C, Omega.

**Dial in:** 300–14,400 baud: (703) 313–5910. Connect
parameters: N-8-1 Available 24 hours a day.

**Voice recording of constellation status:** (703) 313–5905.

**Radio braodcasts:** WWV minutes 14 and 15 and WWVH minutes 43 and 44, high frequency.

**For further information:** Contact the GPSIC operators.
Telephone (703) 313–5900, 14 hours a day; fax: (703) 313–5920.

#### United States Coast Guard Information on the World Wide Web

The U.S. Coast Guard's home page on the World Wide Web provides information about GPS. It includes information on standard and precise positioning services. The title is U.S. Coast Guard Maritime GPS Service. The address is http://www.navcen.uscg.mil, go to the DGPS page. The address for the correction standard is

RTCMS
1800 Diagonal Rd. Ste. 600
Alexandria, Virginia 22314

#### U.S. Naval Observatory
#### Automated Data Service (ADS)

Operated by the U.S. Naval Observatory. Offers electronic mail and downloadable files including GPS timing data and information such as constellation status, scheduled outages, user advisories, and time-transfer performance.

**Dial in:** Call for the password. Over 1200 baud: (202) 653–0155, –0068, or –1079. Connect parameters: N-8-1. Available 24 hours a day.

**Telnet:** Call for the password. TYCHO.usno.navy.mil
(192.5.41.239), log in as "ads."

**For further information about ADS or the password:** Telephone (202) 653–1525, DSN 294–1525, or e-mail (fmv@tycho.usno.navy.mil).
**For connection information:** Telephone (202) 653–0487, DSN 294–0487, or e-mail (res.@tuttle.usno.navy.mil).

This center can also be reached on the World Wide Web. Its address is: http://tycho.usno.navy.mil/

### Precise Orbital Information

Federal Government: Precise orbital positions and velocities based on post computations of tracking data collected from stations of the Cooperative International GPS Tracking Network (CIGNET) are available from the National Geodetic Survey. This information can be obtained from an NGS home page on the World Wide Web. Its address is: http:/www.ngs.noaa.gov/GPS/GPS.html

The mailing address and phone number is:

National Geodetic Information Center, N/CG17
National Geodetic Survey
National Ocean Service, NOAA
Rockville, Maryland 20852
(301) 443–8775

You can also obtain information by contacting:

GPS Test Coordinator
Instrument Subcommittee
Federal Geodetic Control Committee
c/o National Geoetic Survey, OAA
N/CG 14, Rockwall 306
Rockville, Maryland 20852
(301) 443–8171

## State DOTs

Another source of GPS information is state government. For example, in Texas the Department of Transportation maintains information on global positioning system data for users. The address of TxDOT is: http://www.dot.state.tx.us/instdot/orgchar/isd/gps/gps.htm

### Other State Agencies

In addition to state DOTs, other state agencies hold GPS information. For example, in North Carolina GPS data is provided by the North Carolina Geodetic Survey. Base station information contacts for additional information in the state can be found at the web address: ospl.state.nc.us/geodetic/

# APPENDIX B

## The White House

### Office of Science and Technology Policy

### National Security Council

EMBARGOED FOR RELEASE ON
March 29, 1996 Contact: (202) 456-6020

**FACT SHEET**
**U.S. GLOBAL POSITIONING SYSTEM POLICY**

The President has approved a comprehensive national policy on the future management and use of the U.S. Global Positioning System (GPS) and related U.S. Government augmentations. Background: The Global Positioning System (GPS) was designed as a dual-use system with the primary purpose of enhancing the effectiveness of U.S. and allied military forces. GPS provides a substantial military advantage and is now being integrated into virtually every facet of our military operations. GPS is also rapidly becoming an integral component of the emerging Global Information Infrastructure, with applications ranging from mapping and surveying to international air traffic management and global change research. The growing demand from military, civil, commercial, and scientific users has generated a U.S. commercial GPS equipment and service industry that leads the world. Augmentations to enhance basic GPS services could further expand these civil and commercial markets.

The "basic GPS" is defined as the constellation of satellites, the navigation payloads which produce the GPS signals, ground stations, data links, and associated command and control facilities which are operated and maintained by the Department of Defense; the "Standard Positioning Service" (SPS) as the civil and commercial service provided by the basic GPS; and "augmentations" as those systems based on the GPS that provide real-time accuracy greater than the SPS. This policy presents a strategic vision for the future management and use of GPS, addressing a broad range of military, civil, commercial, and scientific interests, both national and international.

#### Policy Goals

In the management and use of GPS, we seek to support and enhance our economic competitiveness and productivity while protecting U.S. national security and foreign policy interests.

#### Our goals are to:

1. Strengthen and maintain our national security.
2. Encourage acceptance and integration of GPS into peaceful civil, commercial and scientific applications worldwide.
3. Encourage private sector investment in and use of U.S. GPS technologies and services.
4. Promote safety and efficiency in transportation and other fields.
5. Promote international cooperation in using GPS for peaceful purposes.
6. Advance U.S. scientific and technical capabilities.

#### Policy Guidelines

We will operate and manage GPS in accordance with the following guidelines:

1. We will continue to provide the GPS Standard Positioning Service for peaceful civil, commercial and scientific use on a continuous, worldwide basis, free of direct user fees.
2. It is our intention to discontinue the use of GPS Selective Availability (SA) within a decade in a manner that allows adequate time and resources for our military forces to prepare fully for operations without SA. To support such a decision, affected departments and agencies will submit recommendations in accordance with the reporting requirements outlined in this policy.
3. The GPS and U.S. Government augmentations will remain responsive to the National Command Authorities.
4. We will cooperate with other governments and international organizations to ensure an appropriate balance between the requirements of international civil, commercial and scientific users and international security interests.

5. We will advocate the acceptance of GPS and U.S. Government augmentations as standards for international use.
6. To the fullest extent feasible, we will purchase commercially available GPS products and services that meet U.S. Government requirements and will not conduct activities that preclude or deter commercial GPS activities, except for national security or public safety reasons.
7. A permanent interagency GPS Executive Board, jointly chaired by the Departments of Defense and Transportation, will manage the GPS and U.S. Government augmentations. Other departments and agencies will participate as appropriate. The GPS Executive Board will consult with U.S. Government agencies, U.S. industries and foreign governments involved in navigation and positioning system research, development, operation, and use. This policy will be implemented within the overall resource and policy guidance provided by the President.

### Agency Roles and Responsibilities

*The Department of Defense will:*

1. Continue to acquire, operate, and maintain the basic GPS.
2. Maintain a Standard Positioning Service (as defined in the Federal Radionavigation Plan and the GPS Standard Positioning Service Signal Specification) that will be available on a continuous, worldwide basis.
3. Maintain a Precise Positioning Service for use by the U.S. military and other authorized users.
4. Cooperate with the Director of Central Intelligence, the Department of State and other appropriate departments and agencies to assess the national security implications of the use of GPS, its augmentations, and alternative satellite-based positioning and navigation systems.
5. Develop measures to prevent the hostile use of GPS and its augmentations to ensure that the United States retains a military advantage without unduly disrupting or degrading civilian uses.

*The Department of Transportation will:*

1. Serve as the lead agency within the U.S. Government for all Federal civil GPS matters.
2. Develop and implement U.S. Government augmentations to the basic GPS for transportation applications.
3. In cooperation with the Departments of Commerce, Defense and State, take the lead in promoting commercial applications of GPS technologies and the acceptance of GPS and U.S. Government augmentations as standards in domestic and international transportation systems.
4. In cooperation with other departments and agencies, coordinate U.S. Government-provided GPS civil augmentation systems to minimize cost and duplication of effort.

*The Department of State will:*

1. In cooperation with appropriate departments and agencies, consult with foreign governments and other international organizations to assess the feasibility of developing bilateral or multilateral guidelines on the provision and use of GPS services.
2. Coordinate the interagency review of instructions to U.S. delegations to bilateral consultations and multilateral conferences related to the planning, operation, management, and use of GPS and related augmentation systems.
3. Coordinate the interagency review of international agreements with foreign governments and international organizations concerning international use of GPS and related augmentation systems.

### Reporting Requirements

Beginning in 2000, the President will make an annual determination on continued use of GPS Selective Availability. To support this determination, the Secretary of Defense, in cooperation with the Secretary of Transportation, the Director of Central Intelligence, and heads of other appropriate departments and agencies, shall provide an assessment and recommendation on continued SA use. This recommendation shall be provided to the President through the Assistant to the President for National Security Affairs and the Assistant to the President for Science and Technology.

# ABBREVIATIONS AND ACRONYMS

ARGO—Automated Reformatter of GPS Observations
AS—Antispoofing

C/A—Course/Acquisition GPS Signal. Also called SPS
CORS—Continuously Operating Reference Station
CDU—Control Display Unit
CS—Control Segment

DOP—Dilution of Precision
DRMS—dimensional case; 2 times root mean squared
DMA—Defense Mapping Agency
DoC—Department of Commerce
DOT—Department of Transportation
DSARC—Defense Systems Acquisition Review Council

ECEF—Earth-Centered, Earth-Fixed

FANS—Future Air Navigation Systems Committee
FRP—Federal Radionavigation Plan

GDOP—Geometric Dilution of Precision
GPS—Global Positioning System

HARN—High Accuracy Reference Network
HDOP—Horizontal Dilution of Precision

ICD—Interface Control Document
IMU—Inertial Measurement Unit
INS—Inertial Navigation System
ION—Institute of Navigation

JPL—Jet Propulsion Laboratory (at Pasadena, California)
JPO—Joint Program Office for GPS (at El Segundo, California)

Km—Kilometer

L-Band—L-Band Frequency (about 1-2 GHz)
LORAN—Long Range Navigation System

MCS—Master Control Station for GPS (at Colorado Springs)

MLV—Medium Launch Vehicle
MSL—Mean Sea Level

NAD—North American Datum
NASA—National Aeronautics and Space Agency
NATO—North Atlantic Treaty Organization
nsec—nanosecond
NGS—National Geodetic Survey
NOAA—National Oceanic Atmospheric Administration

P-code—Precision code; also PPs (precise positioning service)
PDOP—Position Dilution of Precision
PPS—Precise Positioning Service
PRN—Pseudo-random Noise
PTTI—Precision Time/Time Interval

RCVR—Receiver
RF—Radio Frequency
RMS—Root Mean Square
RSPA—Research and Special Programs Administration of DOT
RSS—Root sum squared
RTCM—Radio Technical Commission for Maritime Services

SA—Selective Availability
S/N—Signal-to-Noise (ratio)
SEP—Spherical Error Probable
sigma—Standard deviation
SPS—Standard Positioning Service. Also called C/A-Code
SV—Space Vehicle

USNO—U.S. Naval Observatory (at Washington, DC)
UTC—Universal Coordinated Time

VDOP—Vertical Dilution of Precision
VLBI—Very Long Baseline Inteferonmetry

WGS—World Geodetic System
w.r.t. —With respect to

YPG—Yuma Proving Ground

# GLOSSARY OF GPS TERMINOLOGY

The revolution in surveying due to the implementation of the Global Positioning System has greatly increased the vocabulary associated with geodetic positioning, engineering surveying, and land surveying. Information for this glossary was excerpted from various references including *Guide to GPS Positioning. Procedures and Specifications for Urban GPS Surveys,* and the National Geodetic Survey's *Geodetic Glossary.*

**Almanac**—Information for multiple, GPS satellites that describes each satellite's position for any epoch. The information, which is usually of low accuracy, is used to aid initial lock onto the satellite signals and to generate tables of satellite positions above the observer's location. The tables aid in planning and satellite selection.

**Ambiguity**—See Carrier-phase ambiguity

**Antispoofing**—Making the P-codes available only to authorized military users. Users must possess a decryption device in order to lock onto the P-codes. The P-code is also referred to as the Y-code.

**Bandwidth**—A measure of the width of the spectrum of a signal (frequency domain representation of a signal) expressed in Hertz.

**Base Line**—A base line consists of a pair of stations for which simultaneous GPS data has been collected, enabling direct determinations of three-dimensional position differences.

**Between-epoch difference**—The difference between two complete carrier-phase measurements made by the same receiver on the same signal (same satellite, same frequency), but at different time epochs.

**Between-frequency difference**—The instantaneous difference between (or, more generally, any other linear combination involving) the complete carrier-phase measurements made by the same receiver observing signals from the same satellite at two (or more) different frequencies.

**Between-receiver difference**—The instantaneous difference in the complete carrier-phase measurement made at two receivers simultaneously observing the same received signal (same satellite, same frequency).

**Block I satellites**—The prototype or experimental satellites deployed beginning in 1978. Eleven launches were attempted; seven satellites were placed in two orbital planes inclined 63° to the equator.

**Block II satellites**—This is the operational system of 24 satellites in six orbital planes inclined 55° to the equator, in near circular orbit approximately 20 000 kilometers (12,000 miles) with an orbital period of 12 hours.

**Broadcast message**—Information modulated onto the carrier frequency. This information includes satellite health, clock accuracy and corrections, the almanac for all satellites, detailed orbit parameters for the source satellite, as well as special messages.

**Carrier**—A radio wave having at least one characteristic (e.g., frequency, amplitude, and phase) which may be varied from a known reference value of a radio transmitter.

**Carrier frequency**— The frequency of the unmodulated fundamental output of a radio transmitter.

**Carrier-phase ambiguity**—Uncertainty in the initial number of measurement waves transmitted from the satellite to the receiver, which biases all measurements in an unbroken sequence. An integer cycle bias in the initial measurement.

**Carrier-phase measurement**—The measurement of the change of phase of an observed electromagnetic signal (the carrier frequency), with time, relative to the phase of a GPS receiver's reference frequency.

**C/A code**—Also referred to as the standard positioning service (SPS), the standard (Course/Acquisition, or Clear/Access) GPS code is a sequence of 1,023 pseudo-random binary biphase transitions on the GPS carrier at a chip rate of 1.023 MHz, thus having a code repetition period of one millisecond. The C/A code is intended for general use and is capable of providing instantaneous point position (navigation) accuracy at the 100- to 300-m level.

**Code receiver**—A receiver that uses correlation methods to generate a modulation-free replica of the satellite carrier. Once the modulation is removed, carrier phase measurements can be made.

**Codeless receiver**—A receiver that does not require the ability to decipher the coded signal modulated onto the carrier signal. By use of the so-called "squaring technique," the modulated code and message information are removed and then phase measurements can be made.

**Confidence level**—A statistical probability level beyond which a particular observation should be rejected as an outlier.

**Coverage window**—The period of time during which GPS satellites are above the horizon and "visible" to the observer.

**Correlation-type channel**—A GPS receiver channel that uses a delay lock loop to maintain an alignment (correlation peak) between the replica of the GPS code generated in the receiver and the incoming signal.

**Cycle slip**—A cycle slip is a discontinuity of an integer number of cycles in the measured carrier phase resulting from a momentary loss-of-lock in the carrier tracking loop of a GPS receiver.

**Differenced carrier-phase measurements**—See Between-epoch, Between-frequency, and Between-receiver differenced carrier-phase measurements.

**Doppler shift**—The change in frequency of a received signal proportional to the rate of change of the range between the transmitter and receiver.

**Ellipsoidal height (h)**—The geometric height of a surface point above a referenced ellipsoid.

**Ephemeris**—Predicted or precise information that describes each satellite's position for any epoch. GPS ephemerides (information for multiple satellites) can be used for receiver point position determination or for relative positioning determinations from simultaneous observations. Almanacs can be created for use in software to generate satellite availability tables used for planning and satellite selection.

**FGCC**—Federal Geodetic Control Committee, which is made up of representatives from various parts of the federal government that are involved in conducting or the applications of the national geodetic reference system. The Instrument Subcommittee of the FGCC conducts instrument tests on GPS survey systems.

**Fiducial station**—A fiducial station is one of the several stations in a regional, continental, or global network that are designated to be used as a master or monitor station. A monitor station may be continuously occupied throughout several observing sessions. It may be occupied indefinitely if the tracking data are part of a global data set used for the precise orbit determination (ephemeris).

**Geoid**—The equipotential surface of the earth's gravity field, which closely approximates, in the least squares sense, mean sea level. The mass excesses and deficiencies of earth cause the shape to be irregular.

**Geoidal undulation (N)**—The difference between the surface of reference ellipsoid and the geoid. If the geoidal surface is below the ellipsoidal surface as found in the NAD 83 system within continental U.S., the undulation value for N is negative.

**GRS 80**—Geodetic Reference System 1980, the reference ellipsoid adopted in 1980 as the best fitting for an earth-centered earth-fixed (ECEF) coordinate system. This ellipsoid is used for the NAD 83 coordinate system.

**Health word**—Inserted into the satellite message, the health word describes the health status of each individual satellite.

**Independent base lines**—A base line derived from simultaneous observations at two points, when both sets of observations have not already been used in the formation of other base lines from the same session. These are also called non-trivial base lines. Base lines determined from sets of observations used in other determinations are dependent or trivial.

**Independent observing sessions**—Observing sessions for which all random errors and some systematic errors are not common.

**Ionospheric refraction**—A signal traveling through the ionosphere (which is a nonhomogeneous and dispersive medium) experiences a propagation time different from that which would occur in a vacuum. Phase advance depends on electron content and affects carrier signals. Group delay depends on dispersion in the ionosphere as well, and affects signal modulation (codes). The phase and group advanced are of the same magnitude but opposite sign.

**Kinematic surveying**—Kinematic surveying refers to moving the antenna while maintaining continuous lock on the satellite signals. Instantaneous positions are determined while the antenna is continually moving (such as on a ship, airplane, or moving ground vehicle). This is comparable to a navigation mode. When performed on land, the practice is to stop at points for a very short period (seconds to minutes) where the antenna is fixed, this may be called pseudo- or semi-kinematic. If data collected with the roving receiver is simultaneous with data collected at static locations, then kinematic relative positions can be determined.

**L-band**—The radio frequency band extending from 390 MHz to (nominally) 1550 MHz.

**Monitor station**—See Fiducial station.

**Multipath error**—A positional error resulting from the interference of radio waves that have traveled between the transmitter and the receiver by two paths of different electrical lengths.

**NAVSTAR**—NAVigation Satellite Time And Ranging.

**Non-Trivial base lines**—See Independent base lines

**Observing session**—The period of time during which GPS observations are collected simultaneously by two or more receivers.

**P-code**—The Precise (or Protected) GPS code, a very long (about 10 bit) sequence of pseudo-random binary biphase modulation on the GPS carrier at a chip rate of 10.23 MHz that does not repeat itself for about 267 days. Each one-week segment of the P-code is unique to one GPS satellite and is rested each week. The P-code is capable of providing instantaneous point position (navigation) accuracies at the 55- to 10-m level. The P-code is not available to the general public. It is an encrypted code developed for the U.S. Department of Defense.

**Point positioning**—A position determined from observations of a single receiver.

**Precise positioning service (PPS)**—The highest level of dynamic positioning accuracy that will be provided by GPS, based on the dual frequency P-code.

**Pseudorange**—The time shift required to align (correlate) a replica of the GPS code generated in the receiver with the received GPS code, scaled into distance by the speed of light. This time shift is the difference between the time of signal reception (measured in the receiver time frame) and the time of emission (measured in the satellite time frame). This time shift is converted to a range distance.

**Phase observable**—See Carrier-phase measurements.

**Relative positioning**—The determination of three-dimensional coordinate differences between two or more receiver/antenna stations that are simultaneously tracking the same GPS radio signals.

**S-code**—See C/A-code.

**Satellite configuration**—The geometric relationship of the satellite constellation at a specific time, relative to the site location of a specific observer or set of observers.

**Satellite constellation**—The arrangement in space of the complete set of satellites of a system like GPS.

**Satellite message**—Information contained in the modulated GPS L-band carriers that includes an almanac, predicted ephemeris, satellite health status, and timing information.

**Selective availability**—An intentional degradation of the full C/A code capability. When SA is turned on, it degrades the C/A codes positioning capability. Many civil applications eliminate this degradation by relative positioning of multiple receivers and making liberal use of carrier-phase observations.

**Simultaneous measurements**—Measurements referred to time frame epochs that are either exactly equal or so closely spaced in time that the time misalignment can be accommodated by correction terms in the observation equation, rather than by parameter estimation.

**Standard positioning service (SPS)**—The level of "point" positioning or navigation accuracy that will be provided by GPS based on the use of the single frequency C/A-code.

**Static positioning (surveying)**—Collecting data continuously for same span of time while the antenna is not moving. These data are processed for a point position determination and when simultaneous with observations collected at other stations, relative positions can be determined.

**Trivial base lines**—A base line derived from simultaneous observations at two points, when both sets of observations have already been used in the formation of other base lines from the same observing session. See Independent base lines.

**WGS 84**—World Geodetic System of 1984.

**Window of availability**—See Coverage window.

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