



# Applied GPS for Engineers and Project Managers

Clement A. Ogaja, Ph.D., L.S.



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# **Applied GPS for Engineers and Project Managers**

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*I lift my eyes to the Maker  
Of the mountains I cannot climb,  
To my Parents for their teachings and bringing me into this earth,  
To a researcher who fortified a belief in myself: Chris Rizos,  
To engineers for their efforts to improve quality of life*

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# Preface

Global positioning systems (GPS) technology is an indispensable tool in every sector of the world economy. Although it is primarily a military system, GPS users have developed the technology capable of meeting requirements for countless numbers of civilian applications. In the field of engineering, many successful projects have utilized GPS to overcome challenges. Although many GPS-related research projects have been done in the past, to my knowledge this book is the first to examine the subject of GPS application to engineering and project management. The book is aimed at researchers, students, instructors, engineers, and project managers who have an interest in understanding how GPS technology works in the context of engineering and project management.

Consider a project in which a local firm is interested in tracking the thousands of steel brackets they use to ship glass material to customers across the entire state of California. The brackets are for temporary use in the shipping process, and the customers are expected to return them in a timely manner. The firm is a local distributor for glass materials manufactured in China. On a yearly basis they ship glass to more than half a million customers at construction sites spread across the entire state. The firm is experiencing repeated loss of thousands of their steel brackets due to, for instance, customers shipping them back to the wrong distributors. Part of the problem is that when the material is shipped to customers, some of the steel brackets sit in their warehouses for weeks, months, or years. The firm is now thinking of tracking the steel brackets to determine their whereabouts at any given time. As part of the project, the firm is interested in being able to remotely display, on a digital map, the location of every steel bracket that leaves its local distributing center.

One day, while pondering this problem, a colleague mentions to the manager how GPS was used in a project addressing material loss and theft at a construction site. According to the colleague, GPS was inexpensive, easy to use, and provided very accurate results. GPS seems perfect for this project, so the manager decides to sample information from a few GPS vendors. If several small GPS receivers are bought and carefully installed onto or inside the steel bracket frames, the manager thinks, they could be used to obtain coordinates for the location of every steel bracket dispatched to a customer. A concealed GPS tracking system would be

perfect, but the manager soon discovers that only the GPS processing engine can be concealed inside objects—a GPS antenna must be exposed to receive signals from satellites. Additionally, the manager discovers that although GPS signals can pass through glass, unaided GPS cannot work inside buildings, tunnels, or underground. Given these problems, the manager is told, it may not be possible to determine the location of the steel brackets at all times. It is doubtful whether GPS alone can solve the problem.

The above scenario, while fictional, is loosely based on the elements of actual projects. It serves to illustrate the potential benefits as well as weaknesses of GPS. This book is written to help users maximize those benefits while avoiding the pitfalls. GPS is a deceptively simple technology: the receiver can be as small as a cell phone, can cost less than \$100, and can provide coordinates that are accurate to within 10 m with the press of a few buttons. Or they can be robust, cost thousands of dollars, and provide coordinates to within centimeters or even millimeters. As with any tool used in projects, there must be careful planning and wise considerations to avoid wasting money and effort.

One of the purposes of this book is to provide guidance to engineers and project managers who wish to incorporate GPS into their projects or research, regardless of their past experience with the technology. While there is not a one-size-fits-all approach to using GPS, certain key concepts and methods are common to any project. Using GPS in a project requires more than just getting a GPS receiver, turning it on, and pushing a few buttons. Decisions must be made about the level of accuracy required to address the project or research problem. For example, is 1-cm accuracy needed or is 1-m accuracy sufficient? How will the data be collected and analyzed or displayed? Is a 10-Hz data logging rate needed or is 1-Hz sufficient? These are just some of the questions to be addressed in an engineering perspective. The answer will influence the types of receivers purchased, the data collection and management approach, as well as the GPS error correction methods applied. There is great value in asking these questions and important lessons to take away from this book.

The book has eight chapters divided into two distinct parts: *Part I—Basics of GPS* and *Part II—Applications in Engineering and Megaprojects*. Part I consists of the first five chapters, describing the basics of GPS technology. Part II presents some application examples of GPS in engineering and megaprojects. The topics are designed to address the technology in an engineering context, describing:

- The basics of how GPS works and what the technology offers to engineers and project managers
- Basic positioning and measuring principles
- Strategies and methods used to improve the measurement accuracy
- Low-cost GPS systems and existing infrastructure
- High-precision GPS systems and existing infrastructure
- GPS sensor technology, opportunities, and challenges
- Considerations in developing a GPS application
- Application examples in engineering and megaprojects

- The future aspects of GPS technology in light of emerging similar technologies and systems worldwide.

While many of the illustrations were prepared by the author, many others have been used with permission from various copyright holders. I would like to acknowledge the original authors of such artwork. On the same note, I especially thank the following individuals whose artworks were freely available for reproduction: Joseph Priestner of LandMarker Geospatial, Oscar L. Colombo of the University of Maryland and the NASA Goddard Space Flight Center, Sharon Kedar of the NASA Jet Propulsion Laboratory, Dr. Tracy L. Kijewski-Correa of the University of Notre Dame, and Yehuda Bock of the Scripps Orbit and Permanent Array Center (SOPAC). The following institutions are also acknowledged for some of the illustrations and photographs: U.S. Air Force, UNAVCO, National Oceanic and Atmospheric Administration (NOAA), European Space Agency (ESA), *Inside GNSS* magazine, u-blox, Trimble Navigation, Leica Geosystems, and Garmin.

I sincerely thank the American Society of Civil Engineers (ASCE) for publishing this book, and Betsy Kulamer of ASCE Press for overseeing all the editorial and technical reviews. The comments from reviewers improved both the proposal and the manuscript. To my wife Julie, daughter Alicia, and son Joshua, thank you for your support in this endeavor.

Lastly, it is important to note that the inclusion by name of a company or a product is not an endorsement by the author. In principle, such inclusions are necessary at times because some items have specific characteristics that help to explain the topic being addressed.

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## PART 1

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# Basics of GPS

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# Introduction

## GPS: The System

In order to incorporate global positioning systems (GPS) into a project, it is important to understand the workings of the system. Even though GPS receivers are usually quite simple to operate, there is much going on behind the scenes. A basic understanding of how the system works, the individual components, and how they interact to calculate a position can be very valuable.

A position is generally described in terms of coordinates in one-dimensional (1-D), two-dimensional (2-D), or three-dimensional (3-D) space. For instance, the common Cartesian coordinate system nomenclature for 3-D is X-Y-Z.

The essence of calculating a position is to be able to answer the question “Where am I?” People have always been on the move and are always looking for a better way to get to where they are going. A traveler without a map is just a wanderer but, even with a map, where landmarks are scarce—on plains, in deserts, on oceans, in space—the traveler needs a means of navigation, a method for determining position, course, and distance.

History is marked by incremental improvements in mapping and navigation. With each improvement, people have traveled farther, faster, and with greater confidence. The pace of improvement in transportation and navigation accelerated exponentially during the last century. We have left footprints on the moon and we have landed robotic explorers on Mars. We make routine missions into space, and the presence of satellites orbiting around the Earth has become part of our everyday reality. One of the more remarkable benefits of our ability to send satellites into orbit is a new power to navigate with incredible precision. This new navigational ability is due to GPS, a system developed by the U.S. Department of Defense.

GPS was originally designed to provide navigation information for ships and planes, but with advances in miniaturization and integrated circuits, GPS receivers have become more economical and more widely applied. Today, GPS technology is installed in many cars, boats, and small planes as well as on construction and farm equipment. Portable, handheld GPS receivers have become widely accessible and are making all kinds of work more efficient, and helping to ensure the safety of people who work outdoors.



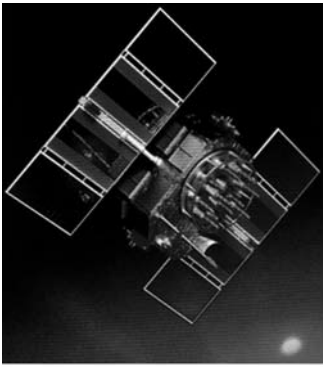
## History

GPS, officially named NAVSTAR GPS (NAVigation Satellite Timing And Ranging Global Positioning System), is managed by the NAVSTAR GPS Joint Program Office at the Air Force Materiel Command's Space and Missile Systems Center at Los Angeles Air Force Base, California. The GPS satellite network is operated by the U.S. Air Force to provide highly accurate navigation information to military forces around the world, although 90% of worldwide GPS users are civilian users, with a growing number of commercial products. Since the first launch in 1978, there have been four generations of GPS satellites:

- **Block I** satellites (1978–1985) were used to test the principles of the system, and lessons learned from the first 11 satellites were incorporated into later blocks.
- **Block II and IIA** satellites (1989–1997) made up the first fully operational constellation and majority of them are still in operation, exceeding their design life.
- **Block IIR** satellites (1997–2007) were deployed as replenishment as the Block II/IIA satellites reached their end-of-life and were being retired. **Block IIR-M** satellites (2005–2008) carried some new and different signals augmenting the older signals.
- **Block IIF** satellites (2010–2012) are the fourth-generation satellites and will be used for operations and maintenance (O&M) replenishment.
- **Block III** satellites are planned to be the fifth-generation satellites, with capacities beyond those of Block IIF satellites.

The very first satellites, the Block I (1978–1985) satellites, were retired in late 1995. Block II satellites were launched in 1989 and, although the expected mean mission duration (MMD) was 10.6 years, it is remarkable that the majority of them were operating in orbit and still healthy as of 2010. There are also upgraded Block II satellites, known as Block IIA, the first of which was launched in 1990. Block IIA satellites can function continuously for 6 months without intervention from the Control Segment (described in “Control Segment” below), but the broadcast ephemeris and clock correction would degrade if that were done.

Like Block I satellites, Block II satellites were equipped with rubidium and cesium frequency standards. The next generation of satellites after Block II satellites were the Block IIR satellites (the R is for replenishment). The first of these was launched in 1997 and the launches continued through 2007 (Figs. 1-1 and 1-2). There are some notable differences between Block II and Block IIR satellites. For instance, Block IIR satellites can determine their own position using intersatellite crosslink ranging called AutoNav. They have onboard processors to do their own fixes in flight, and the Control Segment can change their flight software while in orbit. Furthermore, Block IIR satellites can be moved into new orbits with a 60-day advance notice. Block IIR-M satellites brought significant improvements, with some new and different signals that augmented the older reliable signals. The first



GPS IIA Satellite



GPS IIR-M Satellite



GPS IIF Satellite

**Figure 1-1.** GPS NAVSTAR satellites.

Courtesy U.S. Air Force (2010).

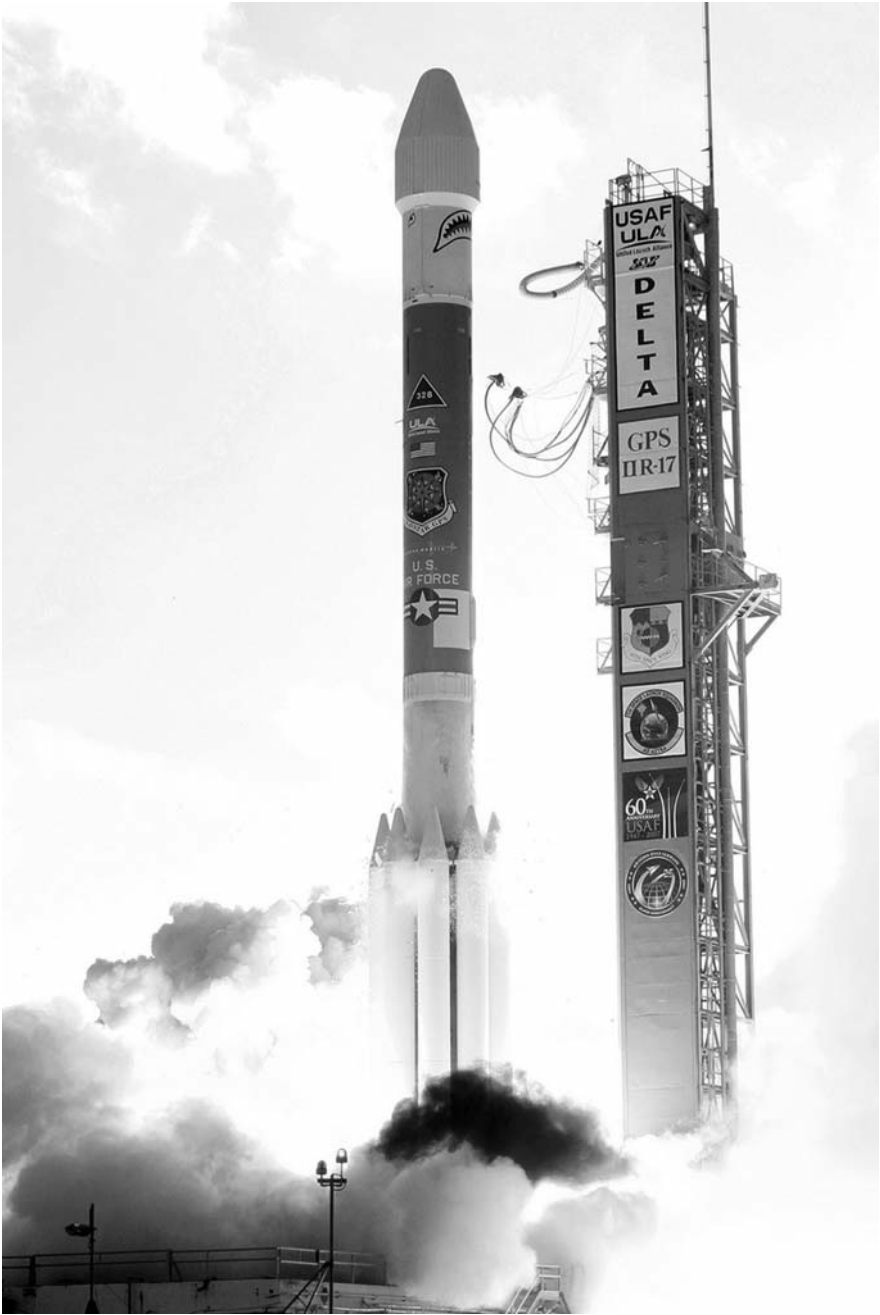
Block IIR-M satellite was launched in 2005. These satellites had increased L-band power on both L1 and L2 and also broadcast new signals such as L2C and M-code. The fourth-generation satellites, Block IIF (the F is for follow-on), are planned to have an expected lifetime of 12 to 15 years with faster processors and more memory onboard. They will carry two rubidium frequency standards and one cesium. Like Block IIR satellites, they can be reprogrammed while in orbit. They will give civilians direct access to three separate signals: C/A (Coarse/Acquisition) code on L1, L2C on L2, and L5 code on L5. Block III satellites will have the capabilities of Block IIF and beyond. For example, they will include an enhanced new civilian code L1C, carried on the L1 frequency. Information about the current GPS constellation can be found at the website of the United States Naval Observatory (USNO) at <http://tycho.usno.navy.mil/gpscurre.html>.

### **Three Components of GPS**

The GPS system is made up of three components: the *space segment*—the satellites orbiting the Earth; the *control segment*—the infrastructure monitoring and operating the satellites; and the *user segment*—all users of the GPS signals broadcast by the spaceborne satellites. Figure 1-3 illustrates how these individual components interact to enable the users to calculate their position anywhere on Earth or in space.

#### **Space Segment**

The space segment is a network of spaceborne satellites orbiting the Earth in equally spaced, predictable orbits at an altitude of approximately 20,200 km (12,550 mi.). Orbits at this altitude are referred to as MEOs—medium Earth orbits. In comparison, geostationary satellites orbit the Earth at much higher altitudes, about twice that of GPS satellites.



**Figure 1-2.** Lifting toward space aboard a Delta II rocket, the fourth modernized GPS IIR-17(M) satellite blasts off from Cape Canaveral, October 17, 2007. The satellite joined the constellation of 30 operational GPS satellites on-orbit providing global coverage and increased overall performance of the GPS services to users worldwide.

Courtesy U.S. Air Force.

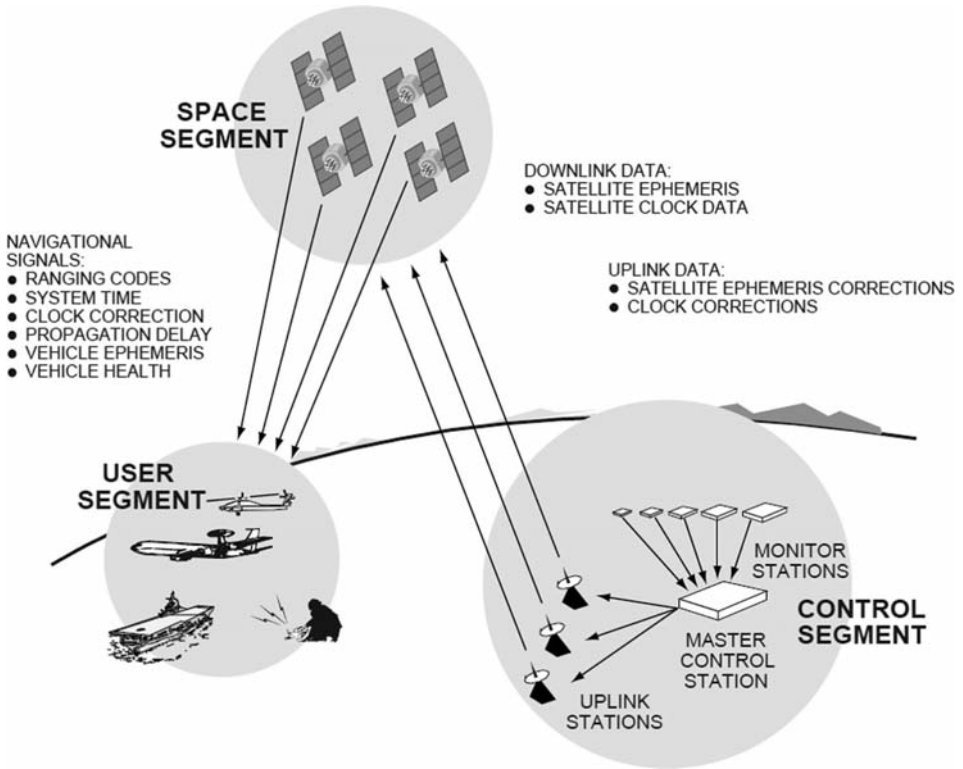


Figure 1-3. Three components of the GPS system.

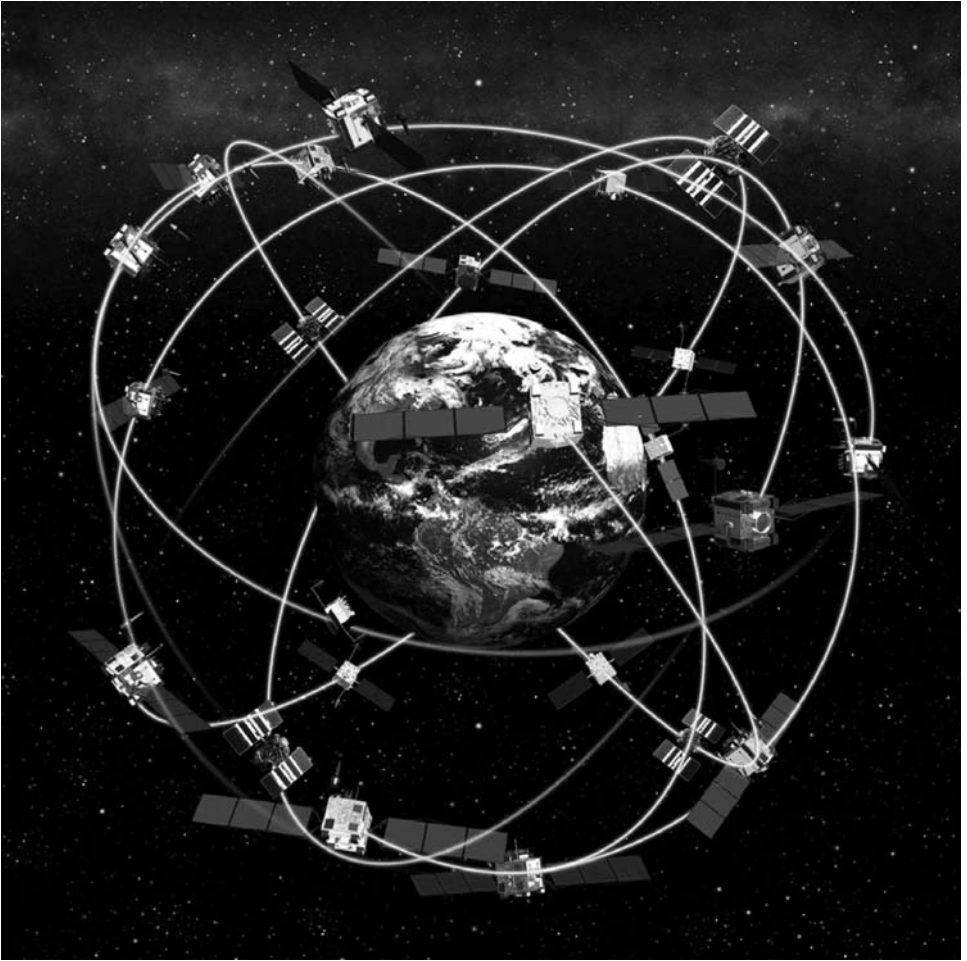
The constellation of GPS orbits (Fig. 1-4) was designed so that at least four satellites are visible anywhere on Earth at any time. Each satellite broadcasts radio signals that receivers can use to calculate a position. Information on satellite health, satellite position, and data that can be used to determine the satellite time are all transmitted via these signals.

The satellites orbit the Earth at a speed of 3.9 km/sec (2.4 mi./sec) and have a circulation time of 12 h sidereal time, corresponding to 11 hours 58 min. Earth (solar) time. This means that the same satellite reaches a certain position about 4 min. earlier each day.

The satellites are arranged on six orbital planes, each of them containing at least four slots where satellites can be arranged equidistantly. The inclination angle of the planes toward the equator is 55 deg and the planes are rotated in the equatorial plane by 60 deg against each other. Typically, more than 24 satellites orbit the Earth, improving the availability of the system.

**Control Segment**

The integrity of the GPS system relies on the satellites precisely maintaining their orbit. It is imperative that the satellite positions in space be monitored. This is the responsibility of the Master Control Station (MCS) in Colorado Springs, Colorado.



**Figure 1-4.** The GPS satellite constellation consists of satellites orbiting 20,200 km (12,550 mi.) above the Earth in orbital planes designed to keep at least four satellites above the horizon anywhere on the planet.

The MCS and 10 additional “passive” monitoring stations around the world monitor the position of the satellites in their orbits, the health of each satellite, and the signals they transmit. With this arrangement, every satellite can be seen from at least two monitor stations. In the near future, more stations will be added so that every satellite can be seen by at least three monitor stations. This allows the calculation of precise orbits and ephemeris data. The MCS is operated by the U.S. Air Force 24 hours a day to ensure the system functions properly.

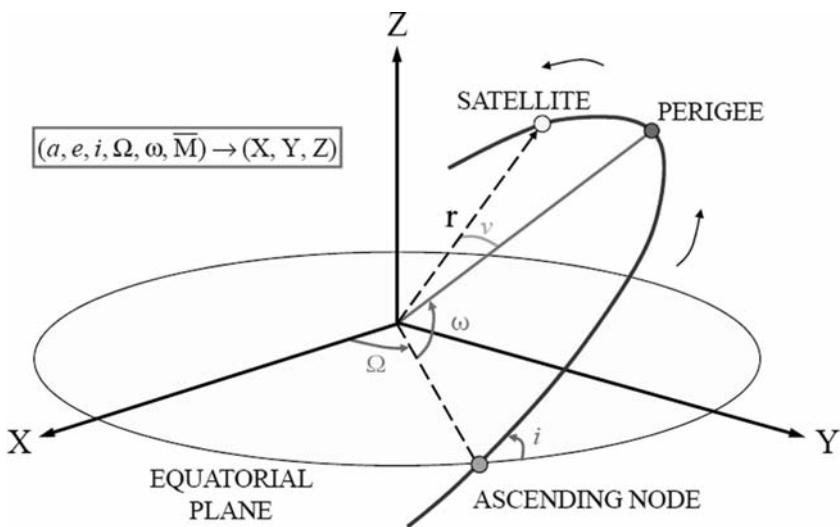
The passive monitor stations track all satellites in their respective ranges and collect data of the satellite signals. The raw data are sent to the MCS where they are processed, and new information about orbits, ephemeris, and the satellite clocks are calculated. Personnel at the MCS upload new time and orbital data to

each satellite on a regular basis. Once or twice a day these data and other commands are sent back to the satellites via the transmitting antennas on Ascension Island (in the south Atlantic, off the coast of Africa), Diego Garcia (in the central Indian Ocean), or Kwajalein (in the mid-Pacific) by means of an S-band signal (S-band: 2,000–4,000 MHz). Included in the transmission is an *almanac*, which contains satellite orbital positions, satellite status, clock corrections, and atmospheric delay parameters. Also included in the uploaded information are *ephemeris* data, which contain the predicted positions of satellites. The almanac and ephemeris data reduce the signal error by resetting the errors in time and position that have gradually accumulated since the last update.

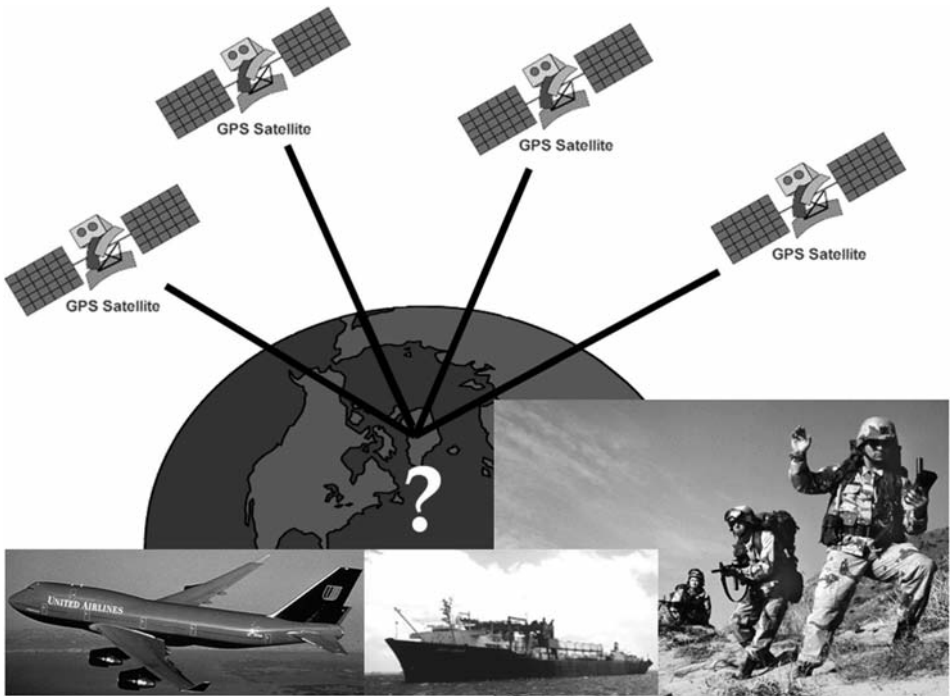
The ephemeris information is uploaded to the satellite in a compact format using Keplerian elements (Fig. 1-5). This simplifies the process of predicting the satellite orbits. For instance, given time information and the Keplerian elements for any satellite, its time-dependent positions can be predicted in an X-Y-Z coordinate format (refer to Appendix 3). Knowing these time-dependent X-Y-Z positions of every satellite is an important part of calculating a position for the user located anywhere on Earth or in space.

### User Segment

The third segment is made up of the users of the GPS signals. Anywhere on Earth or in space, a GPS receiver calculates its position by solving a set of equations based on the distance between it and three or more satellites (Fig. 1-6). This



**Figure 1-5.** Keplerian elements for predicting the satellite position in space. These elements (for each satellite) are contained in the ephemeris which are part of the uplink and downlink data as shown in Fig. 1-3. X, Y, Z are the satellite Cartesian coordinates and the rest of the symbols are defined in Appendix 3.



**Figure 1-6.** The GPS user segment includes all users interested in calculating their positions using the broadcast GPS signals.

calculation is known as *trilateration*, a centuries-old surveying technique literally taken to new heights. Location is determined by measuring the travel time of radio signals from the available satellites. Reference to at least three satellites is required for accurate horizontal location, and to at least four for accurate horizontal and vertical location. The more satellites that are used for the calculation, the more accurately a location can be pinpointed. More precise determination of position and added integrity can be achieved by using additional signals from regional ground-based and satellite-based augmentation systems (GBAS and SBAS, respectively). The Wide Area Augmentation System (WAAS) of the U.S. Federal Aviation Administration is an SBAS example. These and other methods for improving accuracy as required in high-precision engineering will be discussed in later chapters of the book.

In addition to engineers, the aviation, transportation, and agriculture industries, mass-market consumers, the public service sector, and many others rely on the system. Irrespective of the application, all GPS users apply the ephemeris and almanacs transmitted by the satellites to derive new information: time, position, and/or velocity. This information allows users to answer such basic questions as “Where am I?” and “What time is it?” with a level of accuracy unthinkable prior to GPS. This has led to some innovative uses of GPS.

## How It Works

Given the complicated and expensive technology involved, the principles behind the GPS system are amazingly simple. The basic principle relies on the equation  $Distance = Speed \times Time$ . By knowing how fast something is traveling and how long it takes to travel, the distance traveled can be calculated. In the case of GPS, the object being timed from the satellite in space to the user is a radio signal, which travels at the speed of light. The process is called *ranging*; by receiving multiple radio signals from multiple satellites, it's then only a matter of geometry—*trilateration* is used to determine the exact position of the user.

Consider, for instance, that you can measure how far away a lightning strike is by counting the seconds between seeing the flash and hearing the boom, and multiplying by the speed of light to obtain the distance. The instant of the lighting flash is when the sound waves started. But for GPS, how can we know when the timing signal set off? The solution is to include with the radio signal exact information on the instant when the signal was transmitted. Time of receipt minus time of arrival then enables the distance to be easily calculated (see details in Chapter 2, “Ranging Methods”). The locations of the satellites are known extremely precisely (to centimeter accuracy) and the receivers have a built-in almanac that contains the theoretical positions of each satellite. Corrections to these positions are also transmitted by each satellite so that the absolute receiver positions can be precisely calculated.

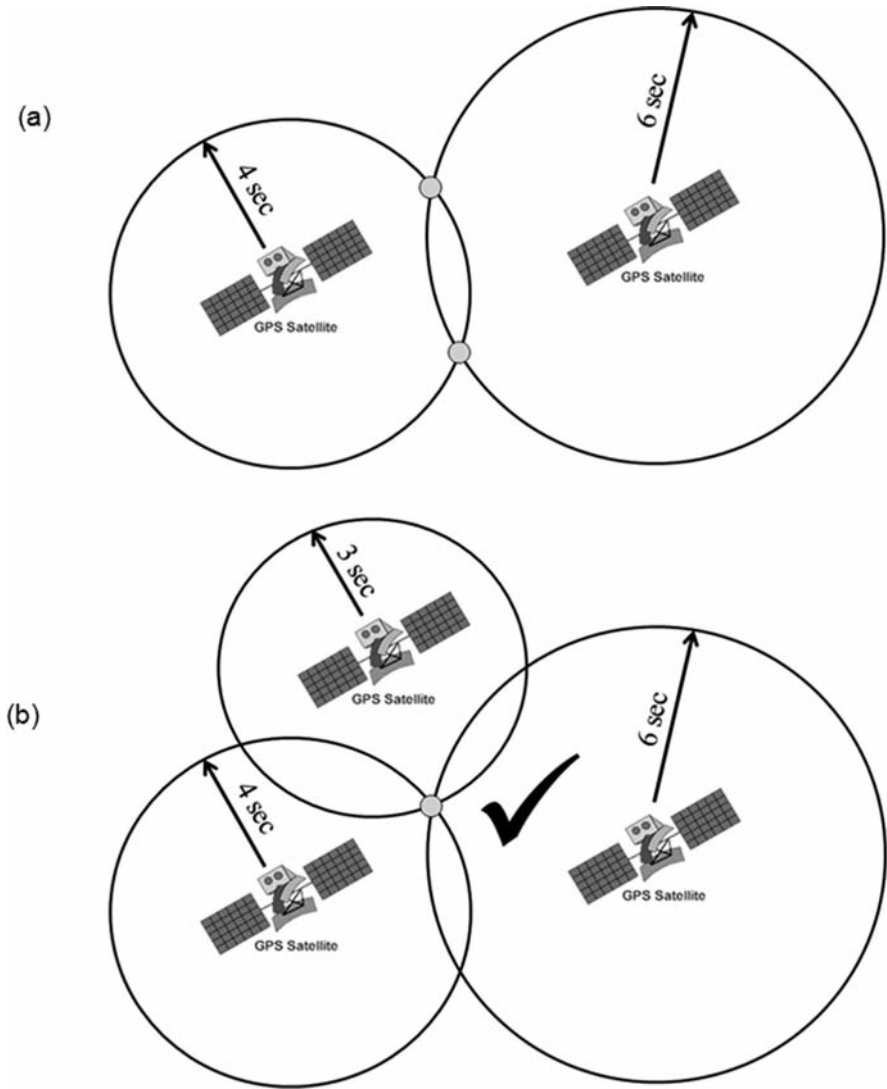
## Perfect Timing

The satellites and receivers have clocks installed that are designed to be in synchronization for the perfect timing of the radio signals. However, each satellite has atomic clocks (four of them for redundancy) whereas receivers have ordinary clocks; otherwise they would cost more than US\$200,000 apiece. How then do we know that the satellite and receiver are actually on the same time? At the speed of light, it takes about 0.07 sec for the GPS signal to arrive at the receiver, and an error of 0.01 sec leads to an error of 2,993 km (1,860 mi.)!

Timing errors mean incorrect ranges, which lead to an incorrect receiver position. To illustrate this, here is a simplified description of calculating a position. If we are lost and we know that we are 4 sec away from one of the satellites, we are somewhere on a circle the center of which is the satellite and the radius is 4 sec (Fig. 1-7a). If we also know that we are 6 sec from another satellite, we can narrow down where we must be—at one of two points where the circles intersect. If we also know that we are 3 sec away from a third satellite, our situation improves immensely—the only place we can be is the point at which all three circles intersect (Fig. 1-7b). But this is only possible if both the satellite and receiver clocks are correct and perfectly synchronized. This is not always the case! Each satellite contains atomic clocks accurate to within a nanosecond, and the receiver contains ordinary clocks that are consistently accurate over relatively short periods of time, as long as they are reset often.

If the receiver clock is off by, for example, 1 sec, incorrect ranges from incorrect timing would not intersect at a single point (Fig. 1-8). The receiver position is

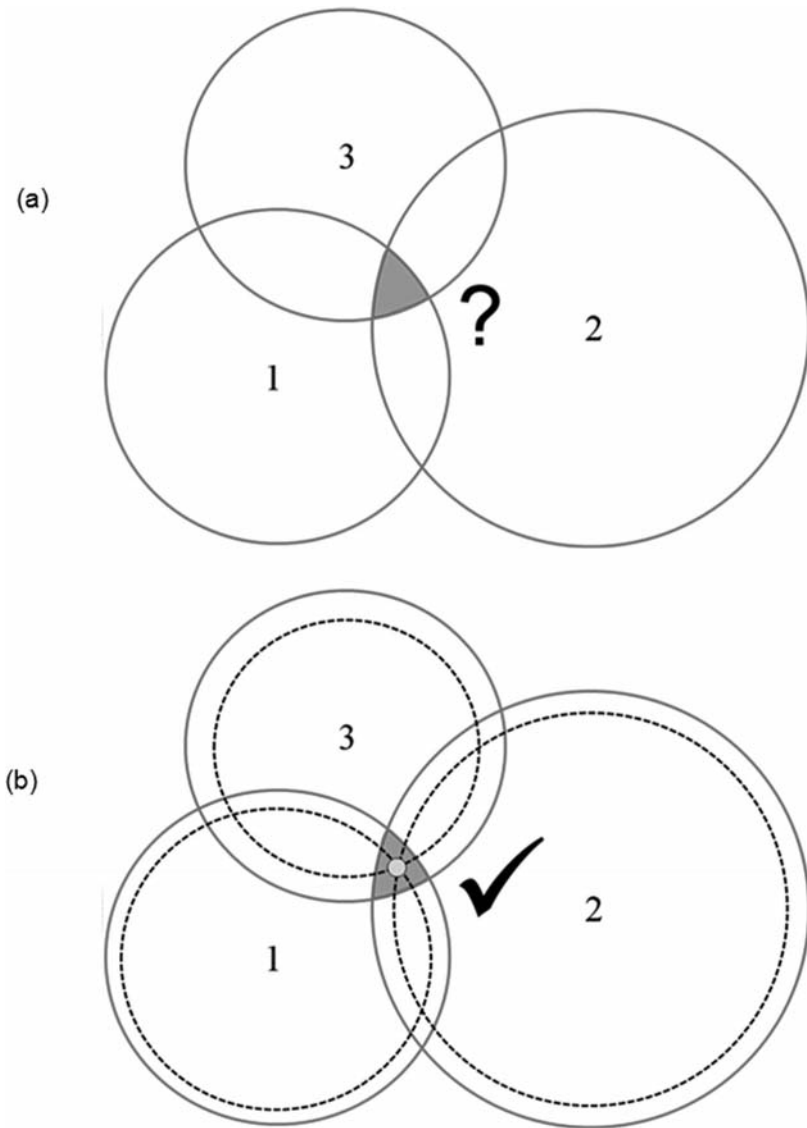




**Figure 1-7.** A measurement from one satellite puts you somewhere on a circle whose center is the satellite position. (a) Two measurements reduce your possible locations to two points where two circles intersect. (b) Three measurements determine a single location.

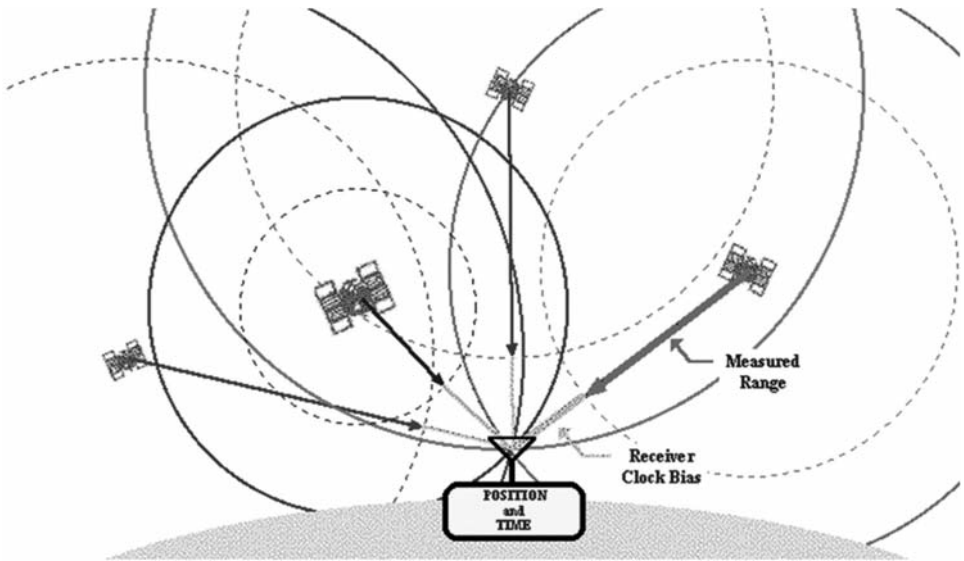
only known to within a region of intersection. The receiver logic assumes, then, that because the ranges do not intersect, the receiver's clock must be out of synchronization. To resolve this problem, the clock offset is adjusted until all the satellite ranges converge at a single location (Fig. 1-8b).

The problem is solved by adding a fourth range to the measurement, as shown in Fig. 1-9. The receiver runs a simple routine to adjust the clock until all four ranges intersect at the same point. This is known as *correcting clock bias* and it is



**Figure 1-8.** (a) Incorrect ranges due to incorrect timing will not intersect at a single point. (b) Removing the receiver clock bias enables the three circles to converge on a single point.

how the receiver resets its clock. This process occurs when your receiver has just been activated and is initializing. A least-squares routine is applied to the four measured ranges to solve for four parameters (three receiver coordinates and the clock bias), leading to a better estimate of the receiver position. However, as will be explained in Chapter 2, a variety of potential sources of errors can result in the position being off by tens of meters or more.



**Figure 1-9.** GPS receiver position is determined from multiple range measurements. Four satellites are needed to determine X, Y, Z, and receiver clock bias.

### Relativistic Effects

Another important element in the timing of the signals are the “special” and “general” relativistic effects on satellite clocks: Due to orbital speed and weaker gravity around the GPS satellites, their clocks appear to run faster than the clocks in GPS receivers. Fortunately, these effects can be accurately computed and corrected before the satellite launch.

The GPS satellites are travelling at an orbital velocity of 3.9 km/sec. Although very small compared to the speed of light, this is sufficient to make the time dilation (resulting from the relative speed with respect to the observer) very significant in timing the signal. This results in the “slowing down” of satellite clocks at the rate of  $7 \mu\text{s/day}$ , according to the Special Theory of Relativity (i.e., the “special” relativistic effect).

Secondly, the altitude of the satellites means that the atomic clocks experience a different gravitational field than a clock on the Earth’s surface. As a result, the satellite clocks run faster than the Earth-bound clocks ( $45 \mu\text{s/day}$ ), according to the General Theory of Relativity.

The net result of the opposing effects of “special” and “general” corrections is that the clocks on the satellites need to be offset before launch. Without the relativistic corrections, GPS range measurements would be in error by a massive  $38 \mu\text{s/day}$ , equivalent to a 10-km/day range error. Therefore, to ensure that the clocks will actually achieve a fundamental frequency of 10.23 MHz in space, their frequency is set a bit slow before launch, to 10.22999999545 MHz.

The engineers who originally designed the GPS system included these relativistic effects when they designed and deployed the system. The frequencies of the atomic clocks were slowed down before they were launched so that once they were in their proper orbits their clocks would appear to run at the correct rate as compared to the clocks at the GPS ground stations. Furthermore, each GPS receiver has a built-in microcomputer that (among other things) performs the necessary relativistic calculations when determining the user's location.

## Why Use GPS?

### *What Engineers Do*

Engineers use math and science to design new artifacts and technologies that may be used to solve practical problems. For instance, the U.S. Department of Defense created the GPS system to help in worldwide navigation. They followed an engineering design process that has eight basic steps:

1. Identify the need or problem.
2. Research the need or problem.
3. Develop possible solutions.
4. Select the best possible solution(s).
5. Construct a prototype.
6. Test and evaluate the solution.
7. Communicate the solution.
8. Redesign to improve your original design.

The American Engineers' Council for Professional Development [ECPD, the predecessor of the Accreditation Board for Engineering and Technology (ABET)] has defined "engineering" as:

The creative application of scientific principles to design or develop structures, machines, apparatus, processes, or works utilizing them singly or in combination; or to construct or operate the same with full cognizance of their design; or to forecast their behavior under specific operating conditions; all as respects an intended function, economics of operation and safety to life and property. (ECPD 1947)

This definition includes engineers functioning as project managers. They operate (manage) their works or solutions with full cognizance of the design with respect to an intended function, the economics of operation, and safety to life and property. They forecast the behavior of systems or artifacts and test and evaluate solutions so they can improve their original design for better performance. Engineers have many specializations and a variety of functions:

- Engineers design structures, machines, devices, and processes for automation. For example, they design robotics and machinery used in precision farming.

- Engineers assist in the planning, design, implementation, operation, and maintenance of processes or works such as in large construction sites.
- Engineers assess the performance of their design (e.g., of civil structures such as buildings, bridges, dams, roads, airports) under specific operating conditions.
- Engineers design power transmission for systems and processes, electric equipment or motors, aircraft, and lighting in buildings.
- Engineers measure land, location of phenomena, and property boundaries for urban design and land development.
- Engineers find solutions for environmental problems such as air and water pollution, global warming, severe weather, and seismic hazards.
- Engineers manage complex projects, systems, processes, and platforms ensuring safety and efficiency, such as ship navigation at large ports and harbors.
- As managers, engineers are also social scientists, dealing with human interactions and behavior; they make observations and measurements of features, patterns, and events by individuals. They design and track efficient movement of people and material in large industrial complexes and construction sites.

These are just a few examples from the entire spectrum of what engineers do. As an engineer, you perform services in your area of competence, and you may find that your professional duties fall in one or more of these specific examples.

### ***What GPS Provides***

GPS is a valuable resource for recording unique locations of people, phenomena, and objects of interest, in a 3-D reference frame. It is a much more time- and cost-efficient means of recording positional data compared to alternative methods such as traditional surveying. Even more important is the fact that the GPS system is built around very stable atomic clocks, adding a fourth dimension to the measurements—time. It can be used for precise timing applications in addition to providing point location data. The system is globally accessible and all GPS signals are in the L-band of the frequency spectrum.

The true benefit of GPS is in being able to provide 3-D position, velocity, and time in a common global reference system, anywhere on or near the surface of the Earth, on a continuous basis. Because L-band waves penetrate clouds, fog, rain, and storms, GPS units can receive data in any local weather conditions. However, in certain circumstances GPS units may not receive signals accurately, for example, inside concrete buildings or walls, in some mountainous regions, or under especially heavy vegetation or forest canopies. Accuracy may also be affected by characteristics of both the satellite and the receiver. Despite this, the overall reliability of GPS is remarkably good.

Although the technology has been fully operational only since early 1990s, it has continuously become more popular, accessible, and affordable, allowing engineers to more easily incorporate it into their work. As an important tool for capturing location coordinates, it is widely used in mapping, site control and design, robotics, and machine control. Large-scale projects utilize GPS to measure the

vibrations, twist, sway, and deflections of built structures, using those data to improve knowledge for better design. GPS seismometers can measure high-rate positional data (50 Hz) without requiring double integration, a process commonly used in acceleration and displacement transducers. The field of transportation studies has eagerly adopted GPS for many applications, from locating features of road networks and improving general reference maps, to inventorying and repairing road damage, to examining accident causes. Using the technology, project managers can locate and track materials and people, route cargo and large ocean liners, and navigate ships through intricate waterways.

It is a relatively easy technology to use and is also cost-effective. However, the ease of use of this technology can be deceptive. Without adequate planning and training, the data collection efforts could result in data containing unusable positional coordinates. Many factors must be considered when applying GPS to a particular project, and these will be discussed in more detail in later chapters.

The method by which a position is located is simple, but the manner in which the GPS functions is complex. It is vitally important that users understand how GPS functions to avoid the “black box” syndrome, wherein the user is unaware of the quality or appropriateness of the data being collected or provided by the receiver. More specifically, this syndrome is characterized by the user expecting the receiver to always function correctly, thereby failing to recognize when there are problems with the system.

In the previous section you learned how a GPS receiver uses the radio signals emitted from the satellites to calculate a set of coordinates. The accuracy obtainable using that approach can be accurate to within a few meters, sufficient for many purposes for which low-cost GPS receivers can be purchased for as little as US\$100. However, most engineering applications require higher accuracy involving use of expensive receivers (see especially Chapter 5 for a discussion of high-precision systems). Part II of this book will introduce you to the considerations necessary when developing a GPS project. One of the most important of these is related to accuracy requirements.

## ***Comparison of GPS to Other Methods of Locating Points***

### **One Antenna, Three Dimensions**

Using a single GPS antenna, you get three dimensions (Kee et al. 2010). There is no need to observe separate parameters such as distances, angles, and point elevations to derive a 3-D position—an approach commonly used in many traditional positioning methods. Furthermore, in this method there are no cumulative sensor drift errors that are commonly associated with displacement transducers and inertial measurement systems.

### **Unobstructed Sky View**

GPS receivers require unobstructed view to the satellites. This limits the use of GPS to reasonably open areas (unobstructed grounds, building rooftops, the top

surface of a dam wall, bridge decks and towers, etc.). The accuracy of GPS positioning depends on the distribution (spatial geometry) of the observed satellites in space with respect to the receiver, the data processing strategies and algorithms, and the modeling of various error sources that contaminate the measurements (Parkinson and Spilker 1996). The common error sources (biases) that affect GPS positioning are discussed in Chapter 2.

### **Continuous Data**

Although relative movements of points in the lateral and vertical directions can be obtained from the integration of data from transducers such as accelerometers, only part of the movement vector (noncontinuous) is available. GPS can provide absolute position on a well-defined global reference frame [the World Geodetic System 1984 (WGS-84)] and direct, instantaneous 3-D displacement, permitting near-real-time analysis. The connection to the WGS-84 frame makes it easier to assess how a point might have moved relative to another reference point, for example, how a structure might have moved with respect to the surrounding bedrock after a shock such as an earthquake. Sensors that can only measure 1-D positions may be unable to detect certain modes of deformation. Moreover, GPS positional accuracies range from 1 cm (instantaneous) to 1 mm (with averaging), making it suitable for a variety of applications.

### **Weather-Independent**

Traditional methods, whether manual or automated, are influenced by the prevailing weather conditions. For example, most survey measurements must be made during the day and sometimes require near-perfect visibility conditions. Temperature influences may affect the mechanical, electronic, or optical components of the instruments. In contrast, GPS can be used at any time of the day or night and in varying local weather conditions.

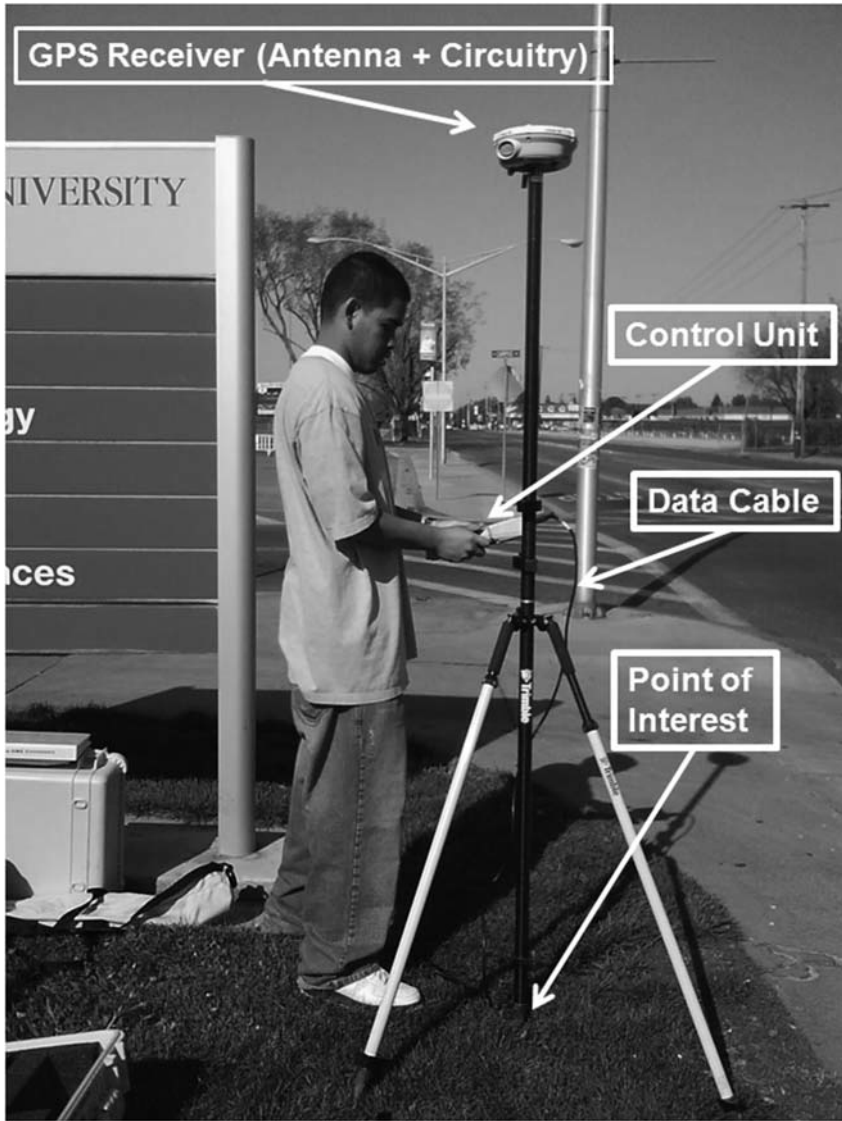
### **Station Intervisibility in Surveying Networks**

Unlike surveying and mapping applications, there is no need for intervisibility between the measuring stations. Hence, there is greater flexibility in the selection of GPS station locations than is the case with traditional methods.

## **What Does a GPS Measurement System Entail?**

### ***Small- to Medium-Scale Projects***

Portable integrated GPS measurement systems are increasingly replacing some of the older designs in which a GPS antenna (RF section) is external to a “black box” (microprocessor). GPS equipment for professional use is considerably more precise and are still typically larger in size. Many measurement systems now exist in which the antenna circuitry, microprocessor, and power supply unit are all embedded in a single box (Fig. 1-10). An external control unit can be used to probe or set up the equipment as required.



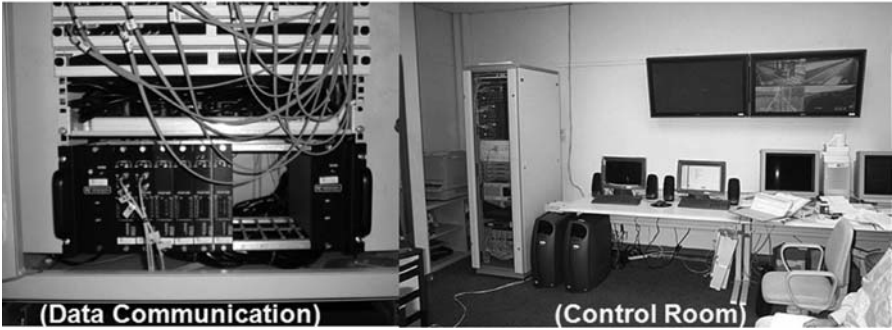
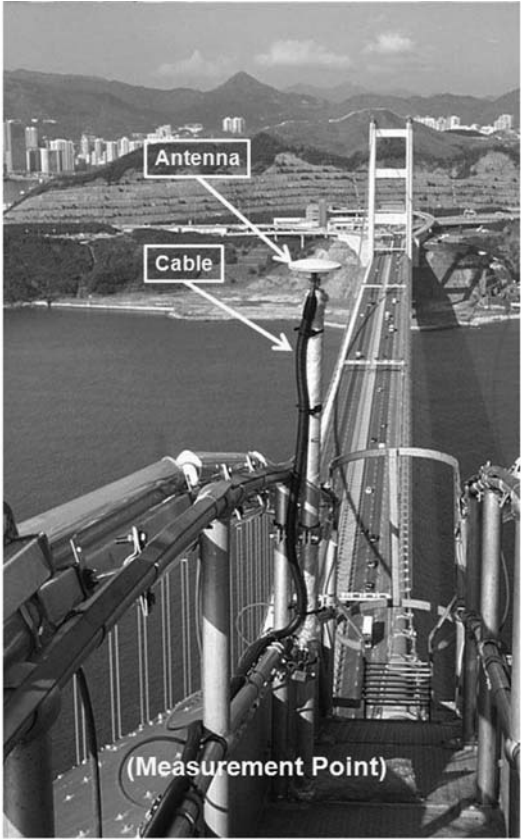
**Figure 1-10.** A GPS measurement system in a medium-scale project.

### ***Full-Scale Projects***

At its most basic, a GPS measurement system is a single compact receiver. However, GPS measurement systems can be described at a variety of scales, but the most complex is the scale of a network of receivers. Many engineering projects involve detailed data collection and analysis at this scale and, when the time dimension is included, the complexity increases. Consider a project in which hundreds of receivers are placed at strategic locations on a long-span suspension bridge to capture, in real time, the bridge performance in response to live traffic,



wind, seismic, and temperature loads (Fig. 1-11). The data from all the GPS units are aggregated to one area—a control room where all data handling and management decisions take place. At this scale, the individual GPS units (antennas attached to bridge rails and towers) are simply data collectors. A bigger part of the measurement system is made up of data-logging equipment and software,



**Figure 1-11.** A GPS measurement system in a full-scale project.

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power supply, data communication and telemetry, data storage and backup, and visual display units, among other components. Such a system would consume a large office space and would also need human operators.

## **GPS Receiver Types and Accuracy**

GPS receivers are classified according to achievable positional accuracy and intended application (Appendix 1). These classifications are also inherently based on the positioning principles behind them, the basis for discussions in Chapters 2 through 5.

### ***Navigational/Recreational Receivers***

Navigational receivers provide the lowest positional accuracy. A single standalone receiver can provide autonomous accuracy of between 2 and 15 m. They are the most affordable GPS units on the market and are typically used by hikers, sportsmen, and other people who want to locate and navigate to particular locations for recreational purposes. They are designed to be very user-friendly and it does not take long to learn how to operate one. Despite their low accuracy, they can be useful for collecting data for some research purposes.

The basic ranging principle behind navigational receivers is presented in Fig. 1-9; a more detailed discussion is offered in Chapter 2. They can be manufactured compactly and can be integrated in wristwatches and other miniature technology such as cell phones. In comparison, GPS receivers for professional use (such as for mapping and land surveying) are typically bigger and considerably more precise.

### ***Mapping-Grade Receivers***

Mapping-grade receivers are developed with the mapping professionals in mind. They are more expensive than recreational receivers, are much more accurate, and have many more features. The mapping-grade receivers provide sub-meter accuracies (0.1 to 5 m). The positioning principles behind these types of receivers are presented in Chapter 4. One of the most important features offered by mapping-grade receivers is the capability of collecting differentially corrected data at a *logging rate* that can be set by the user—the rate at which a position is calculated and the coordinates stored. For example, a higher logging rate would be used for mapping a road centerline while driving versus standing in one spot to record the location of a building. This also has implications for the amount of data that can be stored in the receiver's internal memory, and hence the bigger size of the receiver. Another feature is the greater control by the user over the conditions under which data are collected (e.g., satellite selection, elevation masking, and signal-to-noise ratio masking).



(a)



(b)

**Figure 1-12.** Example of high-precision, geodetic-quality (scientific) receiver (a) and antenna (b). High-end geodetic receivers have multiple data communication ports to input RTCM or RTK and to output position or raw GPS data to the data recorder. Although a geodetic receiver, antenna, and controller are usually designed as separate components, there are some receiver types with a combined antenna and circuitry, such as shown in Fig. 1-10. RTCM (see Glossary) stands for Radio Technical Committee for Maritime Services and RTK stands for Real-Time Kinematic.

### ***Geodetic-Grade (Scientific) Receivers***

These are the types of receivers commonly used by engineers (Figs. 1-10 and 1-11). The positioning principles behind them are presented in Chapter 5 and involve complex data processing algorithms. They are the most accurate (i.e., meant for millimeter- to centimeter-level accuracy), but are also the most expensive. In 2010 a typical high-precision, geodetic-quality GPS receiver (Fig. 1-12a) cost between US\$5,000 and US\$40,000, depending on configuration. The cost of a geodetic antenna (Fig. 1-12b) is between US\$2,000 and US\$10,000. They are typically used in medium-scale projects involving carefully planned setups to minimize errors, and in full-scale operational projects where in most cases the equipment is installed on an object or at the project site to continuously collect, store, and/or transmit data.

# GPS Positioning and Measurement Principles

## Positioning and Measuring Objects

It is important to realize that GPS is most often used to determine coordinates of individual locations, also known as *points*. However, some GPS receivers can also be used to collect and generate line and area data. This can be done in a variety of ways. One method is to collect discrete points along the length of a line (i.e., positions are recorded at each break or curve in the line) or at each corner of an area. A second method, if the receiver has this capability, is to turn the receiver on and continuously record positions while traversing the length of the line or the perimeter of the area. In other words, GPS can be used to measure 1-D, 2-D, or 3-D data as desired by the user. In 1-D, a single coordinate value (e.g., Easting, Northing, or Height) or its variation with time (i.e., a time series) is of interest. In 2-D, the horizontal coordinates are of interest and can be expressed as a single point, line, or area on a 2-D plane, or as a scatter plot or trajectory if the point or object being measured is moving. In 3-D, both horizontal and vertical coordinates are of interest to the user—this is one of the most important benefits of using GPS since many actual projects require all three coordinates to be measured.

## The Satellite Coordinate System

Given that coordinates are the primary output of a GPS measurement, it is necessary to understand coordinates and coordinate systems. They allow us to pinpoint a specific location on or above the Earth's surface. In GPS positioning, the satellite coordinates are known, the ranges are measured, and the receiver coordinates are computed on that basis. Therefore, knowing the satellite coordinate system is a good starting point.

### **World Geodetic System 1984 (WGS-84)**

The orbits of the GPS satellites are geocentric around the center of the Earth's gravity. This important consideration by the system designers (U.S. Department

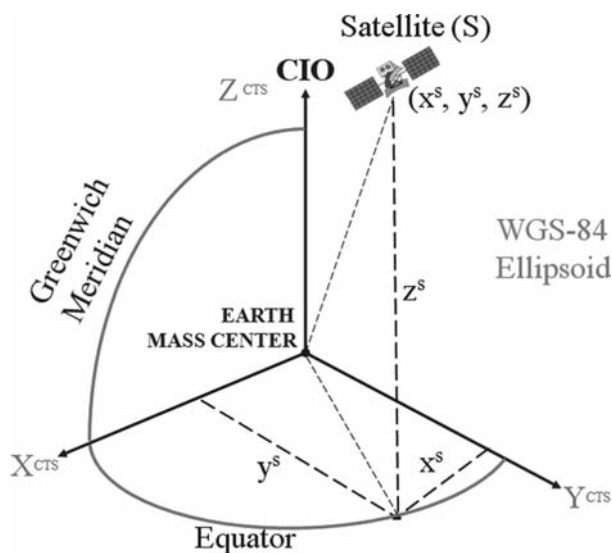
of Defense) necessitated the development of a coordinate system appropriate for global use. The coordinate system would be based on a global geodetic datum (a mathematical surface, an ellipsoid, used to approximate the Earth's shape and size). The satellite technology required that the center of the ellipsoid and the center of the geoid (Earth's mass) coincide, meaning that the ellipsoid is geocentric around the center of the Earth's gravity, just as the orbits of the GPS satellites are.

The GPS satellite coordinates are referenced to the World Geodetic System 1984 (WGS-84), a geocentric datum (an ellipsoid, the center of which is located at the Earth's mass center) that has size and shape parameters of: semi-major axis  $a = 6,378,137$  m and inverse flattening  $1/f = 298.257$ . WGS-84 is described in detail in the Glossary; also refer to Table A6-1 in Appendix 6.

Three different 3-D coordinate systems can be used as a means of expressing point positions with respect to the WGS-84 ellipsoid. All three systems have useful applications in different situations. The user should understand the differences between and the relationships among the three systems.

### Geocentric Cartesian Coordinates

Geocentric Cartesian coordinates ( $X, Y, Z$ ) of a point are referred to an Earth-centered (geocentric), Earth-fixed, right-handed, orthogonal, 3-D axis system (Fig. 2-1). This system is sometimes referred to as the ECEF (Earth-centered Earth-fixed) system. The origin of the coordinate system is at the Earth's center of mass that corresponds with the center of the WGS-84 ellipsoid (intersection of equatorial plane and axis of rotation). The X-axis lies in the equatorial plane with its positive end intersecting the Greenwich meridian. The Y-axis lies in the equa-



**Figure 2-1.** Geocentric WGS-84 Cartesian coordinates for satellite S. CIO is the Celestial International Origin and the superscript CTS stands for Conventional Terrestrial System.

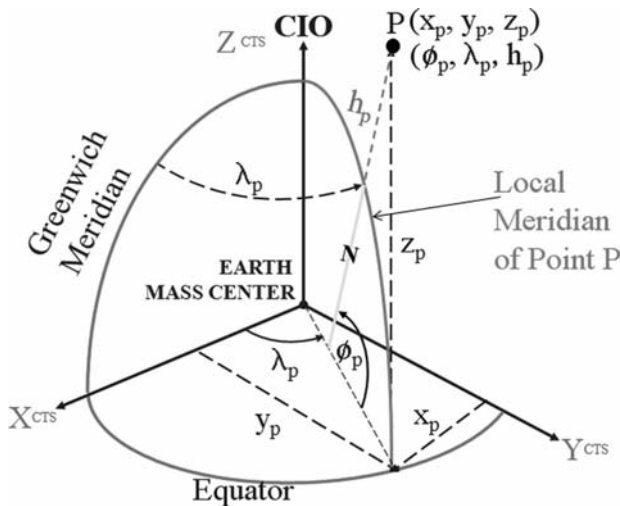
torial plane with its positive end intersecting the ellipsoid at 90°E longitude. The Z-axis is coincident with the Earth's spin axis, positive toward the North Pole, also referred to as the Celestial International Origin (CIO).

### Geodetic Coordinates

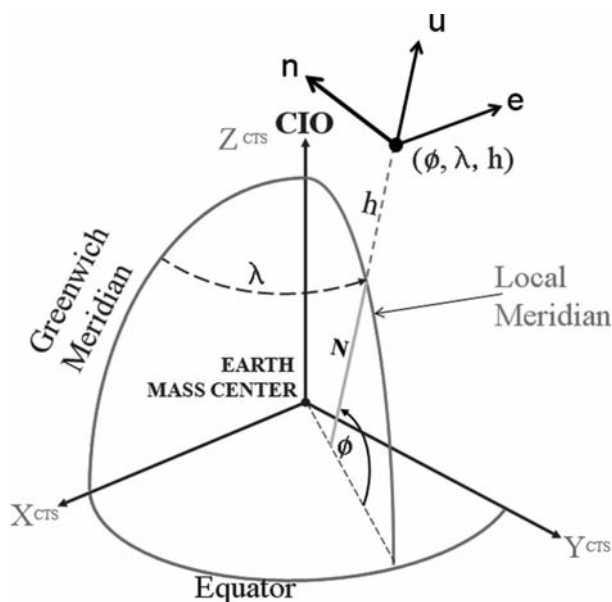
The geodetic (or ellipsoidal) coordinates of a point are expressed using the geodetic latitude ( $\phi$ ), geodetic longitude ( $\lambda$ ), and height above or below the ellipsoid surface ( $h$ ). They are also sometimes referred to as geographic coordinates. These values also form a right-handed, Earth-fixed, 3-D coordinate system. The longitude is expressed as positive to the east of the Greenwich meridian. Latitude is the angle measured from the equatorial plane to the normal at the point (i.e., a line, normal to the ellipsoid, passing through the point) and is expressed as positive to the north. Ellipsoid height is expressed in meters. Figure 2-2 illustrates both the Cartesian and the geodetic coordinates for a point P located above the ellipsoid surface.

### Local Geodetic Horizon Coordinates

*Local geodetic horizon coordinates* or *local topocentric coordinates* are extremely useful when integrating GPS-determined positions with terrestrial (e.g., total station) observations. The local geodetic coordinate system is an Earth-fixed, right-handed, orthogonal, 3-D coordinate system having its origin at any point specified (Fig. 2-3). The north axis lies in the meridian plane and is directed positive toward the North Pole (CIO). The up axis lies along a normal to the ellipsoid at the origin, positive outside the ellipsoid surface. The east axis forms the right-handed system by being perpendicular to the meridian plane, positive to the east. The origin of the system has local geodetic coordinates (0, 0, 0)—the implication is that an infinite



**Figure 2-2.** Geocentric WGS-84 Cartesian and geodetic (ellipsoidal) coordinates for point P. CIO is the Celestial International Origin and the superscript CTS stands for Conventional Terrestrial System.



**Figure 2-3.** Local geodetic coordinate system ( $e, n, u$ ). CIO is the Celestial International Origin and the superscript CTS stands for Conventional Terrestrial System.

number of local geodetic systems may be established, typically at each instrument setup.

In terrestrial measurements, such as using total stations, the local geodetic coordinates of any point can be referred to the origin of the local geodetic system using the *geodetic azimuth* ( $\alpha$ ), *vertical angle* ( $\angle$ ), or *zenith angle* ( $\sphericalangle$ ) and *mark-to-mark slant range* ( $r$ ) from the origin to the point being measured (Fig. 2-4). The following relations are defined using trigonometry:

$$e = r \cos(\angle) \sin \alpha = r \sin(\sphericalangle) \sin \alpha \quad (2-1a)$$

$$n = r \cos(\angle) \cos \alpha = r \sin(\sphericalangle) \cos \alpha \quad (2-1b)$$

$$u = r \sin(\angle) = r \cos(\sphericalangle) \quad (2-1c)$$

### Coordinate Conversions

To convert from geodetic coordinates (latitude, longitude, height) to Cartesian coordinates ( $X, Y, Z$ ), use the following formulas:

$$\begin{aligned} X &= (N + h) \cos \phi \cos \lambda \\ Y &= (N + h) \cos \phi \sin \lambda \\ Z &= [N(1 - e^2) + h] \sin \phi \\ N &= \frac{a}{\sqrt{1 - e^2 \sin^2 \phi}} \quad (\text{radius of curvature in the prime vertical}) \end{aligned} \quad (2-2)$$

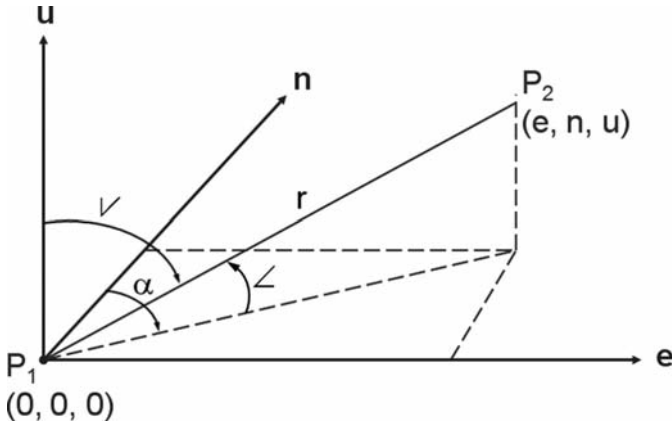


Figure 2-4. Points in the local coordinate system.

where the parameters  $a$  and  $h$  are as defined earlier in the text (i.e.,  $a$  is semi-major axis and  $h$  is height above or below the ellipsoid surface) and  $e$  is eccentricity which is also expressed in terms of flattening  $f$  as  $e^2 = 2f - f^2$ . For WGS-84, flattening  $f = 1/298.257$ .

To convert from Cartesian coordinates  $(X, Y, Z)$  to geodetic coordinates (latitude, longitude, height), use the following formulas:

$$\begin{aligned}
 h &= \frac{\sqrt{X^2 + Y^2}}{\cos \phi} - N \\
 \phi &= \arctan \left\{ \frac{Z}{\sqrt{X^2 + Y^2} \left[ 1 - e^2 \left( \frac{N}{N+h} \right) \right]^{-1}} \right\} \\
 \lambda &= \arctan \left( \frac{Y}{X} \right)
 \end{aligned}
 \tag{2-3}$$

Iteration is required in this second formula because  $\phi$  and  $h$  are dependent upon one another. First, assume  $h = 0$  and solve for  $\phi$ . Next solve for  $h$  and once again for  $\phi$ . Continue the iteration until the change in  $\phi$  between successive iterations is insignificant.

Finally, to convert from Cartesian coordinates  $(X, Y, Z)$  to local coordinates  $(e, n, u)$ , use the following formulas:

$$\begin{bmatrix} e \\ n \\ u \end{bmatrix} = \begin{bmatrix} -\sin \phi & \cos \phi & 0 \\ -\sin \lambda \cos \phi & -\sin \lambda \cos \phi & \cos \lambda \\ \cos \lambda \cos \phi & \cos \lambda \cos \phi & \sin \lambda \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}
 \tag{2-4}$$



In this last conversion, the geodetic coordinates (latitude and longitude) of a point are also required in order to be able to convert the Cartesian coordinates to a local system.

### **WGS-84 and Local Datums**

It is also important to understand that, besides the WGS-84 datum, other datums exist for different uses around the world. For example, the North American Datum 1983 (NAD 83) is designed in a similar manner to WGS-84 except for the location of the center of its ellipsoid, which is not designed to be at the geocenter (center of Earth's gravitational mass). WGS-84 is a worldwide system, whereas NAD 83 is used only in North America except Mexico. In 1987, the two systems did not differ significantly as the shift between them fell within the overall error budget. At that time, they differed only by a centimeter or two. However, the new definitions of the two systems—NAD 83 (CORS96) and WGS-84 (G1150)—differ by up to 1 to 2 m within the continental United States. The main difference is that while WGS-84 is global and therefore is in constant motion due to the shifting of tectonic plates around the world, the NAD 83 system is fixed to one plate, the North American plate. Consequently, within the continental United States, NAD 83 moves approximately 10 to 20 mm per year in relation to the WGS-84 system. This has implications when using GPS in certain situations. For instance, as will be discussed in Chapter 5, some local GPS networks and service providers broadcast corrections for GPS users to apply to improve the accuracy of their position coordinates. The conversion between such corrections and local datums such as NAD 83 can cause errors with datum shifts. Furthermore, U.S. survey foot and international foot conversions can cause additional errors when dealing with such local datums.

Appendix 6 includes brief notes on datum transformations and map projections. However, for detailed exploration of these two topics, some excellent sources include Elithorp and Findorff (2009), Hofmann-Wellenhof et al. (2001), and Van Sickle (2008).

### **GPS Receiver Position Measurement Principle**

The true range, or geometric range, from a GPS receiver to a GPS satellite can be represented in terms of WGS-84 coordinates (Fig. 2-5):

$$\rho_r^s = |r^s - r_r| = \sqrt{(x^s - x_r)^2 + (y^s - y_r)^2 + (z^s - z_r)^2} \quad (2-5)$$

where

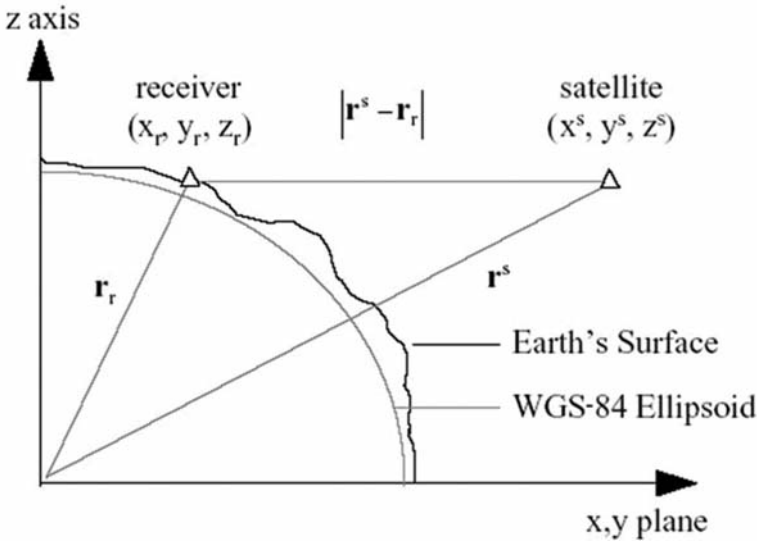
$\rho_r^s$  is the geometric range from the receiver to the satellite (m)

$r^s$  is the satellite position vector referenced to the WGS-84 (m)

$r_r$  is the receiver position vector referenced to the WGS-84 (m)

$x_r^s, y_r^s, z_r^s$  are the satellite WGS-84 coordinates

$x_r, y_r, z_r$  are the receiver WGS-84 coordinates.



**Figure 2-5.** Geometric range from a receiver to a satellite.

The two fundamental GPS measurements for range (and hence position) determination (explained in Chapter 2, “Ranging Methods”) are the *pseudorange* (Eq. 2-6) and *carrier-phase* (Eq. 2-7) observations. The basic observation equations for these measurements are (Lachapelle et al. 1992; Langley 1993):

$$P_r^s = \rho_r^s + d\rho^s + c(dt^s - dT_r) + d_{ion}^s + d_{trop}^s + \varepsilon(p_{rx}) + \varepsilon(p_{mult})_r^s \quad (2-6)$$

$$\Phi_r^s = \rho_r^s + d\rho^s + c(dt^s - dT_r) - d_{ion}^s + d_{trop}^s - \lambda N_r^s + \varepsilon(\Phi_{rx}) + \varepsilon(\Phi_{mult})_r^s \quad (2-7)$$

where

$P_r^s$  is the pseudorange measurement by the GPS receiver to the satellite (m)

$\rho_r^s$  is true range or “geometric” range (m)

$d\rho^s$  is the orbit error term (m)

$dt^s$  is the satellite clock error (m)

$dT_r$  is the receiver clock error (m)

$d_{ion}^s$  is the ionospheric delay term (m)

$d_{trop}^s$  is the tropospheric delay term (m)

$\varepsilon(p_{rx})$  is the error in pseudorange measurement due to receiver noise (m)

$\varepsilon(p_{mult})_r^s$  is the error in pseudorange measurement due to multipath (m)

$c$  is the speed of light ( $\text{ms}^{-1}$ )

$\Phi_r^s$  is the carrier phase measurement by the GPS receiver to the satellite (m)

$N_r^s$  is the carrier phase ambiguity between the GPS receiver and the satellite (cycles)

$\lambda$  is the wavelength of the carrier phase (m)

$\varepsilon(\Phi_{rx})$  is the error in carrier phase measurement due to receiver noise (m)

$\varepsilon(\Phi_{mult})_r^s$  is the error in carrier phase measurement due to multipath (m).

The major differences between Eq. 2-6 and Eq. 2-7 are the presence of the integer carrier phase ambiguity term ( $\lambda N_r^s$ ) in the carrier-phase measurements, and the reversal of sign for the ionospheric bias term ( $d_{ion}^s$ ).

The level of carrier-phase measurement noise (at the millimeter level) is much lower than the level of the pseudorange measurement noise (typically at the meter level). The inability of civilian users to access the P-code pseudorange measurements (under the U.S. military's anti-spoofing policy of guarding against fake transmissions of satellite data by encrypting the P-code to form the Y-code) reduces the accuracy of GPS pseudorange positions. Therefore, pseudorange measurements are generally used in applications where the accuracy requirement is not high (the few-meter level), as is typical for single-epoch navigation applications. On the other hand, carrier-phase measurements are extensively used in precise (centimeter-level) GPS applications.

The various error sources affecting the GPS ranging signal (contributing to the error terms in the above equations) are explained in "Error Sources" below.

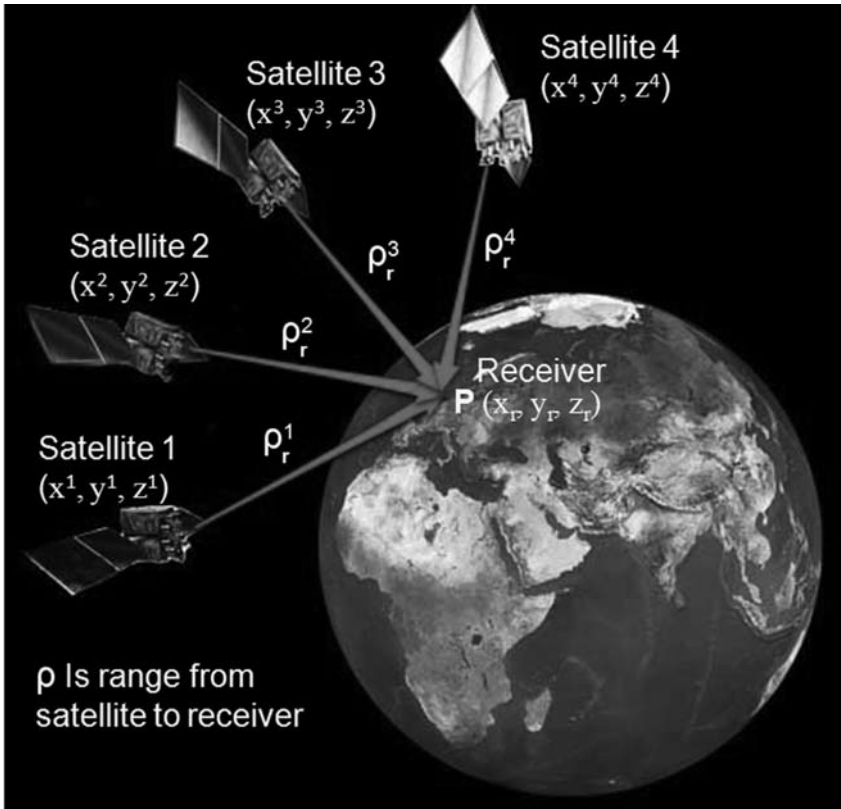
### **Calculating the Receiver Position**

At its most basic, a receiver needs to observe at least four satellites (i.e., four unknowns) to be able to estimate its position coordinates and a clock bias. This requirement is based on the principle of least squares adjustment—a statistical approach to finding the most probable result from a number of values. Satellite coordinates and pseudoranges (satellite–receiver ranges) are needed to calculate the average position (Fig. 2-6). The "Ranging Methods" section below discusses the methods by which the satellite–receiver ranges (pseudoranges) are determined. First, let's consider how the satellite positions are determined in the Cartesian coordinate system.

#### **Satellite Positions**

In order to determine the geometric ranges from the satellites to the receiver (Eq. 2-5), the satellite position at the time of transmission of the GPS signal has to be known. The satellite almanac and ephemeris data are needed for this purpose. The almanac data provide only a rough satellite position; ephemeris data are needed to determine the exact position. The almanac can be used to obtain a rough indication of where the satellites are at a certain time, such as is needed for the first acquisition (detection) of the satellites or to draw satellite plots in software. Ephemeris data provide the Keplerian parameters (Fig. 1-5) and small orbit corrections such as changes in the inclination of satellite orbits that can amount to as much as  $0.25 \times 10^{-7}$  deg/s or as little as 0.001 deg per week. The calculation for the satellite position in ECEF coordinates at time  $t$  within the ephemeris week is provided in Appendix 3.

Since it takes the signals some time reach the receiver, the satellite will have moved during that time. Therefore, a small correction is needed between the satellite position as calculated for the time of arrival (TOA) and the actual position on the time of departure (TOD).



**Figure 2-6.** GPS trilateration.

$$\beta = \frac{\omega_e \cdot \rho_0}{c}$$

$$\begin{aligned} X^s &= X^s \cos \beta + Y^s \sin \beta \\ Y^s &= -X^s \sin \beta + Y^s \cos \beta \\ Z^s &= Z^s \end{aligned} \quad (2-8)$$

$$\omega_e = 7.2921151467 \times 10^{-5} \text{ rad/s (Earth's angular velocity)}$$

The estimated range,  $\rho_0$ , is derived from the pseudorange measurement and, if possible, corrected for the receiver clock bias. Otherwise the computation needs to be iterative, that is, compute an estimated position using the measured pseudoranges and derive the receiver clock bias from these measurements, then recalculate the exact satellite position using the corrected pseudoranges.

### Estimating the Receiver Position

In order to calculate the position by least squares, the GPS receiver needs to have a starting approximate position. Usually, a receiver, on startup, would be able to retrieve the last position that was computed before it was switched off, and these

would be sufficient as starting coordinates. Estimated receiver position can be entered into a receiver in WGS-84 ellipsoidal coordinates and is internally transformed to ECEF Cartesian coordinates.

### Finding the Receiver Position

With the satellite coordinates, measured pseudoranges, and the estimated receiver position, the most probable position of the receiver can now be found. In a least squares adjustment (Hofmann-Wellenhof et al. 2001, p. 256), the computed ranges (from satellite coordinates and the estimated approximate receiver coordinates), observed ranges, and receiver clock bias are applied to a set of linearized model equations (equal to the number of satellites involved) to find the final receiver position (see Appendix 4).

## Ranging Methods

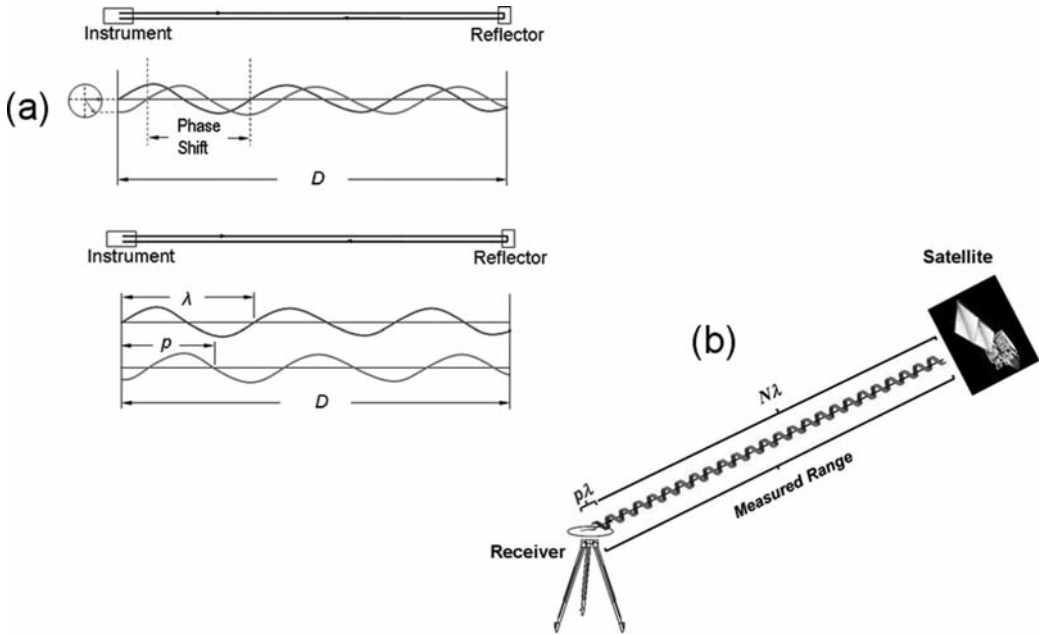
### The Ranging Principle

In GPS trilateration (Fig. 2-6), receiver–satellite ranges and satellite coordinates are known. But how does the receiver or the user know the measured range? The answer is in *GPS ranging*. GPS ranging is comparable to distance measurement by electronic distance meters (EDMs) or total stations. An EDM instrument measures distances by sending modulated waves to a distant reflector (Fig. 2-7a). The waves are reflected back to the instrument, traveling double the distance ( $D$ ) between the instrument and the reflector. While some EDMs use pulsed laser emissions based on travel time, a phase shift EDM is based on knowing the total number of whole (and partial) wavelengths between the instrument and the reflector. This is partly possible due to the partial wavelength ( $p$ ) being measured from the phase shift between the transmitted and reflected waves, according to the distance equation:

$$D = \frac{\lambda[N + p]}{2} = \frac{1}{2}[\lambda N + \Phi] \quad (2-9)$$

where  $N$  is an integer number of whole wavelengths (integer ambiguity), and  $p$  is the partial wavelength (in cycles) from the phase shift between outgoing and incoming wave ( $\Phi = p\lambda$  is the phase in linear units). The primary task is to solve for the integer ambiguity.

An EDM can send three or four different wavelengths by using phase modulation. By introducing different wavelengths to measure the same distance, the cycle ambiguity can be resolved, enabling the measurement of tens of kilometers with millimeter precision. This method is convenient for the EDM's two-way ranging system but is impossible in the one-way ranging used in GPS measurements. Unlike in EDM, a GPS carrier signal travels the one-way distance ( $\lambda N + p\lambda = \lambda N + \Phi$ ) between the satellite and the receiver (Fig. 2-7b). The GPS ranging must use an entirely different strategy for solving the cycle ambiguity problem because the



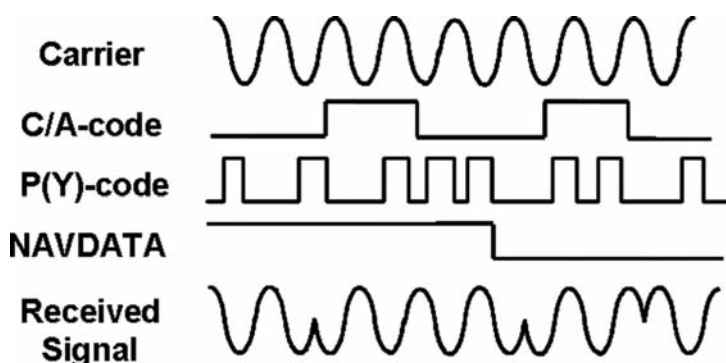
**Figure 2-7.** Comparing electronic distance meter (EDM) distance ranging to the GPS ranging principle: (a) EDM “two-way” ranging; (b) GPS “one-way” ranging.

satellites broadcast carrier signals of constant wavelengths, and the GPS satellites are constantly in motion.

In order to further explain the GPS positioning principle, it is important to first explain the satellite signal structure and the phase modulation for signal transmission.

### Signal Structure

GPS satellites broadcast radio (microwave-band) signals to enable GPS receivers to determine location and time. GPS signals include ranging signals (used to measure the distance to the satellite) and navigation messages. The navigation messages include ephemeris data (used to calculate the position of the satellite in orbit) and information about the time and status of the satellite constellation. For the ranging signals and navigation message to travel from the satellite to the receiver, they must be modulated onto a carrier signal. This is done by means of phase modulations. The choice of GPS carrier signals is briefly explained in Appendix 2 (L-band is used, based on the system design needs). The GPS design uses carrier signals modulated by different binary codes and navigation data (Fig. 2-8). The binary codes include, for instance, the C/A-code carried on L1, L2C carried on L2, and P(Y)-code carried on both L1 and L2. Navigation data are broadcast on all carriers (L1, L2, and L5). C/A-code and L2C are for civilian GPS receivers and the P(Y)-code is reserved for military use.



**Figure 2-8.** GPS signal structure and carrier signal modulation.

Block II and IIR satellites both broadcast the same fundamental GPS signals that have been in place since the beginning of the system. Their frequencies are centered on L1 (1,575.42 MHz) and L2 (1,227.60 MHz). As mentioned in Chapter 1, the civilian C/A code is carried on L1. The “precise” code (P-code) is carried on both L1 and L2. When encrypted, the P-code is known as the P(Y) code, or simply the Y-code.

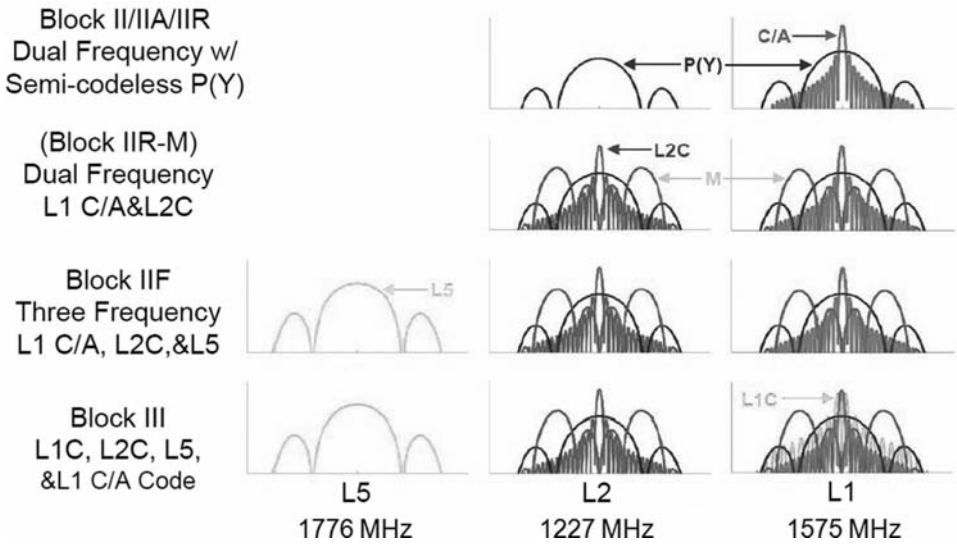
With the launch of the first Block IIR-M satellite (September 21, 2005) came the new and different signals that would augment existing codes. As mentioned in Chapter 1, one of the significant improvements was the increased L-band power on L1 and L2, and the broadcast of new signals such as L2C and the M-code (the M stands for Modernized).

### ***The M-code***

The M-code is a new military code. It is carried on both L1 and L2, and will probably replace the P(Y) code eventually. It has the advantage of allowing the U.S. Department of Defense to increase the power of the code to prevent jamming. It was designed to share the same bands with existing signals, on both L1 and L2, and still be separate from them (see the two green peaks in the M-code in Fig. 2-9). The M-code is designed in such a way to allow minimum overlap with the maximum power densities of the P(Y) code and C/A code, which occur near the center frequency. This is because the actual modulation of the M-code is accomplished with the binary offset carrier (BOC) modulation, which differs from the binary phase shift key (BPSK) modulation used with the C/A and P(Y) codes. An important characteristic of BOC modulation is that the M-code has its greatest power density at the edges of the L1 (and L2). This both simplifies the implementation at the satellites and the receivers and also mitigates interference with the existing codes. The M-code signal is tracked by direct acquisition, that is, the receiver correlates the incoming signal with a receiver-generated replica of the code.

### ***L2C signal***

The L2C signal is a new civilian signal carried on the L2 carrier (the C is for Civil). This means there are now two new codes broadcast on the L2, a carrier that pre-



**Figure 2-9.** GPS signal evolution.

viously exclusively carried only one military signal, the P(Y) code. Now the L2 will carry a new military signal, the M-code, and a new civilian signal, the L2C (see the red peaks on L2 in Fig. 2-9). Although L2C has a very similar power spectrum to the C/A code, it is important to note that they are not merely copies of each other. L2C is a bit more sophisticated than C/A code. It is actually composed of two codes, L2CM and L2CL. The CM stands for Civil-Moderate length code, which carries the improved navigation data. This new navigation message is known as CNAV (the legacy navigation message is known by the acronym NAV). The NAV is broadcast at 50 bps while the CNAV is at 25 bps (Van Sickle 2008).

### ***The benefits of M-code and L2C signal***

There are two more new signals (Figs. 2-9 and 2-10) to discuss under the latest developments. But first, what are the practical benefits of the M-code and L2C signal?

It has already been said that the M-code will allow the military to counter intentional jamming by, for example, being able to increase the power of the signal. But what are the practical advantages of the civilian L2C? L2C is approximately 2.3 dB weaker than C/A on L1. Surprisingly, this is not a disadvantage. Without going into the details, the CL (for Civil-Long) in L2CL is tracked in such a way that it provides for a correlation about 250 times stronger than the C/A code, even though L2C is weaker than C/A code. Because of this, L2C has better tolerance to interference than does the C/A code. L2C also has better stability and improved tracking in obstructed areas such as near buildings, urban canyons, and forested areas.

There are many other practical benefits. For instance, a handheld code-based receiver using one civilian code (C/A on L1) can achieve a positional accuracy of



Carrier	Signal	Block IIR	Block IIR-M	Block IIF	Block III
L1	P(Y)	•	•	•	•
L2	P(Y)	•	•	•	•
L1	C/A	•	•	•	•
L2	L2C		•	•	•
L1	M		•	•	•
L2	M		•	•	•
L1	L1C				•
L5	Civil			•	•

**Figure 2-10.** New signal availability.

about 15 to 20 m under very good conditions. One of the largest error sources degrading a GPS receiver position is the ionospheric delay (refer to Table 2-1). With two civilian signals, one on L1 (C/A) and another on L2 (L2C), it becomes possible to model the ionospheric delay in code phase. It is then possible to achieve accuracies in the range of 5 to 10 m or even at the sub-meter level, given the trend of potential future developments.

It should also be noted that both L2C and C/A codes have a slow chip rate of 1.023 MHz. The signal chip rate affects both the size and power consumption of a

**Table 2-1.** Error Source Contributions

<i>Error Source</i>	<i>Average Contribution</i>
Satellite ephemeris	2.1 m
Satellite clock	2.1 m
Ionosphere delay	4.0 m
Troposphere delay	0.7 m
Receiver noise	0.5 m
Multipath	1.4 m

GPS chipset. The slower the chip rate, the longer the battery life and the smaller the GPS chipset. This means a potential for further miniaturization of receiver components.

### ***L5 signal***

L5 is a new carrier signal included with Block IIF satellites. The basic structure looks similar to that of L1, and the data that are carried on L5 are similar to that carried by L2CM. However, unlike L2C, L5 has the benefit of being in a band designated by the International Telecommunication Union (ITU) for aeronautical radionavigation services. Thus, L5 is in a “protected” frequency band (unlike L2), and it is greatly anticipated for critical navigation and other applications. It will not be prone to interference by ground-based navigation aids and it will be available for aviation applications. No other GPS signals occupy this band, but L5 will share the band with E5—a signal from GALILEO, which is an entirely different satellite system (described in Chapter 8).

### ***L1C (third civil signal)***

With Block III satellites, a number of phased enhancements will include, for example, a new civilian code on the L1 frequency called L1C. L1C has a modulation type different from all other GPS codes but the same as the planned GALILEO codes. This new signal is a result of an agreement reached between the United States and the European Union (EU) in June 2004 to create an interoperable GPS/GALILEO signal on L1. This makes the manufacturing of combined GPS/GALILEO receivers much simpler. While the details of the L1C signal are still provisional at the time of this writing, it is intended to provide some enhancements over the C/A code and will have some similarities with L2C. It will have double the power of the C/A signal and will carry a navigation message known as C-NAV2 (cf. L2C).

### ***Pseudo random noise (PRN) code***

The C/A code is a 1,023-chip-long pseudo random noise (PRN) code transmitted with a frequency of 1.023 MHz (repeats every millisecond). Each second, 1,023,000 chips are generated. A “chip” or “bit,” described by a 1 or a zero (Fig. 2-11), defines one cycle of the digital signal. Using the speed of light, the length of one chip can be calculated to be 300 m. The P-code is also a PRN. It has a very long PRN code that only repeats once a week. Whereas the C/A-code PRNs are unique for each satellite, the P-code PRN is actually a small segment of a master P-code. For protection against interference, the P-code can be encrypted in Y-code



**Figure 2-11.** A short pseudo random noise (PRN) code sample.

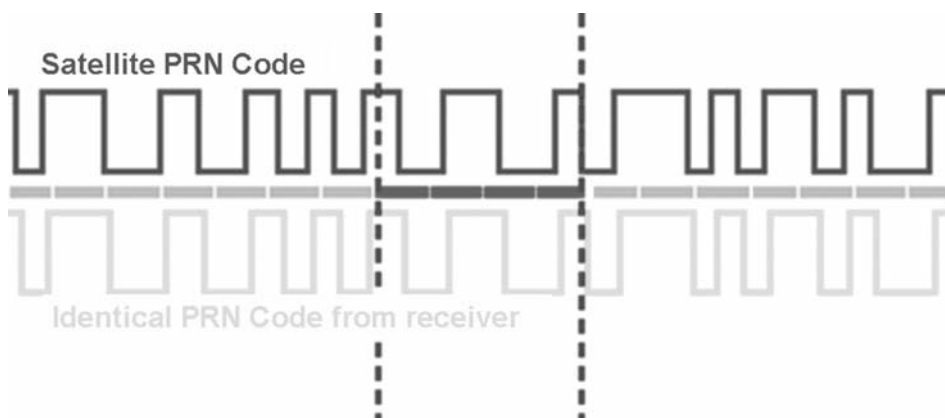
[anti-spoofing (AS) mode]. The unique C/A-code PRN for each satellite does not correlate with any other satellite's PRN code. The codes are highly orthogonal to each other, allowing a GPS receiver to recognize multiple satellites on the same frequency. The receiver identifies satellites by their PRN numbers, which appear on the satellite view screens of many GPS receivers.

### **GPS Code-Based and Carrier Phase-Based Pseudorange**

The GPS positioning principle is based on two approaches for estimating the satellite–receiver distance: (1) *code phase-based range determination* based on time-shift from PRN code correlation, and (2) *carrier phase-based range determination* using the satellite's carrier signal instead of the coded messages contained within the carrier signal.

#### **Code Phase-Based Range Determination**

In this approach, the receiver compares its internally generated “replica” PRN codes with those transmitted by the satellites (Fig. 2-12). When a perfect match occurs through time-shifting, the signal travel time is established. This process is called *locking onto the signal* and can take several minutes. From knowledge of the speed of light and the travel time, the distance can be estimated. The distance estimated in this way is known as the *pseudorange* and the technique is often referred to as *code phase*. It is not so precise due to clock biases and other factors (see “Error Sources” below). The satellite's PRNs are based on atomic clocks whereas the replica PRNs are based on ordinary receiver clocks. Although the two codes should be in phase when there is a match, they are always a little out of phase. The PRN codes have a cycle width of almost a microsecond (at the speed of light, a microsecond is almost 300 m). Good receiver design ensures that the signals are almost perfectly in phase, with an error that is a percentage or two of the cycle width. This translates to about 3 to 6 m.



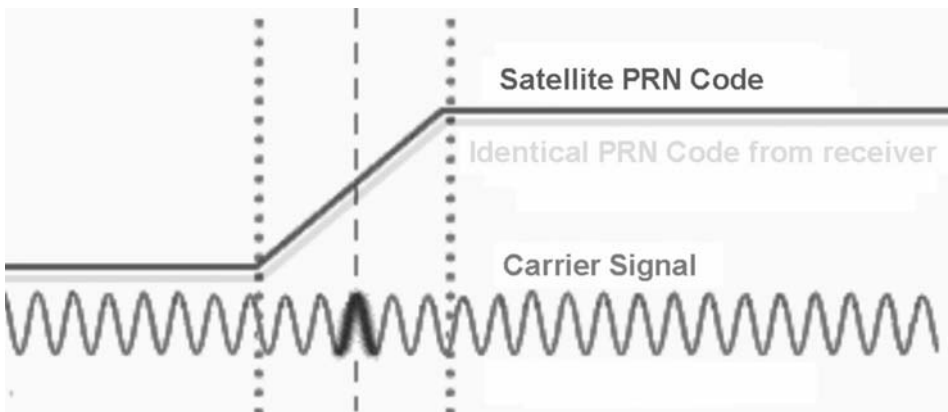
**Figure 2-12.** Time-shift from PRN codes (the “slide” needed to match them is the travel time).

### Carrier Phase-Based Range Determination

In carrier phase-based ranging, the satellite–receiver distance is estimated using the satellite’s carrier signal instead of the coded messages contained within. Identifying the cycle being received allows for sub-meter accuracy (the L1 wavelength is about 19 cm). Identifying the phase position in a cycle allows sub-centimeter accuracy (3 or 4 mm! if we can get to within 1% of perfect phase, like in code phase-based receivers). In other words, the carrier frequency is much higher, so its cycles are much closer together and therefore more accurate. The difficulty in making carrier phase-based measurements is properly aligning the signals. While the code signals are deliberately encoded to allow them to be easily aligned, all carrier cycles are similar. This makes it difficult to know whether the signals are properly aligned or are off by one or more cycles, and thus introducing an error of 20 cm or a larger multiple of 20 cm. Therefore, the essence of the method is to count the exact number of carrier cycles between the satellite and the receiver (Fig. 2-7). The problem is that the carrier frequency is hard to count because it is so uniform. Every cycle looks like every other and the cycle phase can be ambiguous (for example, whether the signal has a 0-deg phase or a 180-deg phase).

**Solving the ambiguity problem.** Geodetic- and scientific-grade receivers start with the pseudo random code and then move on to measurements based on the carrier frequency for that code. Thus, the key to carrier phase-based GPS (“carrier-phase GPS”) is to use code-phase techniques to get close to the answer. If the code measurement can be made accurately to, say, a meter, then there will be only a few wavelengths of carrier to consider for determining the actual cycle (phase) that marks the edge of the timing pulse (Fig. 2-13). Resolving the “carrier phase ambiguity” for just a few cycles would be a complex computational challenge. Today, that process has been aided by algorithmic developments and the power of modern computers and microprocessor technology.

The GPS receiver position calculations are based on satellite combinations (four or more at once). Without knowledge of the particular carrier cycle being



**Figure 2-13.** Carrier phase ambiguity.

observed for each satellite, thousands of position solutions are possible. But with enough data it is possible to demonstrate one most-probable solution by statistical methods. The essence of centimeter-level GPS positioning is to acquire enough data sets (or epochs) to resolve the cycle ambiguities. Once the cycle ambiguities are resolved for a station, the lock may be maintained by uninterrupted observation. For each data epoch, a geodetic-grade receiver measures and records the carrier cycle count for each satellite on L1, L2, and L5; the relative carrier phase shifts between all satellite signals; and the estimated time of the data epoch.

## Antenna Phase Center

### *The Satellite and the Receiver*

The phase centers of both the satellite and the receiver antenna are important, as they serve as the end points of the measured distance between the satellite and the receiver on the ground. Their exact position is modeled by a consistent set of phase center offset (PCO) and variation (PCV) values. The PCO describes the vector from the receiver antenna reference point (ARP) or the satellite's center of mass to the mean phase center, whereas the PCV values provide additional zenith- and/or azimuth-dependent corrections to get the actual phase center position. These definitions are shown in Figs. 2-14 and 2-15.

In order to define the phase center, it is important to first define a GPS antenna *gain pattern*, which is the change in gain over a range of azimuths and elevations. It is a series of contours of equal phase around the “electrical center” of the antenna. Every GPS receiver antenna is designed to be omnidirectional and has a specific gain pattern. The gain pattern ought to be hemispherical around the antenna but it is usually not perfectly so.

### *GPS Receiver Antenna Phase Center*

For most antennas, and especially for high-precision applications, the gain pattern is designed to reject satellite signals from very low elevations to reduce the effects of multipath and atmospheric delay. However, the most important aspect of the gain pattern is its electrical center, which also referred to as the *phase center*. Figure 2-14 is an exaggerated illustration of a GPS antenna phase center. In a perfect GPS antenna, the phase center of the gain pattern would be exactly coincident with its actual physical geometrical center. If that were possible, the centering of the antenna over a measured point would ensure its electronic centering as well, but that absolute certainty remains elusive for several reasons (Van Sickle 2008).

### Phase Center Variations

The position at each end of a GPS baseline is the position of the phase center of the antenna at each end, not their physical geometrical centers. For each antenna, the location of the phase center changes slightly with each satellite's signal. For

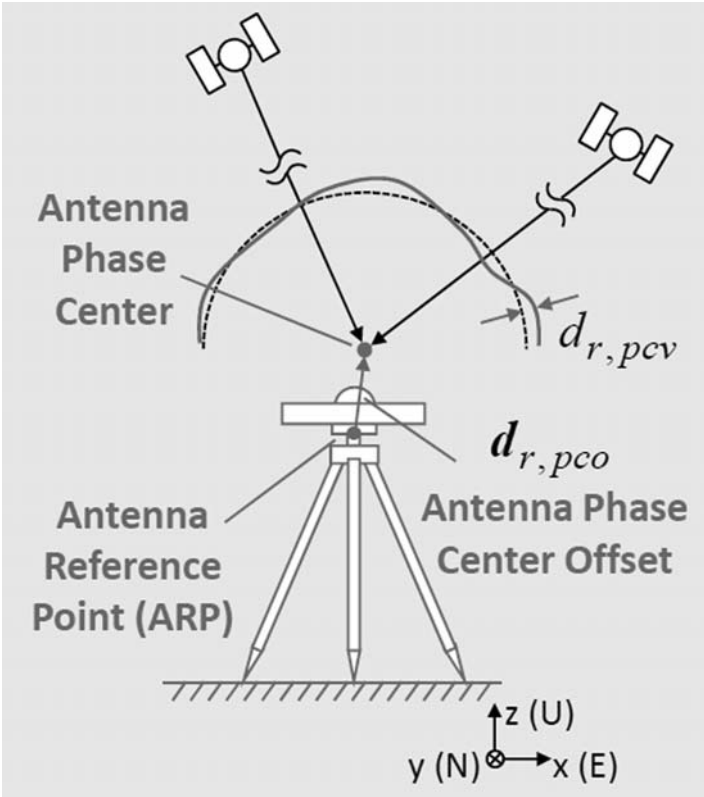


Figure 2-14. Receiver antenna phase center.

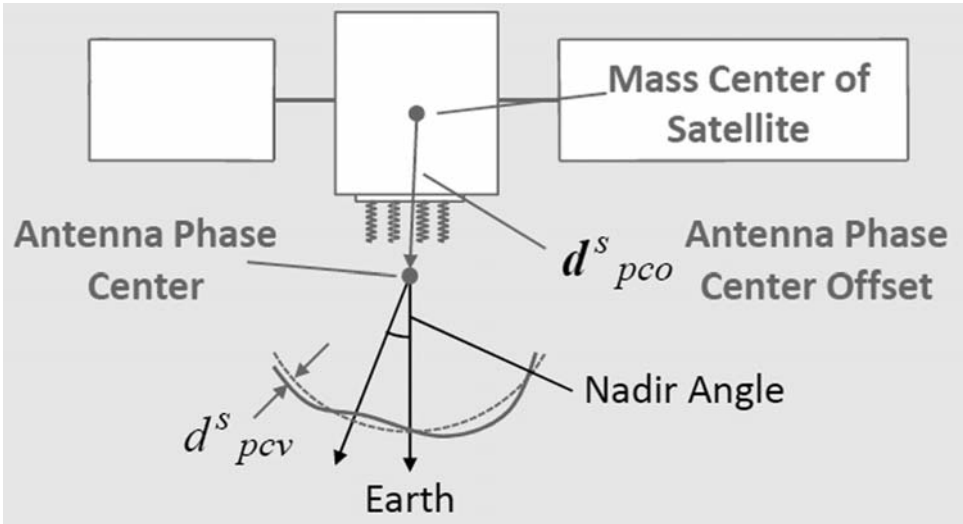


Figure 2-15. Satellite antenna phase center.

instance, it is different for the L1, L2, and L5 signals. As the azimuth, elevation, and intensity of the received signal changes, the difference between the phase center and the physical center also changes. For the most part, the phase center variation is due to changes in satellite elevation. The variations may be as much as a few centimeters, although with today's patch antennas it can be as little as a few millimeters. Fortunately, the phase center variations are systematic errors that can be modeled and compensated for when making measurements.

The International GNSS Service (IGS) provides reliable models for antenna phase center corrections for most of the modern geodetic-grade receivers. By using such models, it is possible to adjust the phase center impact out of the baseline solution. In addition, most manufacturers recommend that users take care when making simultaneous observations so that their antennas are oriented in the same direction. Some manufacturers provide physical reference marks on their antennas so that each one may be rotated to the same azimuth, usually north, to maintain the same relative position between their physical and electronic centers.

## **Error Sources**

There are four standard sources of error that contribute to the degradation of the accuracy of a calculated receiver position. These include satellite orbital and clock errors, signal propagation errors (ionospheric effects, tropospheric effects, and multipath), receiver noise and clock errors, and position dilution of precision (PDOP) due to satellite geometry.

### ***Satellite-Related Biases***

The satellite-related biases include satellite orbit (ephemeris) errors and satellite clock errors.

#### **Ephemeris (Orbital) Errors**

These errors originate at the satellite and occur when the GPS signal does not transmit the correct location of the satellites. The satellite orbit information is generated from the tracking data collected by the monitor stations within the Control Segment (Chapter 1, "Control Segment"). On a regular basis, the Master Control Station (MCS) in Colorado updates the satellite positions, calculates their predicted paths, and uploads this information back to the satellites. The information is stored in *almanac* files, which are automatically downloaded to the GPS receivers when they track the satellite signals. The receiver uses the almanac data to calculate the distance to the satellite. In reality, it is impossible to perfectly model the satellite orbit. Hence, the predicted satellite path would differ from the actual orbit. These discrepancies are the *satellite ephemeris errors*. If the satellite is in a different location from its predicted location in the almanac, the distance to the satellite is calculated incorrectly, which in turn generates inaccurate coordinates.

### Satellite Clock Errors

Because the receiver bases its calculation on the amount of time it takes for the signal to travel from the satellite to the receiver, any errors in the satellite clocks will affect the range measurement. The *satellite clock bias* is the difference between the satellite clock time and true GPS time. Despite the fact that high-quality atomic clocks (accurate to a nanosecond) are used in the GPS satellites, the satellite clock bias is still unavoidable. Satellite clock bias can cause deviation of up to  $10^{-8}$  seconds, leading to an error of roughly 3.5 m.

### Signal Propagation Biases

When the satellite signals travel from the satellite to the receiver, the signals will be affected by atmospheric delay and multipath. The atmosphere consists of two main layers, the ionosphere and troposphere, which affect the propagation of GPS signals.

### Atmospheric Errors

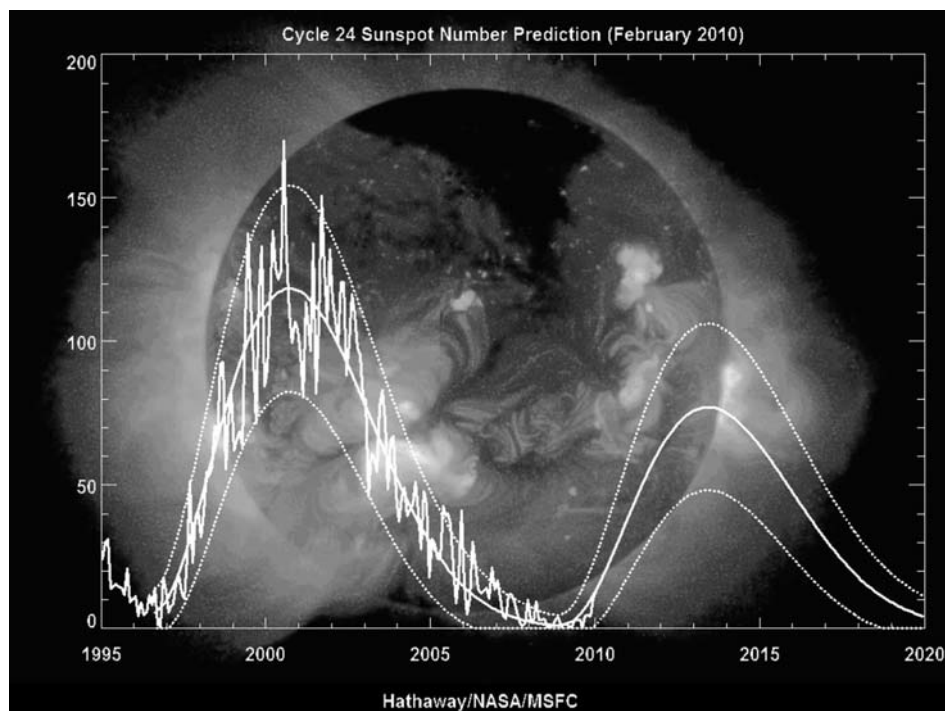
As the GPS signals leave the satellites, they first pass through the *ionosphere*. The ionosphere is the band of the atmosphere from about 50 to 1,000 km (30 to 625 mi.) above the Earth's surface (Hofmann-Wellenhof et al. 2001). It consists of layers of electrically charged particles or ions. Because of free electrons in this layer, the GPS signals do not travel at the speed of light as they transit this region. As a result, the measured pseudoranges become too long (Eq. 2-6) while, on the other hand, the measured phase ranges become too short (Eq. 2-7). The *ionospheric delay* is a function of the total electron content (TEC) along the signal path and the frequency of the propagated signal (Lin 1997). The TEC depends on time, season, and geographic location, with major influencing factors being the solar activity and the geomagnetic field (Fig. 2-16). In temperate zones, the ionosphere is more stable and the ionosphere delay can cause 2- to 5-m errors. However, in polar and equatorial regions where the ionosphere is less stable, errors can be greater. In extreme cases, the error can range from about 50 m (165 ft) for signals at the zenith of the observer to as much as 150 m (500 ft) for measurements made at the receiver's horizon.

The *troposphere* is that band of the atmosphere from the Earth's surface to about 50 km. The *tropospheric delay* is a function of elevation and altitude of the receiver, and is dependent on many factors such as the atmospheric pressure, temperature, and water vapor content. The tropospheric delay ranges from approximately 1 m for signals at the zenith to about 10 m for signals at an elevation angle of 10 deg.

### Multipath Errors

*Multipath* is the error caused by nearby reflecting surfaces at the receiver location. Just as light reflects off a shiny surface, radio signals can be reflected by solid objects and surfaces. GPS signals cannot penetrate solid objects like buildings,





**Figure 2-16.** Amount of sunspots since January 1995, with a forecast up to 2020. Source: NOAA.

thick tree canopies, cars, ships, and bridges. Instead, these objects deflect them, causing the signals to arrive at the receiver via multiple paths (Fig. 2-17). The reflected signals will interfere with the signals that are received via a direct path. The reflected signal travels for a longer time instead of traveling a direct signal path. As a result, this causes the receiver position to be calculated incorrectly, with the position shifting in the direction of the multipath source. Theoretically, the maximum pseudorange multipath error is approximately one chip length of the code [that is, about 300 m (1,000 ft) for the C/A-code and approximately 30 m (100 ft) for the P-code], while the maximum carrier phase multipath error is about one-quarter of the wavelength (that is, about 5 cm for the L1 carrier and 6 cm for the L2 carrier).

### **Receiver-Related Biases**

The receiver-related biases include the receiver clock bias, internal interchannel biases, antenna phase center variation, and receiver noise.

#### **Receiver Clock Bias**

Similar to the satellite clock bias, the *receiver clock bias* is an offset between the receiver clock time and true GPS time. Due to the fact that GPS receivers are usu-

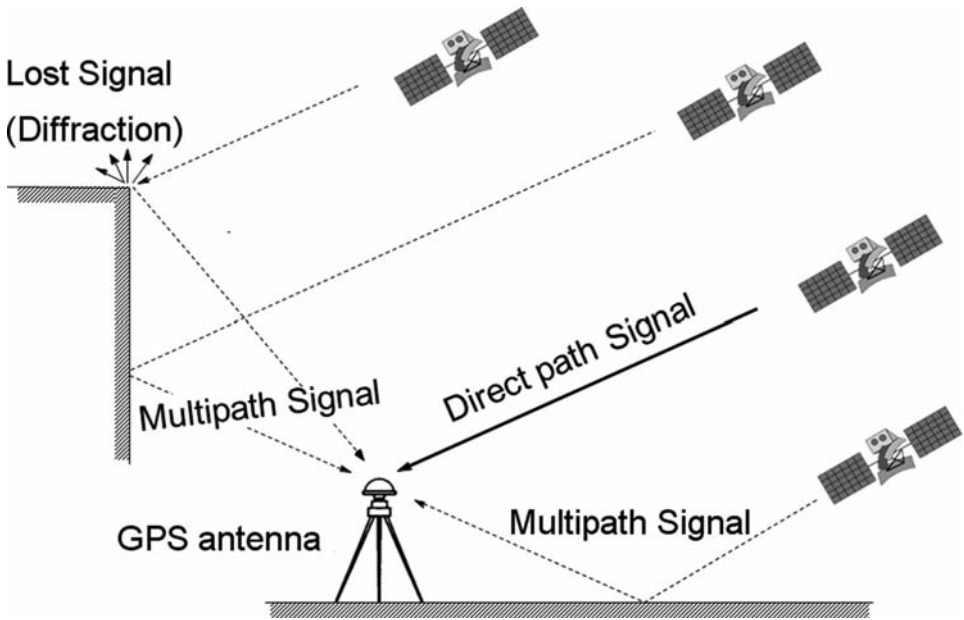


Figure 2-17. Multipath.

ally equipped with relatively inexpensive clocks, the receiver clock bias is very large compared to the satellite clock bias. GPS time is based on highly accurate atomic clocks, while GPS receivers contain inexpensive clocks similar to those in common digital watches. The atomic clocks are precise enough to determine time up to 11 decimal places (e.g., 10:05:46.01234567890), while a GPS receiver's clock is less precise and may only determine time to six decimal places (e.g., 10:05:46.012345). The slight difference between the two, as a result of rounding off, is due to the poorer precision of the receiver clock. Despite being a small discrepancy, it often results in an error of up to 1 m.

### Phase Center Offset

In GPS positioning, the measurements made by the receiver are usually referred to as the distance between the electrical center of the satellite's transmitter and the electrical center of the receiver's antenna. The discrepancy between the electrical center and the physical (geometric) center is the *phase center offset*. The electrical center tends to vary with the direction and strength of the incoming signal. In addition, the phase center variations for the L1 and L2 carriers may have different properties. For most antenna types, the antenna phase variation is usually calibrated by the manufacturers. In addition, the antenna phase center models for various antennas can be obtained from the National Geodetic Survey (NGS). These models can subsequently be applied to mitigate the effect of antenna phase variations. It is, however, recommended that for high-precision applications (discussed in detail in Chapter 5), care be taken not to mix antenna types or to swap antennas between sites and receivers during data collection.

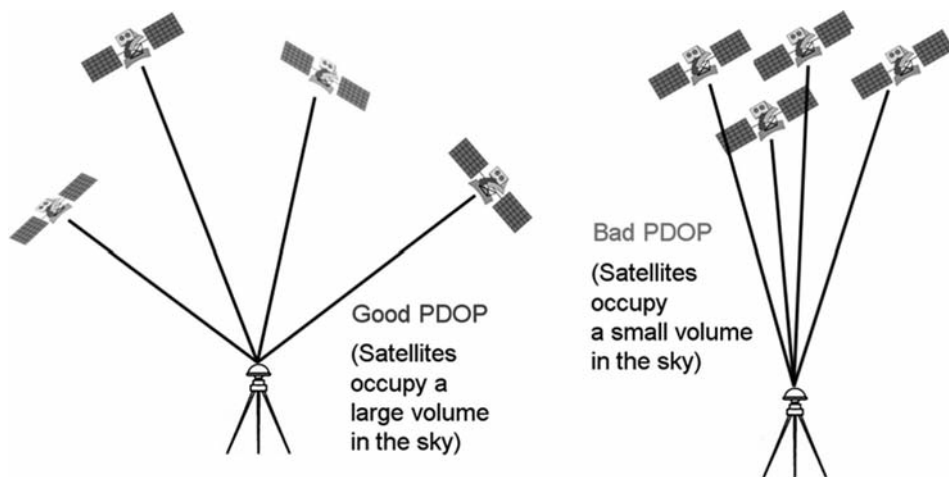
## Receiver Noise

The magnitude of the receiver noise is dependent on parameters such as the signal-to-noise ratio and tracking bandwidth. According to a rule of thumb for classic receivers, the measurement noise is approximately 1% of the signal wavelength. Therefore, the level of noise in pseudorange measurements is about 3 m (~300-m wavelength) for C/A-code and on the order of 0.3 m (~30-m wavelength) for P-code, while the level of noise in carrier phase is a few millimeters for L1 (~19-cm wavelength) and L2 (~24-cm wavelength). Modern receiver technology tends to bring the internal phase noise below 1 mm and to reduce the C/A-code noise to the decimeter level.

## Position Dilution of Precision (PDOP)

*Position dilution of precision (PDOP)* refers to the geometry of the satellites that are being used to calculate a position (Fig. 2-18). It is a measure of the quality of the GPS position coordinates based on the geometry of the satellites used to compute the position. When satellites are widely spaced relative to each other, the PDOP value is lower and the position accuracy is greater. When satellites are close together in the sky, the PDOP is higher and the GPS positions may contain a greater level of error. An ideal geometry of satellites is one in which four or more satellites are evenly distributed in the sky. A poor geometry is one in which satellites are close together.

PDOP is a combination of two other DOPs, the horizontal dilution of precision (HDOP) and the vertical dilution of precision (VDOP). Altogether, five different types of DOPs can be defined. For mathematical definitions behind the calculations of DOP values, see, for example, Axelrad and Brown (1996, p. 414) and



**Figure 2-18.** Geometrical interpretation of position dilution of precision (PDOP).

Hofmann-Wellenhof et al. (2001, pp. 271–275). It is important to note that the PDOP value has a scaling effect on the total error contributed by all of the above sources (satellite- and receiver-related biases, and signal propagation errors).

While values of PDOP can range from 1 to 100, in most circumstances the values are low, with the typical PDOP value worldwide being 2.7. The total error generated by all the other error sources is multiplied by PDOP value to give a final overall error for the position coordinates. Therefore, if you assume a 5-m error from all the other error sources, a PDOP of 3 gives an overall error of 15 m, while a PDOP of 7 gives an overall error of 35 m.

### **Overall Error Contributions**

All the errors discussed here make it sound like GPS is not as accurate as proclaimed. However, when all the errors are combined, they average out to about 3- to 15-m accuracy worldwide. Due to basic error correction algorithms built into them, all receivers are capable of compensating for offsets due to receiver clock bias. Table 2-1, adapted from Table 2 in Parkinson (1996, p. 480), shows a breakdown of the theoretical contribution of each error source.

### **Error Correction Methods**

Two methods for error correction are *point averaging* (for removing systematic errors such as multipath) and *differencing* (a focus of Chapter 3). Point averaging is used in high-end recreational receivers and some mapping-grade receivers. Differencing, also known as *differential correction*, is a more advanced error correction method that improves the calculated coordinates based on error measured by another receiver at a known location (see Chapter 3, “Differential GPS”). There are two types of differential correction: *postprocessing* and *real-time*. In both methods, two receivers are utilized, both of which must be mapping-grade or higher quality. One receiver, known as the *base station*, is located at a precisely surveyed location. The second receiver, known as the *rover*, is used to collect data (the rover can be either stationary or moving while collecting the data). For differential correction to work properly, the two receivers must be working concurrently and must be within 20 km (13 mi.) of each other. They are required to observe common satellites. Through data differencing, most of the errors (ephemeris, clock biases, and atmospheric errors) can be removed to improve accuracy to the level that is required for high-precision applications.

### **Correction for Satellite Clock Biases**

One way to account for the satellite clock bias is to use the broadcast clock error model generated by the Master Control Station and defined by polynomial coefficients. Even with the best efforts in monitoring the behavior of each satellite clock, their behavior cannot be precisely predicted. As a result, there is a residual error after applying the broadcast clock error model. In the case of relative positioning (Chapter 3, “Relative Positioning”), the satellite clock bias can be eliminated by

differencing the measurements obtained from two receivers since the satellite clock bias is the same for two receivers observing the same satellite at the same time.

### **Correction for Ionospheric Delay**

Due to the fact that the ionospheric delays are highly correlated over distances of up to a few tens of kilometers, the impact of the ionospheric delay can be significantly reduced by forming a difference between the measurements made by two receivers on short baselines to the same satellite (see Chapter 3, “Relative Positioning”).

### **Correction for Tropospheric Delay**

Unlike the ionospheric delay, the tropospheric delay is not frequency-dependent. It cannot be eliminated through linear combinations of L1 and L2 observations. Several “standard” troposphere models can be used to estimate the magnitude of the tropospheric delay (e.g., the Saastamoinen model, the Hopfield model, the Black model, and others). The signal refraction due to the troposphere is separated into two components, the dry component and the wet component. Due to the high variation in the wet component, it is difficult to predict or model this component. As a result, the standard models can account for about 90% of the total delay (the dry component). Similar to the ionospheric delay, the tropospheric delay can be largely eliminated by forming a difference between the measurements made by two receivers on short baselines to the same satellite. For high-precision static applications, the residual tropospheric delays in the double-differenced observables may be treated as additional unknown parameters in the baseline estimation procedure.

### **Correction for Multipath Effect**

Since the multipath error depends on the receiver’s environment, it cannot be eliminated or reduced by using the data differencing technique (Chapter 3, “Relative Positioning”). To reduce multipath effects, (1) make a careful selection of the data collection site(s) in order to avoid reflective environments; (2) use a good-quality antenna that is multipath-resistant; (3) use a receiver that can internally digitally filter out the multipath disturbance; and (4) do not observe low-elevation satellites (their signals are more susceptible to multipath).

# Improving Accuracy

## Positioning and Data Processing Methods

### ***Point Positioning***

If one receiver is used to determine the absolute coordinates of any point on Earth, in the WGS-84 system (described in Chapter 2), the positioning technique is known as *single point positioning*. This technique can be further divided into two classes depending on the range measurements used, namely, *pseudorange-based point positioning* and *carrier phase-based point positioning*.

In the pseudorange-based point positioning mode, the basic principle is to use resection (trilateration) by distances to determine the receiver's coordinates. If the satellite coordinates are assumed to be known (as they are provided to the user within the almanac or ephemeris), the receiver's coordinates can be computed from the resection using the measured pseudoranges. For civilian users, the accuracy of this method is currently about 5 m in the horizontal component and 10 m in the vertical component (at the 95% confidence level).

Due to the availability of precise GPS orbits and satellite clock corrections, a technique referred to as GPS *precise point positioning* (PPP) is possible, based on the principle of carrier phase-based single point positioning. This technique uses the carrier phase measurements from both frequencies (L1 and L2), with the post-mission information in the estimation procedure, producing high-precision point positioning results. Nevertheless, it requires a reasonably large amount of data and postprocessed GPS orbit and clock products, implying that instantaneous solutions are not yet possible. The orbit and clock products are offered by some organizations such as NASA's Jet Propulsion Laboratory and the International GNSS Service (IGS). For practical examples of these services, see Chapter 4, "DGPS Networks and Services" and Chapter 5, "Network RTK and CORS Networks Infrastructure."

### ***Relative Positioning***

In the relative positioning method, also commonly referred to as *differential GPS* (DGPS) *positioning*, two GPS receivers are used to observe the same satellites

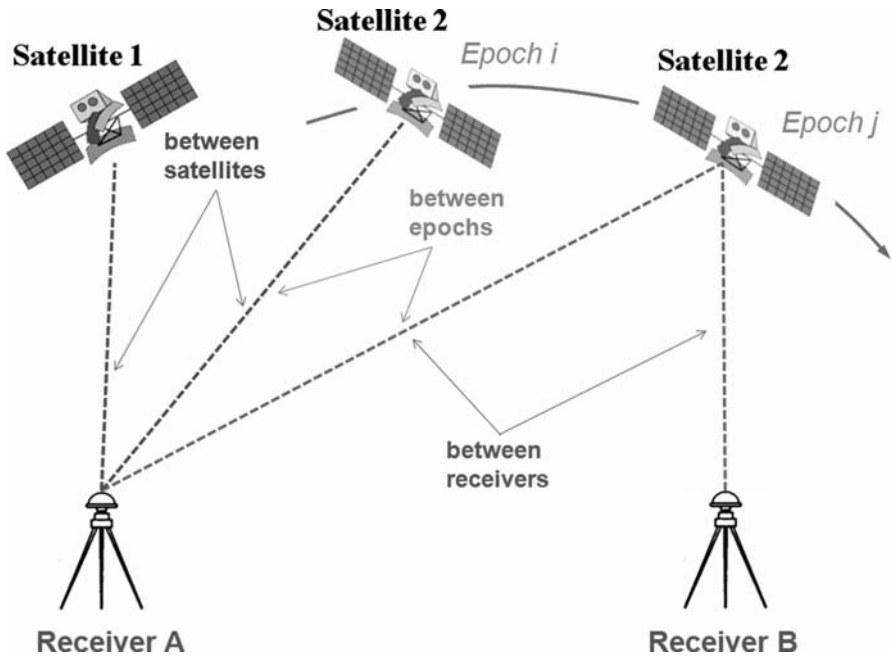
simultaneously. One receiver, designated as the “base,” is set up at a reference station the coordinates of which are known. The other receiver, designated as the “rover,” is used to determine its coordinates with respect to the base (reference) station. In this case, by subtracting the observations at the reference station from those at the rover, the single-difference equations are derived from Eqs. 2-6 and 2-7 in Chapter 2. This technique reduces many of the systematic biases (e.g., satellite orbit bias, satellite clock error, and ionospheric and tropospheric delays) and is extensively used in data processing schemes for applications requiring millimeter- to centimeter-level accuracy. However, the effectiveness of the relative positioning technique is largely dependent on the distance between the two receivers. The residual error increases as the distance between the receivers increases.

Relative positioning can further be divided into two classes depending on the measurements used, namely, *pseudorange-based differential positioning* (code phase DGPS) and *carrier phase-based differential positioning* (carrier phase DGPS).

In code phase DGPS, the estimation of the range error for each satellite is carried out at the reference station. The estimated range errors (or corrections to the measurements) are broadcast to the users by an appropriate communication link (Parkinson and Enge 1996). For operations over a small area, one reference station is typically used and the technique is generally referred to as *local area differential GPS* (LADGPS). However, if a network of reference stations is employed to generate the range corrections for each satellite, the correction data model is valid over a much larger area and the technique is referred to as *wide area differential GPS* (WADGPS). Finally, in a case where the geostationary satellites transmit to users the DGPS corrections for each satellite, together with additional GPS-like ranging signals and an integrity message, the concept is known as a *wide area augmentation system* (WAAS). Detailed explanations of these DGPS techniques can be found in Enge and Van Dierendonck (1996). The DGPS systems, networks, and services are discussed in detail in Chapter 4.

Carrier phase DGPS is realized by either differencing the carrier-phase measurements made to the same satellite by two receivers at the same time, or differencing the carrier-phase measurements to two satellites made by the same receiver at the same time. The former method is referred to as *single differencing between receivers* while the latter is referred to as *single differencing between satellites*. If the difference between the single differenced observations is formed, a process referred to as *double differencing* (the resultant double-differenced observable) is the standard input for carrier phase-based data processing. There is even a third differencing, referred to as *triple differencing*. In this case, a difference is formed between two epochs of double-differenced observations. Each of the three data processing methods is effective in reducing specific systematic errors (Fig. 3-1, Table 3-1, and Appendix 5). However, the standard method used in carrier phase DGPS is double differencing.

Carrier phase DGPS can be carried out in static or kinematic mode. If carried out in kinematic mode, the technique is referred to as *kinematic positioning*, implying that either (or both) the reference and user receivers are in motion. Today, with advanced receiver technology and improved data processing algorithms, it is



**Figure 3-1.** Differencing GPS in different ways to eliminate systematic errors.

**Table 3-1.** Data Processing Methods for Improving Accuracy Using Relative Positioning

<i>Data Processing Method</i>	<i>Overall Impact and Effectiveness in Eliminating Errors</i>
Between-satellite difference (see Fig. 3-1)	<i>Eliminates receiver clock bias.</i> Assume simultaneous observations to each satellite.
Between-receiver difference (see Fig. 3-1)	<i>Eliminates satellite clock bias.</i> Greatly reduces ephemeris, ionospheric, and tropospheric biases (if baseline is short). Assume simultaneous observations by each receiver
Receiver–satellite double difference <i>This is the basic method used for high-precision GPS positioning and in high-end GPS receivers</i>	<i>Eliminates receiver and satellite clock biases.</i> Significantly reduces effect of ephemeris, ionospheric and tropospheric biases (if baseline is short). Carrier phase ambiguity term remains.
Triple difference	<i>Eliminates carrier phase ambiguity term.</i> Useful for preliminary baseline computations using carrier phase data, and for cycle slip detection/repair.
Between-epoch difference (see Fig. 3-1)	<i>Eliminates carrier phase ambiguity term.</i> Greatly reduces ephemeris, ionospheric, and tropospheric biases (if epoch separation is short).



possible to obtain high-precision results (sub-centimeter) in real time using the *real-time kinematic* (RTK) GPS positioning method (discussed in Chapter 5, “Real-Time Kinematic (RTK) Systems”).

### **Differential GPS**

In DGPS, the base antenna is deployed over a benchmark or control point for which the position is known. As demonstrated in Table 3-1, the method can correct for a number of GPS errors and thus enhance the position calculation beyond the regular GPS level. The main classification of DGPS systems is based upon the part of the GPS signal used to calculate the differences:

- Code phase DGPS uses the C/A code of the signal
- Carrier phase DGPS uses the carrier wave (L1, L2, L5)

The other classifications, WAAS and LADGPS [or local area augmentation system (LAAS)], are generally based on the area over which the corrections are valid; for example, WAAS covers an area the size of a continent or an ocean and LAAS covers a small area such as a construction site or an airfield. The classification can also be based on the location of station transmitting the corrections or the type of communication link for transmitting the corrections. For example:

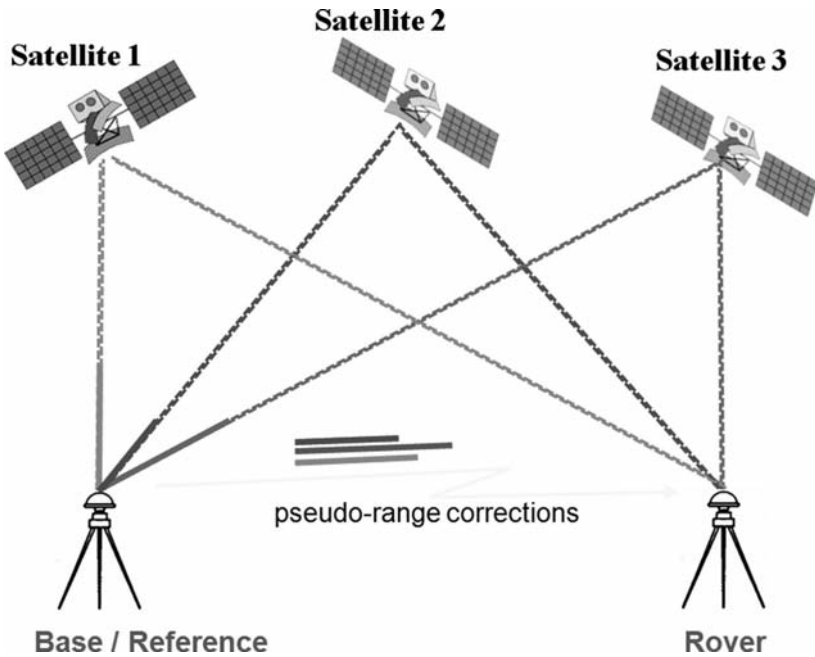
- Satellite-based augmentation systems (SBAS) employ satellites to transmit the corrections toward the mobile receivers. Usually SBAS systems are also WAAS systems, but not necessarily the other way round.
- Ground-based augmentation systems (GBAS) employ transmitters at ground level. These transmitters can either transmit over radio or telephone lines.

The WAAS and LAAS systems are further discussed in Chapter 4.

### **Code Phase DGPS**

In code phase DGPS, the base measures the pseudoranges to the satellites. The base also calculates the theoretical pseudoranges using the known control point coordinates and satellite coordinates. From these calculations follows a range difference between the measured and the theoretical pseudorange, called the *computed minus observed* ( $C - O$ ). The  $C - O$  corrections are then sent, one for each satellite, to the rover using some form of telemetry. The common forms of telemetry are radio telemetry, satellite telemetry, or the use of cellular phones. Figure 3-2 illustrates the code phase DGPS principle.

The true error at the rover will differ from that at the base but, since the satellites are at a relatively long distance compared to the base-rover distance, the  $C - O$  corrections are generally valid. The longer the base-rover separation distance (the “baseline”), the lower the accuracy of the corrections and thus the precision of the rover position. Errors at the base, such as multipath, will have a direct influence on the quality of the DGPS correction and thus on the rover position.



**Figure 3-2.** Principle of code phase DGPS.

In code phase DGPS, a precision on the order of 1 to 2 m can be achieved. However, the actual precision depends on the baseline length and the telemetry frequency chosen for transmitting the corrections.

### Carrier Phase DGPS

In the case of code phase DGPS, the signal travel time is measured using the C/A-code. The C/A-code has a bit rate of about 1 MHz. For transmission from the satellite to the receiver, this code is modulated onto a carrier frequency that is about 1,000 times faster. The carrier signal (L1, L2, or L5) is perfectly shaped as a sine wave with a wavelength of about 20 cm. This carrier can function as a much more accurate reference than the C/A code.

By counting the number of cycles and phase of the carrier wave, the travel time can be determined much more precisely. As a consequence, however, determining the corrections with carrier phase DGPS requires more computations than when using the C/A code. A major issue is the determination of the whole number of wavelengths (cycles) between the satellite and the receiver. This whole number of cycles is called the *integer ambiguity* and needs to be resolved during the initialization of the system. Resolving the integer ambiguity requires two receivers making measurements with at least five common satellites. From this starting point, the receiver tracks the change in cycles as the distance between the satellite and receiver changes with time.

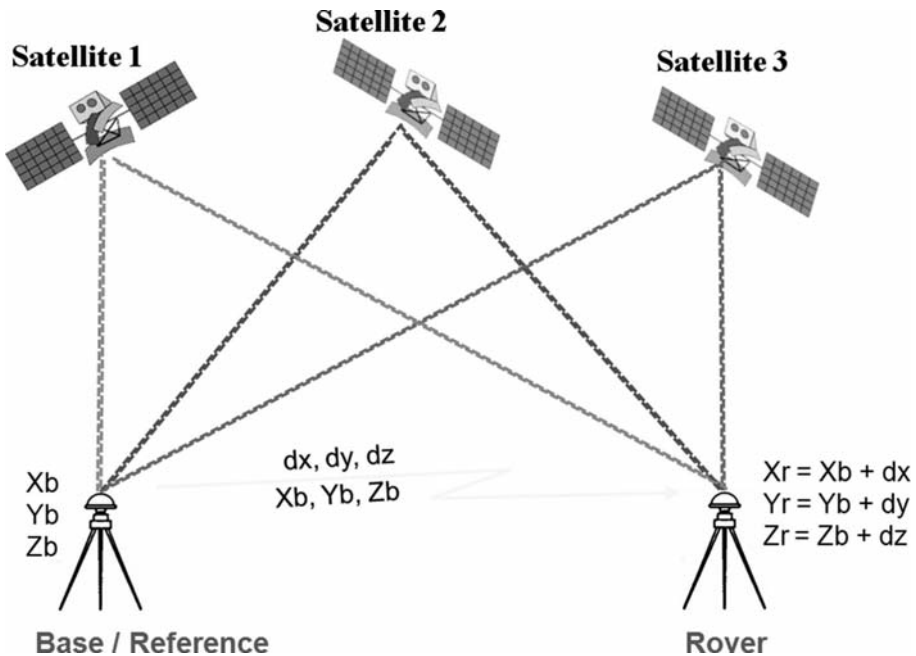
The result of a carrier phase DGPS is a difference in the X, Y, Z coordinates between the base and the rover. No absolute positions are calculated at either the base or the rover—the absolute position of the rover is found by adding the  $dx$ ,  $dy$ ,  $dz$  to the absolute coordinates of the base, as illustrated in Fig. 3-3.

For practical applications, a carrier phase DGPS plays the role of long-range total station equipment, giving the range and bearing without the need for a line-of-sight between the base and the rover. For height measurements, it plays the role of level equipment but its measurements are based on the ellipsoid rather than the geoid, as with a traditional level.

### Carrier Phase Techniques

Table 3-2 provides an overview of the carrier phase techniques that are in use today. It is important to note the following definitions when using the table:

- *Postprocessing*: measurements are taken in the field and processed later in the office.
- *Real time*: measurements are taken and processed in the field and coordinate results are available or visible at the time of the measurements.



**Figure 3-3.** Principle of carrier phase DGPS.

$(X_b, Y_b, Z_b)$  are absolute base coordinates;  $(X_r, Y_r, Z_r)$  are absolute rover coordinates;  $(dx, dy, dz)$  is the distance vector between the base and the rover, derived at the base.

**Table 3-2.** Overview of Carrier Phase Techniques

<i>Technique</i>	<i>Specifics</i>	<i>Precision (Confidence Level)</i>	<i>Applications</i>
Static	Postprocessing Static initialization 1–2-h measurement Range: tens of km	Horizontal: <1 cm (95%) Vertical: centimeters	Geodetic surveys, engineering control
Rapid static	Postprocessing Static initialization 5–15-min. measurement Range: tens of km	Horizontal: 0.5–1 cm Vertical: centimeters (95%)	Geodetic surveys, site control surveys
Kinematic	Postprocessing Static initialization Continuous measurement Range: tens of km	Horizontal: 0.5–2 cm Vertical: 1–5 cm (95%)	Engineering and detail surveys, topographic and location surveys
Real-time kinematic (RTK)	Real-time or postprocessing Initialization during movement Continuous measurement Range: up to 15 km	Horizontal: 0.5–2 cm Vertical: 1–5 cm (95%)	Topographic and location surveys, machine control and guidance, real-time monitoring
Long-range RTK	Real-time or postprocessing Initialization during movement Continuous measurement Range: tens to hundreds of km	Horizontal: 1–5 cm Vertical: 1–10 cm (95%)	Hydrographic surveys, ship navigation and guidance, unpiloted aerial vehicles (UAVs)
Satellite RTK	Real-time or postprocessing Initialization during movement Continuous measurement Range: hundreds of km	Horizontal: 1–5 dm Vertical: decimeters (95%)	Oceanographic surveys, offshore surveys, ship navigation

- *Static initialization*: the GPS measuring equipment or setup may not move during initialization. Initialization is the process of resolving the integer ambiguity.
- *Continuous measurement*: measurements are taken without breaks or sessions, and mostly while moving, thus creating a continuous profile or time series.

**Static and Rapid Static**

*Static* and *rapid static* carrier phase DGPS are the most commonly used techniques for high-precision positioning applications requiring only a single set of precise coordinates for every point measured. Examples of such applications include

geodetic surveys, engineering, and site control. Data are collected on one or more points for 1 to 2 hours (or longer) in the static mode or 5 to 30 min. in the rapid static mode. The data are postprocessed to solve the integer ambiguity, and baselines between surveyed points are calculated. In general, three other known points external to the points being calculated are used to validate the baseline measurements and to calculate absolute positions from the relative baselines. The external points (control points) are used as project control. When used correctly with well-known control points, the accuracy of these techniques can be less than 1 cm for horizontal (X and Y) coordinates and around 2 cm for the vertical (Z) coordinate. The only disadvantage of this technique is that it is postprocessed, so most of the quality information needed is available with a delay of days to weeks (for example, precise orbits are normally available approximately 2 weeks from the date of data collection). In addition, the GPS antennas at the base and the rover must remain stationary during the entire data collection period.

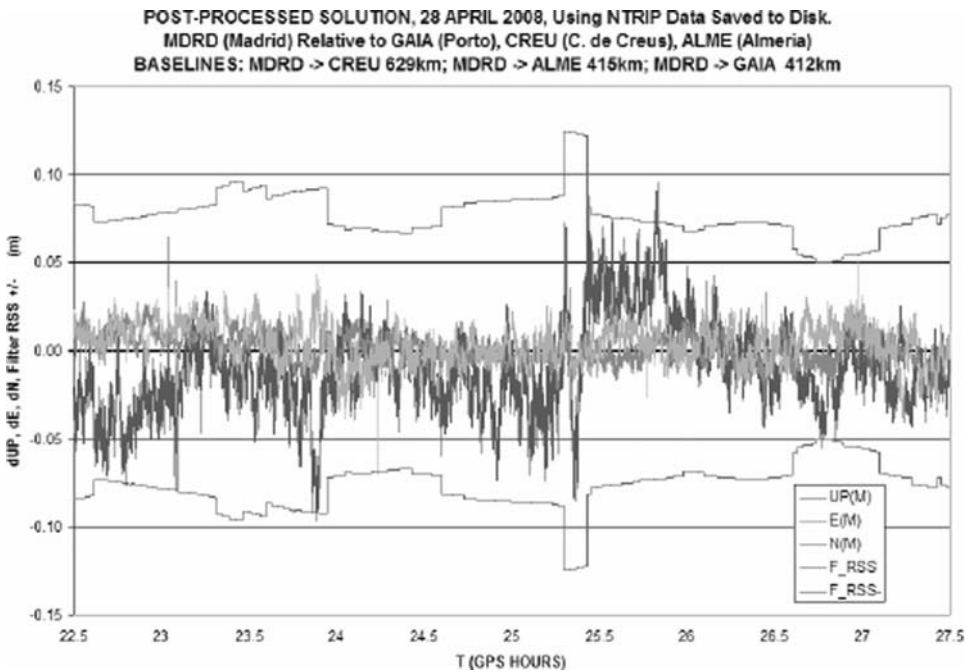
### **Kinematic**

In this technique, the roving antenna is allowed to move after initialization but the base station must still remain stationary. The roving antenna can also remain stationary during the data collection process, and that would not negate the concept of kinematic positioning. The data collected from both the base and the rover are postprocessed. This technique is commonly used in detailed engineering and topographic surveys, and is suitable for applications requiring the positioning of a large number of point, line, or area features within a project location. Although the results are postprocessed, this method provides a cost-effective carrier phase solution and has the advantage of using relatively inexpensive receivers.

### **Real-Time Kinematic**

Real-time kinematic (RTK) is the most commonly used carrier phase DGPS technique. Initialization is done “on-the-fly” (OTF) and, hence, this technique is also sometimes referred to as RTK OTF. Its main advantage is that there is no need for postprocessing or static initialization. The integer ambiguity is solved on-the-fly using data transmitted by the base to the rover, and this can be done while the rover is moving. In standard RTK only one base station is used but new methods have been developed to allow for use of data from multiple base stations, thus increasing accuracy and quality control. The achievable precision ranges from the centimeter-level (with standard RTK) to decimeter-level (with long-range and satellite-based RTK). See examples in Figs. 3-4 and 3-5.

Long-range RTK is based on same technology as standard RTK but has an extended range of tens to hundreds of kilometers (Colombo et al. 2003) using ultra-high frequency (UHF) data links. Similarly, satellite-based RTK has a range of hundreds of kilometers using satellite data links. A technique for real-time, wide-area differential kinematic positioning at the decimeter level has been tested with data from GPS stations in Europe and the United States, streamed in real time over the Internet by various organizations using the protocol known as Network Transport of RTCM via Internet Protocol (NTRIP) (Fig. 3-4).



**Figure 3-4.** Long-range kinematic positioning using data from Networked Transport of RTCM via Internet Protocol (NTRIP) streams. RTCM is Radio Technical Commission for Maritime Services. *Source:* Colombo (2008).

### Network Reference Systems

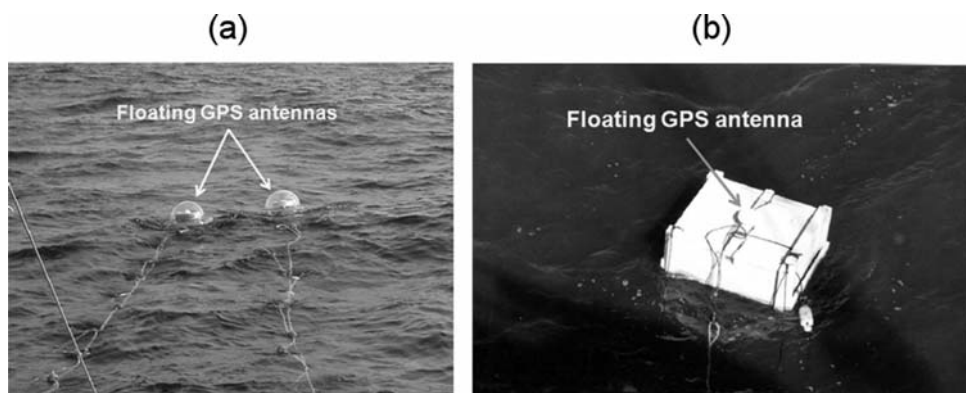
The basic setup of a DGPS system consists of a single base station or a network of base stations. As a general rule, single projects usually only require single base station DGPS. Even on large projects that may employ multiple base stations, the base stations are usually operating independent of each other.

DGPS networks comprised of multiple base (reference) stations have been set up in many regions of the world (see Chapters 4 and 5 for further details). Most of such DGPS networks are operated on a commercial or government basis whereby the base stations continuously exchange measurements and check on each other. This ensures higher network reliability, such that abnormalities or errors in a single base station can be easily detected. In addition, it is possible to use combined error corrections from multiple base stations, in a technique known as a *virtual reference station* (VRS) network solution.

Two types of DGPS network reference systems exist; one is based on centralized processing and the other is based on the onboard processing solution at the rover.

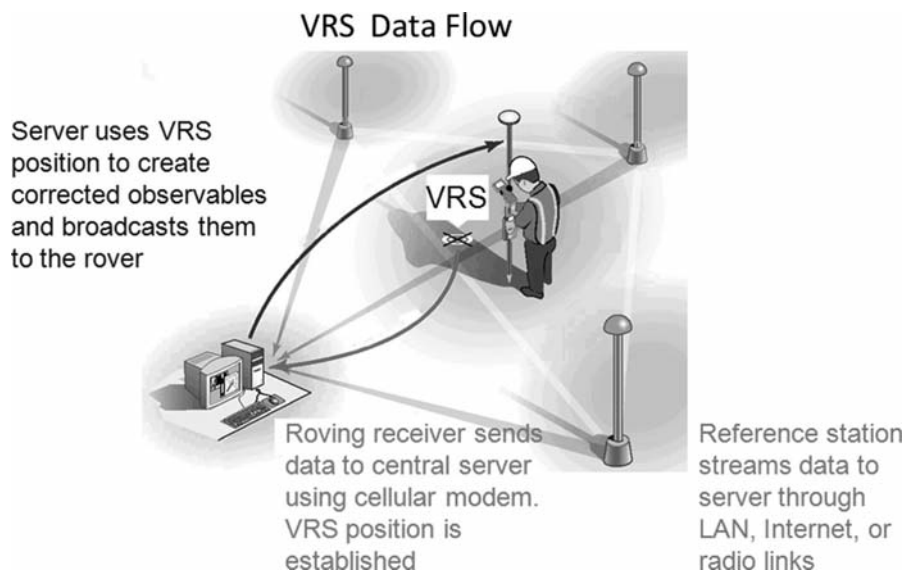
### Centralized Processing Networks

In VRS networks a number of reference stations measure the range corrections and transmit them to a central processing hub. The hub then combines the data



**Figure 3-5.** Long-range (>1,000 km) kinematic positioning of buoys at sea. (a) Buoys being towed by a small craft during test; (b) close-up of a floating buoy showing a small, round GPS antenna on top. *Source:* Colombo et al. (2000).

from the various reference stations into one solution set of range corrections. The combined set of errors is transmitted via a data link to the rover, where the range corrections are applied to the measured pseudoranges. In this kind of network there is a need to transmit the estimated rover position to the network. Hence, a bidirectional telemetry (such as that in cellular phones) is most desirable for data transmission. Figure 3-6 shows the VRS data flow concept.



**Figure 3-6.** Virtual reference station (VRS) data flow.

Courtesy of Trimble Navigation Limited © 2011.

In another form of centralized hub processing, multiple base stations are included in a postprocessing solution for which telemetry is not required. Practical examples of such networks (in addition to VRS) are discussed in Chapters 4 and 5.

### **Onboard Processing at the Rover**

When processing onboard at the rover, a number of telemetry sources can be used, such as SBAS and GBAS corrections. The rover combines these into a single set of corrections for each satellite using a least-squares adjustment technique in which a weighting of the different correction sources can be applied (e.g., based on the telemetry method or the baseline distance between the base and rover). An important aspect of this method is that multiple-reference DGPS receivers are generally more expensive than the single-reference DGPS receivers.



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# Low-Cost GPS Systems

Two important factors can be used to distinguish a low-cost GPS system. First, at the time of this writing they range in price from under US\$100 to US\$5,000 or thereabouts. Second, positioning accuracy requirements are not as stringent as in high-precision systems (the latter are discussed in Chapter 5). For these systems other factors such as signal integrity, availability, and reliability may be more important than high precision. They cost much less, relative to high-precision systems, due to less investment in the hardware and signal processing—the positioning principles are based on point positioning and broadcast differential corrections (described in Chapter 3).

Table 4-1 gives an overview of some of the features of low-cost GPS systems. These features, as shown in the various columns of the table, will be explained throughout this chapter. The discussion is based on two categories of low-cost GPS systems, namely, navigational GPS systems and differential GPS (DGPS) systems.

## **Navigational GPS Systems**

Navigational GPS systems are at the lower end of the spectrum in terms of both accuracy and cost. There are many different types of navigational systems, as we will see shortly. But first, let us look at the features of navigational GPS systems.

### ***Receiver Channels and Frequencies***

The GPS receiver consists of the radio receiver, the microprocessor, and the input/output interface. The radio receiver defines the number of frequencies (L1, L2, L5) that the receiver can receive as well as the number of satellites it can track (acquire) at one time. Signals from different satellites enter the receiver simultaneously via a GPS antenna, but the antenna itself does not sort the information it gathers. The signals are identified and separated from one another in the channels of the radio receiver. A receiver may have as few as 3 or as many as 72 physical channels. However, one should bear in mind that the number of channels is not analogous to the number of satellites tracked; every single frequency for each satellite takes a single channel in a parallel receiver. A 12-channel, single-frequency receiver

**Table 4-1.** Features of Low-Cost GPS Systems

<i>Application</i>	<i>Recreation</i>	<i>Car Navigation</i>	<i>Tracking</i>	<i>Shipping</i>	<i>Aviation</i>	<i>GIS</i>	<i>Construction</i>	<i>Agriculture</i>
Number of channels	–	–	–	–	±	±	+	+
Number of frequencies	1	1	1	1	2	1	2+	2+
Antenna (internal/external)	i	ie	i	e	e	ie	e	e
Power supply	i	ie	i	e	e	ie	e	e
Size	+	+	+	–	–	+	+	+
Weight	+	±	+	±	±	+	±	±
Robustness	+	±	+	±	+	+	+	+
User interface	s	s	–	s	s	s	sc	sc
Display	±	+	±	±	±	+	+	+
DGPS reception	w <sup>1</sup>	w <sup>1</sup>	±	+	+	±	+	+
DGPS range	–	–	±	+	+	±	±	±
Communication	–	–	p	p	p	i	p	p
Data exchange	–	–	±	±	±	+	±	±

–, less important; +, important; ±, may or may not be important.

w<sup>1</sup>: WAAS/EGNOS is a benefit, but not required.

i, internal; e, external; s, screen; c, externally controlled; p, communication port.

can track 12 satellites on L1, whereas a 12-channel dual-frequency receiver can track 6 satellites on L1 and L2. In the past, when radio chipsets were relatively expensive, methods such as sequential and multiplex receiving were used whereby only a few radio channels could be used to track a large number of satellites. The disadvantage of those techniques was that only a few satellites could be tracked at a given time. The alternative is parallel receivers, where the number of satellites that can be tracked depends on the number of channels a receiver has. While this feature is less important in navigational GPS systems and 12 channels were once excessive (c. 1995), multichannel design is now the standard for in-car navigation receivers.

### **Antenna**

Most navigational GPS receivers have a built-in antenna, but many can also accommodate a separate externally connected antenna. The separate antennas with their connecting coaxial cables in standard lengths are usually available from the receiver manufacturers. For most navigational GPS receivers, the antennas are single-frequency capable. The wavelengths of the GPS carriers are 19.0 cm (L1), 24.4 cm (L2), and 25.5 cm (L5); antennas that are one-quarter or one-half wavelength tend to be the most practical and efficient, so GPS antenna elements can be as small as 4 to 6 cm. Most receiver manufacturers use *microstrip* (also known as *patch*) antennas. These antennas can receive one or two GPS frequencies, although dual-frequency microchip antennas often have two patches, one for each frequency. A *quadrifilar* antenna is a single-frequency antenna that has two orthogonal bifilar helical loops on a common axis. Quadrifilar antennas perform better than microstrip antennas on crafts that pitch and roll, like boats and airplanes. They are also used in many recreational handheld GPS receivers.

### **Power Supply**

Power supplies to navigational units are mostly internal battery, some with recharge capability. Some manufacturers also provide external power supplies as additional accessories. A variety of batteries are used and there are various configurations. Some GPS units use camcorder batteries but handheld recreational GPS units often use disposable AA or AAA batteries. The most important question to ask when considering power supply is how long it performs on a single charge. And is there an external power supply to the receiver? In differential GPS applications (see next section), rechargeable batteries are the norm.

### **Size and Weight**

Generally speaking, the size and weight of a GPS receiver relate to the amount of memory required for data processing and storage. Recreational receivers do not have substantial memory as it is not needed for their designed applications. They generally only use the C/A code on the L1 frequency and are accurate to approximately 10 to 30 m. They are smaller in size and weigh much less compared to differential receivers. However, while most recreational and navigational receivers

are not capable of tracking the carrier phase observable (refer to Chapter 2, Eq. 2-7), some have differential capability. These receivers were developed with navigation in mind and, in fact, they are sometimes categorized by the number of waypoints they can store. *Waypoint* grew out of military usage, and it means the coordinate of an intermediate position that a person, vehicle, or airplane must pass to reach a desired destination. With such a receiver, a navigator may call up a distance and direction from the present location to the next waypoint.

### ***User Interface and Display***

Most receivers have a control and display unit (CDU). From handheld keypads to touch-screen to digital map displays and interfaces to other instrumentation, there are a variety of configurations. The control and display unit facilitates the interaction between the operator and the receiver's microprocessor. In recreational handheld receivers, the CDU is screen-based and may offer a combination of help menus, prompts, waypoint map display, the satellites being tracked, the receiver's position in 3-D, GPS time, and velocity information, among other features. In some units, the CDU may also be used to display the satellite numbers (or pseudo random noise, PRN) and dilution of precision (DOP) values. Generally, the information available from the CDU varies from receiver to receiver.

### ***Communication and Data Interface***

Additional accessories for data communication and interface may include external cables for data download and interfacing with external instrumentation or devices.

### ***Handheld GPS Receivers***

Recreational receivers are usually simple in construction, robust, waterproof, and sometimes have additional altimeters, compasses, and thermometers to provide users with all sorts of information. Figure 4-1 shows an example. They are great for outdoor activities such as hiking or mountain biking, but engineers may also use them to find project points in unfamiliar locations. At every level of GPS technology, the trend is to design smaller and better, with more features, and modern handheld GPS receivers also display a small (base) map for crude navigation. Specific games such as geocaching rely on the use of such receivers to guide the gamers toward an item stored at a specific undisclosed location.

### ***Car Navigation GPS Systems***

More than 90% of all GPS units sold today are used in navigation. In-car navigation GPS systems are relatively inexpensive and reliable (Fig. 4-2). They have detailed, reliable in-built maps of portions of the world that are updated on a regular basis. They are the ultimate modern traveling companion and guide, although users ought to be cautious not to overly rely on technology at the peril



**Figure 4-1.** Garmin handheld recreational GPS receiver with compass and barometric altimeter. Such receivers can be DGPS if WAAS-enabled.

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of totally forsaking paper-based topographic maps. The in-car navigation systems have many desirable features. They have wide screens and integrated voice devices—you can create a route and then put your mind on “cruise control” as you follow clear, accurate, voice-prompted, turn-by-turn directions to safely reach your destination. They have simple, intuitive menus that offer access to the shortest and fastest routes, directions, and estimated arrival time at your intended destination. Automated voice prompts alert you to upcoming turns, course deviations, and distance to your final destination. At the touch of a button you can view the locations of all the nearest highway exits, gas stations, restaurants, ATMs, hospitals, and rest areas on a full-color LCD screen.

### ***Other Navigational GPS Systems***

GPS manufacturers are developing more and more specialized receivers for particular industries, such as transportation fleet management and tracking. In addition to the handheld and in-car navigation systems, another class of GPS navigators is the micromodular receivers. They come in ultracompact sizes, making them easy to conceal and integrate with other applications. They are quite affordable, with



**Figure 4-2.** In-car navigation system (can be DGPS if WAAS-enabled)

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low-end receivers costing around US\$100, while higher-end receivers range from US\$200 to US\$1,000. These receivers are designed for low power consumption to fit the requirements of extended operations, and they can be installed simply as position reporting beacons using a transmitter and the Internet (or another data connection). They do not need an integrated user interface or screen display, but they also have a data download capability, such as through specialized data transfer cables. Some high-end receivers in this category can perform real-time differential corrections if they are designed with that capability or are attached to the proper antenna. The market trend is to miniaturize these units, as manufacturers race to design the world's smallest GPS receiver (Chapter 7 discusses this in "Miniature GPS Devices").

A micromodular receiver is an all-in-one device. For example, a 1-in.  $\times$  1-in.  $\times$  0.25-in. "black box" unit may be made up of an internal antenna, a position calculation chip, and a data interface. Using such a receiver, an external controller, and a transmitter, position information can be sent remotely to users. The receiver calculates its location and sends the data to the controller, which

functions as both a modem and a radio controller. The controller then sends “packets” of digital information at programmed time intervals (e.g., every few minutes). The packets are sent to the radio transmitter on a certain frequency that is picked up by numerous receiving stations and Internet gateways. The digital position information is then shared between several servers on the Internet and is used by automatic position reporting systems, overlaid on a detailed map, and graphically presented to the user—anywhere in the world. While this is a hypothetical illustration, it represents the typical application of micromodular navigational GPS systems. Given their intended applications (e.g., continuous tracking), most of the micromodular systems are integrated with *assisted-GPS* (A-GPS) technology in which additional signals from cellular tower networks aid continuous position reporting.

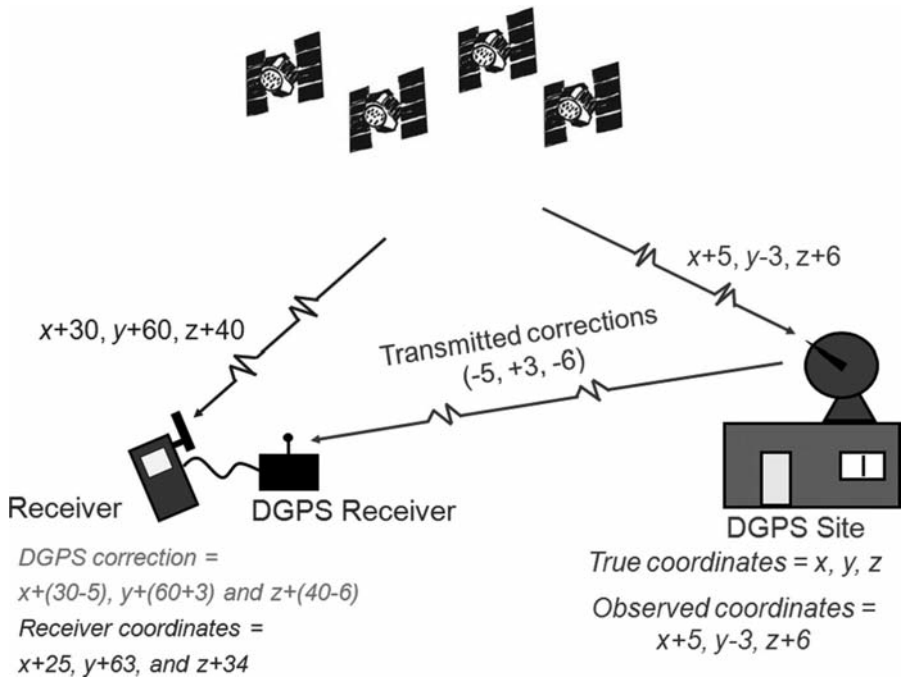
### Differential GPS (DGPS) Systems

Navigational handheld GPS units provide autonomous, single-point positioning by using “unsmoothed” code pseudoranges. The positions from such receivers are not accurate for professional work and applications such as engineering control and geographic information systems (GIS). They can achieve typical accuracies of 10 to 20 m, although some manufacturers make extraordinary claims about what their particular brands of handheld receivers can achieve. In comparison, DGPS using code-based pseudoranges can achieve better real-time or postprocessed position results. Because of this, code-based DGPS systems are often used in collecting GIS and mapping data for which typical accuracies can be anywhere from 5 cm to 10 m. Although DGPS still depends on code-based pseudorange observations, at least two receivers are required. One receiver is placed on a control station and the other is used for positioning. Both receivers simultaneously track the same codes from the same satellites and, because many of the errors are common to both receivers, they are correlated and tend to cancel each other.

In real-time code-phase DGPS, range corrections are computed at the control station (the DGPS site) and broadcast out to the second DGPS receiver. The methodology by which the individual satellite range corrections are computed is explained in Chapter 3, “Differential GPS”. Here, the real-time concept is illustrated in Fig. 4-3, where the range corrections are transmitted in terms of corrections in the three coordinate components (i.e., the corrections are the differences between the true coordinates and observed coordinates at the control station). In this concept, a DGPS receiver must be capable of receiving and applying the transmitted corrections. The DGPS range is the radius within which the DGPS corrections are valid.

Some DGPS receivers combine code and carrier phase data (e.g., using C/A code and L1 carrier phase) for improved accuracy. As a matter of fact, as GPS has become more popular and the technology more advanced, the price for improved accuracy has dropped; many receivers priced under US\$1,000 are capable of real-time differential correction.





**Figure 4-3.** Illustration of differential corrections in real-time code-phase DGPS. The numbers shown are not factual—they are used only for illustration of the DGPS concept.

### Receiver Channels and Frequencies

Most DGPS receivers (code-phase and carrier-phase) in use today can have up to 72 channels and can receive GBAS and SBAS signals (differential correction signals). A 72-channel receiver can track 72 satellites on the L1 frequency or 36 satellites on both the L1 and L2 frequencies. Besides the number of satellites a receiver can track, the signal-to-noise ( $C_0/N$ ) ratio is also very important. The higher the  $C_0/N$  ratio, the more sensitive the receiver is and the better it can track satellite signals in less-favorable conditions. Modern receivers are very sensitive and can track satellites in adverse conditions such as under foliage, in urban environments, and so forth.

### DGPS Reception and Range

When selecting a DGPS system, the method used for transmitting the corrections plays an important role. For instance, there are some free-of-charge corrections, such as WAAS and European Geostationary Navigation Overlay Service (EGNOS) that can only be received with a suitably equipped DGPS receiver. There are also a number of commercial code-phase DGPS services, and they also come with their specially suited receivers. When a certain differential technique is selected, it is

important to select the right type of telemetry (e.g., radio, cell phone, or satellite). A DGPS can range from a few kilometers to thousands of kilometers depending on the type of telemetry; in the case of commercial services, it comes at a price. Even within a certain type of telemetry, there may be differences between manufacturers or service providers.

### ***User Interface and Display***

Most DGPS receivers have color LCD display screens that can perform well under bright sunlight conditions and also change mode when the lighting condition changes. For receivers that are to be used outdoors, good screen readability is important. Experienced users will need a system that, besides simple operations, has a wide variety of customizable settings. Menu options may be used to create projects and feature dictionaries (in the case of GIS), select different data capture methods, and set parameters such as epoch interval and satellite mask angles. The information available from the CDU varies from receiver to receiver. Some DGPS receivers are of the black box type and can only be programmed using an external controller. These kinds of receivers can be suitable for certain applications, such as where a large number of untrained operators use the system.

### ***Communication and Data Interface***

Communication ports and internal data storage are very important features for DGPS receivers. For data transmission to other equipment, the NMEA 0183 protocol is used. This protocol consists of hardware and message specifications, originally conceived in the maritime sector. In addition, most manufacturers use their own specific data messages that can usually contain more information. However, not all software is capable of using this protocol. For some applications, such as GIS, a receiver that can transfer data in a number of formats is required.

For data storage, most receivers have internal memory, although USB memory cards and memory sticks are also widely in use. Most modern receivers employ the same type of memory cards as found in digital cameras and similar electronic gadgets.

### ***Antennas***

A DGPS system needs a minimum of two antennas, one for receiving GPS signals and another for receiving the differential correction signals. Some receivers are equipped with an integrated internal GPS antenna, while others can be connected to an external antenna. The latter is important for receivers that are installed in enclosed spaces such as aircraft and ships. In the WAAS and EGNOS concept (see “DGPS Controllers and Data Collectors” and “DGPS Networks and Services,” below), a single antenna will perform functions of both a GPS antenna and the differential correction antenna.

### GPS Antenna

This antenna collects the GPS signals; its primary function is to convert the electromagnetic waves into electric currents that are then processed as information by the radio frequency (RF) section of the receiver. A GPS antenna can be *passive* or *active*. An active antenna has a built-in amplifier that requires power from the receiver. A passive antenna cannot amplify the signal. Active antennas are more expensive but their advantage is that no signal is lost during transmission from the antenna to the receiver. Furthermore, the receiver must be able to supply the correct voltage to the antenna if any signal is to be received at all. Although a DGPS antenna can be designed to collect only the L1 frequency signals, most GPS antennas can collect both L1 and L2 frequencies. The former is referred to as a *single-frequency antenna* while the latter are *dual-frequency antennas*. In all cases, antennas must be “right-hand circular polarized” (RHCP) to be able to receive the circular polarized GPS signals broadcast from the satellites. And as seen in the previous section, several antenna designs are possible but the common feature is that they must have *high sensitivity* (also called *high gain*) since the satellite’s signal has such low power density, especially after propagating through the atmosphere.

### Differential Correction Antenna

The type of differential antenna depends on the telemetry method (e.g., radio, cell phones, satellite). In radio telemetry, for example, the most common type of antenna is a whip or rod antenna, depending on the type of application. Telemetry using cellular phones requires a Global System for Mobile Communication (GSM)-type antenna, while satellite telemetry antennas are similar to a GPS antenna.

### Power Supply

In high-end DGPS applications, rechargeable batteries are used, and they come in different sizes, weights, and performance characteristics. Lithium-ion, nickel-cadmium (NiCd), and nickel metal-hydride (NiMH) may be the most common batteries, but lead-acid batteries may still have application in some instances. Each of these battery types has its benefits and drawbacks that should be noted. For instance, lead-acid batteries are heavy and generally bigger, and are only logically useful as an external power supply to a receiver. They have a short life cycle but they have high power and are economical and longer-lasting when charged. NiCd batteries are more costly than lead-acid batteries, are small in size, weigh less, and operate well at low temperatures. They are generally used as an internal power supply but can be removed during nonoperation or for recharge. NiCd batteries are just as toxic as lead-acid batteries. Lithium-ion batteries overcome several of the limitations of these other batteries. They are light and have a good life cycle and low toxicity. However, while the other battery types tolerate overcharging, a lithium-ion battery does not. They are widely used in internally powered receivers. Most code-tracking DGPS receivers that do not use the carrier phase observable can operate for about 15 hours on a fully charged 6-amp-hour battery. In com-

parison, GPS carrier phase receivers can operate 5.5 hours or longer on the same size of battery.

### **Robustness, Size, and Weight**

Robustness is important for most DGPS receivers, given their intended applications. Most of these receivers are dust- and watertight and they can operate under various temperature conditions. For some applications, such as GIS and agriculture, the size and weight of the receiver are important, especially for applications where the user will have to carry the system around for an extended period of time. However, for applications such as shipping and aviation, these two features are less important. A receiver of any weight or size can be installed.

### **Maritime and Aircraft GPS Systems**

DGPS receivers used in the maritime and aircraft industries are usually quite bulky and not very sophisticated in terms of design, but are robust and reliable (Fig. 4-4). In contrast to the car navigation industry in which GPS navigation units are usually add-ons, DGPS is a primary means of navigation in the maritime and aviation sectors. Given the safety-of-life applications in these sectors, the GPS systems must be both reliable and available essentially all of the time. In other words, a GPS drop-out in car navigation might only be a matter of inconvenience to the driver, but a similar occurrence in aircraft or ship navigation can have disastrous results. Consequently, DGPS systems in these applications rely heavily on augmentation systems such as WAAS, especially in areas where reliability is an issue such as approaches to airports and harbors and passages in heavily trafficked routes.



**Figure 4-4.** Garmin 400 W aircraft GPS/WAAS receiver.

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### **DGPS Controllers and Data Collectors**

Today the ability to obtain sub-meter accuracy in real time with DGPS service eliminates the need for postprocessing for many applications. In the United States, DGPS service is available through the use of United States Coast Guard (USCG) beacon receivers and satellite-based DGPS service (e.g., WAAS). The USCG service is limited to the coastal areas, at about an 80- to 485-km (50- to 300-mi.) radius of a single DGPS station. For areas where the USCG beacon service is not available, real-time, satellite-based DGPS service is available throughout most of the world at a reasonable cost. New generations of data collectors are equipped with the technology to allow for use of these services. For instance, the Trimble GeoXH (as shown in Fig. 4-5) is capable of 1-m accuracy in the field using WAAS services, but typically requires 1 to 2 min. at each point. Accuracy of less than 1 ft is also possible after postprocessing.

In general, data collectors of 0.1- to 0.3-m (4-in. to 1-ft) accuracy can be used for preliminary site surveys, as-built surveys for collecting asset information, environmental impact reports, road centerlines, and in collecting urban asset data-

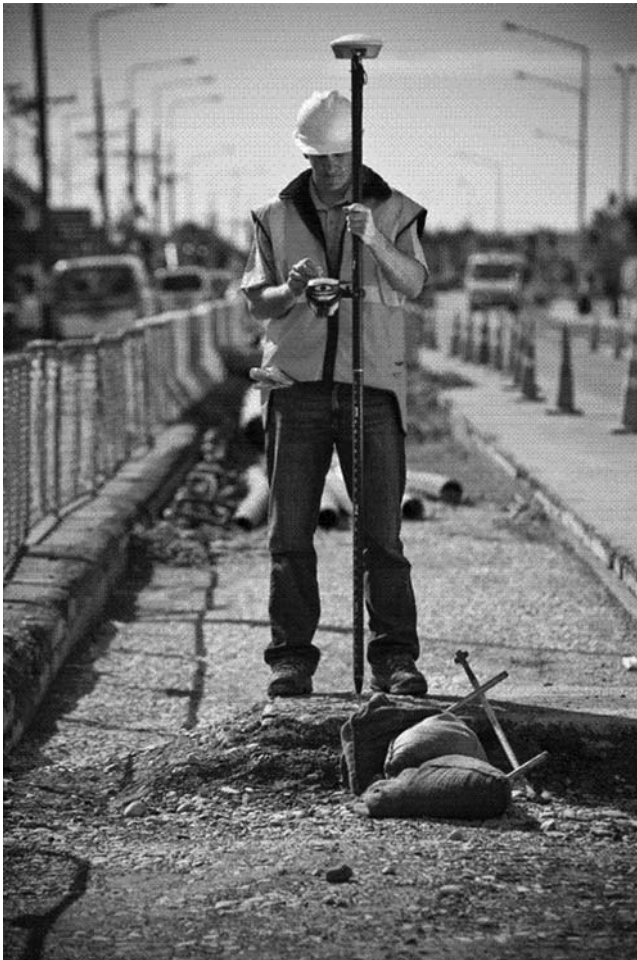


**Figure 4-5.** Trimble GeoXH 6000 series data collector (many other vendors offer similar systems with similar features).

Courtesy of Trimble Navigation Limited © 2011.

bases for GIS. Costs of the high-accuracy mapping systems are typically about one-half to one-third of the cost of a survey-grade GPS unit.

An integrated data collector can be carried in hand with no need for cables or a pole or backpack. However, some are designed for use on a range pole (Fig. 4-6), using communication via Bluetooth or serial cable. They are economically priced between a few hundred to thousands of dollars, have a longer battery life (14–16 hours), and are lightweight, thus making it easier for the user to carry the units all day in the field. In addition, most data collectors have touch-screens and come with a color display. Some have voice-activated systems that come in handy if one wants to dictate notes. Most of the DGPS data collectors have at least two serial ports, USB ports, and infrared ports. Some of them have built-in modems and offer extended memory and compact flash memory card options.



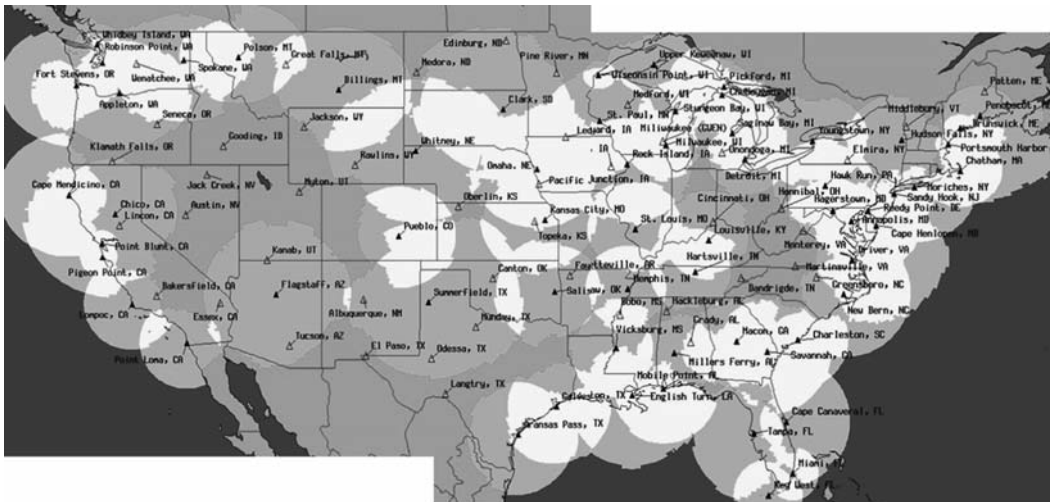
**Figure 4-6.** Data collector on a range pole.

Courtesy of Trimble Navigation Limited © 2011.

## DGPS Networks and Services

Four common sources of real-time differential correction signals are currently available. The first source includes land-based beacon systems, such as the USCG Maritime DGPS Service, which send out correction signals via radio waves. According to the USCG website, their system provides 10-m accuracy in all established coverage areas. The beacons are strategically located to cover the entire coastline of the continental United States, the Great Lakes, Puerto Rico, most of Alaska and Hawaii, and a large part of Mississippi River basin. Use of these signals simply requires the addition of a real-time DGPS beacon antenna to the GPS receiver. However, the range of the beacons is limited and can only be effectively utilized within 485 km (300 mi.) of the DGPS stations. Other countries are beginning to develop their own coastal real-time beacon networks, modeled after the USCG system. The correction broadcast by the USCG Maritime DGPS Service is free to any user who has a receiver that can pick up the signals, but is only transmitted in the United States.

A U.S. nationwide network, the Nationwide Differential GPS (NDGPS, Fig. 4-7), is the descendant of the USCG Maritime DGPS Service. It is designed to fulfill both the USCG's original responsibility [to provide DGPS coverage to all harbors and harbor approaches of the United States (Wolfe et al. 2000)] and an inland component of a nationwide DGPS service. The Maritime Service continues to provide differential corrections along the Atlantic, Pacific, and Gulf Coasts, the Great Lakes, and the coastal waterways of Hawaii, Puerto Rico, and southern Alaska. However, as the number of users and uses of DGPS increased, the need to expand



*Yellow areas show overlap between NDGPS stations.*

*Green areas are little to no coverage. Topography may also limit some areas of coverage depicted*

**Figure 4-7.** The U.S. Nationwide Differential GPS (NDGPS) Network, a type of wide area DGPS (WADGPS).

the DGPS coverage area also increased. As a result, an agreement with the U.S. Army Corps of Engineers (USACE) expanded the USCG’s DGPS coverage to the inland rivers of the United States. A similar agreement with the U.S. Department of Transportation (DOT) expanded coverage to transportation corridors. Thus, NDGPS now provides double DGPS coverage across the continental United States and along the transportation corridors in Alaska, and single coverage over the rest of Alaska, Hawaii, and Puerto Rico. According to the DOT website, the NDGPS service provides 1- to 3-m accuracy to receivers capable of receiving the differential correction signal. The service is operating with the support of three federal agencies: USCG (39 sites), USACE (9 sites), and DOT (38 sites operated and maintained by USCG under contract).

A second source of correction signals is the satellite-based subscription services. The signals are transmitted from geostationary satellites and therefore are available worldwide. These services are expensive, but the benefit is their availability in many areas where base stations do not exist.

A third source of real-time correction signals consists of the free satellite-based services, such as the WAAS and similar systems worldwide [Canadian WAAS (CWAAS), European Geostationary Navigation Overlay Service (EGNOS), Japanese MTSAT Satellite-based Augmentation System (MSAS), and so forth]; see Figs. 4-8 and 4-9. The WAAS is part of the U.S. Federal Aviation Administration’s GPS-based navigational system. It is a satellite-based DGPS system used to assist airplanes in navigation and landing. WAAS-enabled receivers can generate coordinates with an accuracy of less than 3 m (Garmin 2010). The CWAAS, EGNOS, and MSAS are also satellite-based differential correction systems designed primarily

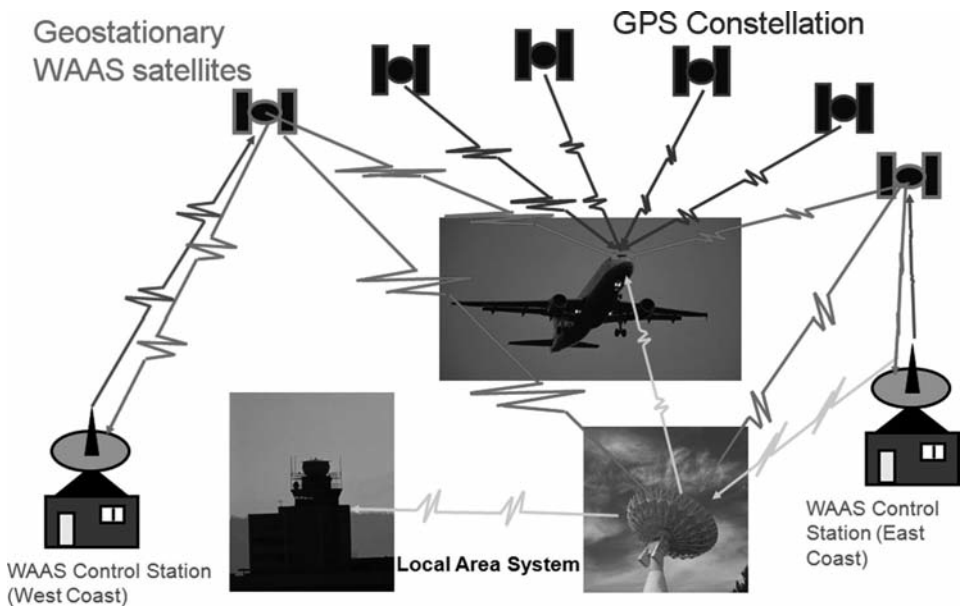


Figure 4-8. Wide-area augmentation system (WAAS).





**Figure 4-9.** Worldwide satellite-based augmentation systems (SBAS) service areas.

to aid in aircraft navigation in Canada, Europe, and Asia. All these services transmit correction information from satellites over their service areas and are free to users who have DGPS receivers capable of receiving the signals.

The fourth real-time DGPS correction source is the less common user-transmitted correction signal. In this case, some high-end GPS receivers have the capability to function as base stations and calculate correction information on-the-fly. They can then transmit correction signals to the roving receiver via radio or cellular link.

# High-Precision GPS Systems

## Achieving High-Precision GPS Results

### *The Concept of Precision*

Although *accuracy* and *precision* are sometimes used interchangeably, it is important to explain the difference between the two for the purpose of this chapter. *Accuracy* is the degree of closeness of an estimate to its true but unknown value, and *precision* is the degree of closeness of observations to their mean. Figure 5-1 illustrates various relationships between these two parameters.

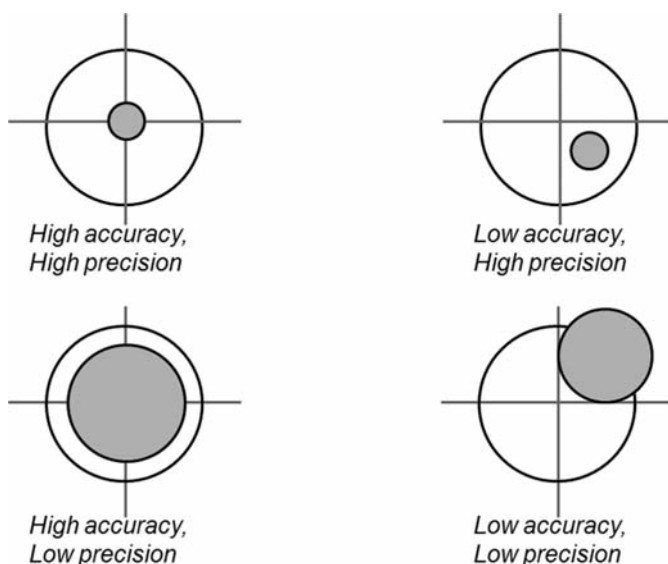
In statistical terms, the “true value” refers to the mean of a *population* of measurements. In other words, *accuracy* is the spread/standard deviation (error) of measurements with respect to the population mean of the parameter being measured. The term *precision* is used with respect to the sample mean of the parameter being measured. In this book, the parameters being measured by GPS are position coordinates; in this context, precision would be more appropriate term to use because the “true” coordinates might not be initially known. In some cases, such as in the GPS continuously operating reference stations (CORS) described later in this chapter, the position coordinates determined from long-term historical data can be taken to be the true (population mean) coordinates of any given CORS station.

Achieving high precision (i.e., smaller standard deviations/errors) requires either using more accurate instrument types or taking more observations using the same instrument type, since the standard error reduces with the square root of the number of repeated observations. The concept of precision using repeated observations is based on the formula:

$$S_{\bar{x}} = S_x / \sqrt{n} \quad (5-1)$$

where  $S_{\bar{x}}$  is the standard deviation of the mean of  $n$  observations, expressed in terms of the standard deviation of a single observation ( $S_x$ ).

These two aspects of achieving precision are some of the ways to help you make decisions when planning a GPS project (further discussed in Chapter 6). The quality of GPS measurements needed, such as  $\pm 1$  cm or  $\pm 5$  m, determines what type of instruments and techniques you should adopt or how many times you should repeat each measurement.



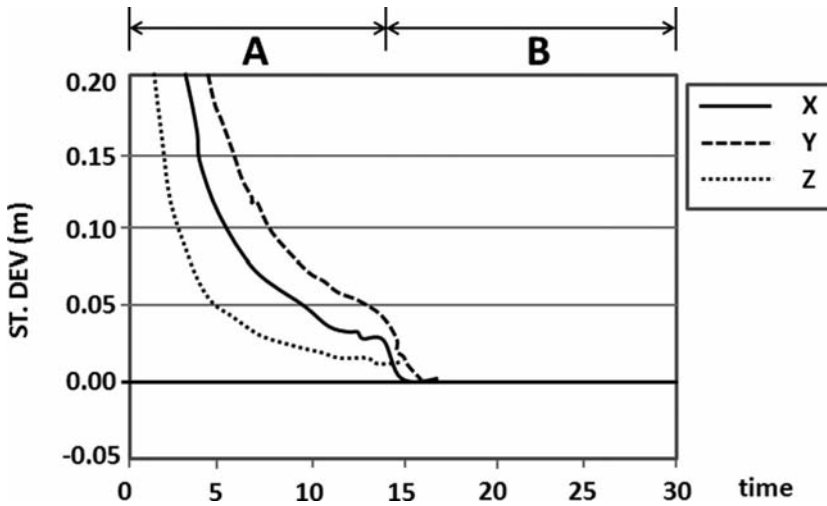
**Figure 5-1.** Various relationships between accuracy and precision. The true value is located at the intersection of the crosshairs, the center of the shaded area is the location of the mean estimate, and the radius of the shaded area is a measure of the uncertainty contained in the estimate.

### **Achieving High Precision Using More Precise Instruments**

To achieve high-precision (centimeter-level), instantaneous GPS positioning, carrier phase measurements are used (Eq. 2-7). This requires two frequencies (L1 and L2) of phase measurements, which is only possible with dual-frequency receivers. *Differencing* techniques are applied to the phase observables to eliminate most of the range errors (e.g., clocks, orbit, and atmospheric). In high-precision receivers the most common approach is *double differencing*. However, since phase measurements also have cycle ambiguities that are unique to every individual satellite (and cannot be solved by double differencing), an additional process known as *ambiguity resolution* (AR) is required. The double differencing and AR requirements increase computational complexity, in comparison to a simple navigation solution using code phase measurements. Different receivers apply different AR techniques (Rizos 1997, pp. 345–381). The rigorous mathematical processes involved are beyond the scope of this book, but it is important to note the difference between an “*ambiguity-free* solution” and an “*ambiguity-fixed* solution.” This is explained with the help of Fig. 5-2 and Box 5-1.

### **Ambiguity-Free Solution versus Ambiguity-Fixed Solution**

In the carrier phase-based solution using AR, a sufficient amount of data must be observed before an *ambiguity-fixed* solution can be reached. Most of the modern high-precision receivers can do this in a matter of a few seconds or minutes (for



**Figure 5-2.** The evolution of the quality of a GPS baseline solution as ambiguities are solved. In region A (the ambiguity-free solution), the precision and accuracy of the position coordinates steadily improve as more data are collected. In region B (the ambiguity-fixed solution), the unambiguous range data (based on precise phase measurements now converted to precise range observations) are processed and there is no improvement in the quality of the solution. The x-axis (time) refers to epochs. *Source: Rizos (1997, p. 369).*

### Box 5-1. Double-Difference Phase Data Solutions

There are two types of double-difference phase data solutions:

- *Ambiguity-free solution* (“bias” or ambiguity “float” solution), in which the parameters to be estimated are the “rover” coordinates (one end of a baseline) and the ambiguity parameters.
- *Ambiguity-fixed solution* (or “bias-fixed” solution), in which some or all the ambiguity parameters have been resolved to their integer values.

The ambiguity-free solution is generally the first step. If successful, after this solution the values of the ambiguity parameters (which theoretically should be integers) may be close to integer values (but not exactly due to the presence of residual biases such as atmospheric refraction, orbit error, multipath, etc.).

If the correct ambiguity values are identified, they can be held fixed in the subsequent ambiguity-fixed solution. Such a solution is very strong because it only contains the coordinate parameters (hence, it is equivalent to processing unambiguous and precise ranges).

Note: It may not always be possible to attempt the ambiguity-fixed solution!

those receivers programmed to do so while observing). The double-differencing process reduces the number of “observables” that need to be processed but, given that each satellite observed at a particular receiver will have an ambiguity parameter, the number of unknowns are still relatively large. Take, for example, a simple baseline involving only two receivers (Fig. 3-3 in Chapter 3). The coordinates of the base receiver are assumed to be known. The unknown parameters consist of ambiguity parameters (which are constants for the entire observation session) and the coordinates of the rover. In the case of six tracked satellites, there are five (double-differenced) ambiguities to be resolved and three unknown coordinates of the rover. The processing of double-differenced observation equations in a conventional least-squares scheme permits the values of these unknown parameters (and their uncertainties) to be estimated. This is the basis of the double-difference ambiguity-free solution. The evolution of the uncertainties of the coordinate parameters as the solution moves from ambiguity-free to ambiguity-fixed (Fig. 5-2) can be explained as follows:

- In region A (the ambiguity-free solution) the precision and accuracy of the position coordinates steadily improve as more data are collected. This is sometimes also referred to as the *float solution*.
- As soon as sufficient data are available to resolve the ambiguities (at epoch 15), there is a dramatic improvement in the coordinate precision.
- In region B (the ambiguity-fixed solution), the unambiguous range data (based on precise phase measurements now converted to precise range observations) are processed and there is no improvement in the quality of the solution.
- If enough data are collected over an observation session, the precision of the ambiguity-free solution (the float solution) will steadily improve, converging to that obtained from an ambiguity-fixed solution.

### ***Real-Time versus Postprocessed Data***

Broadly speaking, there are two applications of carrier phase measurements: kinematic and static positioning. A more detailed classification has been defined previously in Chapter 3 (Table 3-2). In that classification, the real-time techniques offer centimeter- to decimeter-level accuracies depending on the DGPS correction method used. In the real-time kinematic on-the-fly (RTK OTF) method, the integer ambiguity is solved on-the-fly using data transmitted by the base to the rover and “carrier-range” positioning can take place while the antenna is in motion. To explain this further using Fig. 5-2, the OTF method is such that once the ambiguities are resolved (i.e., the rover is initialized) at epoch 15, there is no real justification for continuing to collect data beyond that time. However, through a pre-programmed setup, the data can be logged onto the internal memory of the receiver or into an external data collector for other purposes, such as postmission screening or analysis.

In static positioning, the data are postprocessed and it is therefore not known beforehand at what point (or even if) sufficient data have been collected to ensure

that an ambiguity-fixed solution is obtained. Hence, for applications such as geodetic surveys and engineering control, conservative observation session lengths of not less than 30 min. (and usually 60 min. or more) are recommended. Static applications use observations from receivers that are stationary for the duration of their measurement. Most static applications can afford higher redundancy and a bit more accuracy than RTK GPS. In general, the following strategies can be used to decrease the length of observation sessions and increase the reliability of ambiguity resolution processes:

- Keep baselines short! Chances for ambiguity resolution are much higher for baselines of less than 20 km (12.5 mi.) in length (Fig. 5-3).
- Track as many satellites as possible and ensure good satellite geometry. Generally, a minimum of five visible satellites is recommended.
- Use dual-frequency observations and use precise pseudorange data whenever possible—replacing geometric range quantities by measured pseudoranges.
- Use a priori information such as known baseline length. If baseline components are known, then the double-differenced ambiguities can be directly estimated.

The first two strategies are essential preconditions for reliable ambiguity resolution, but are largely beyond the control of the receiver operator. The last strategy is useful for re-establishment (reinitialization) of the ambiguities when cycle slips occur as the GPS antenna is moved from one point to another.

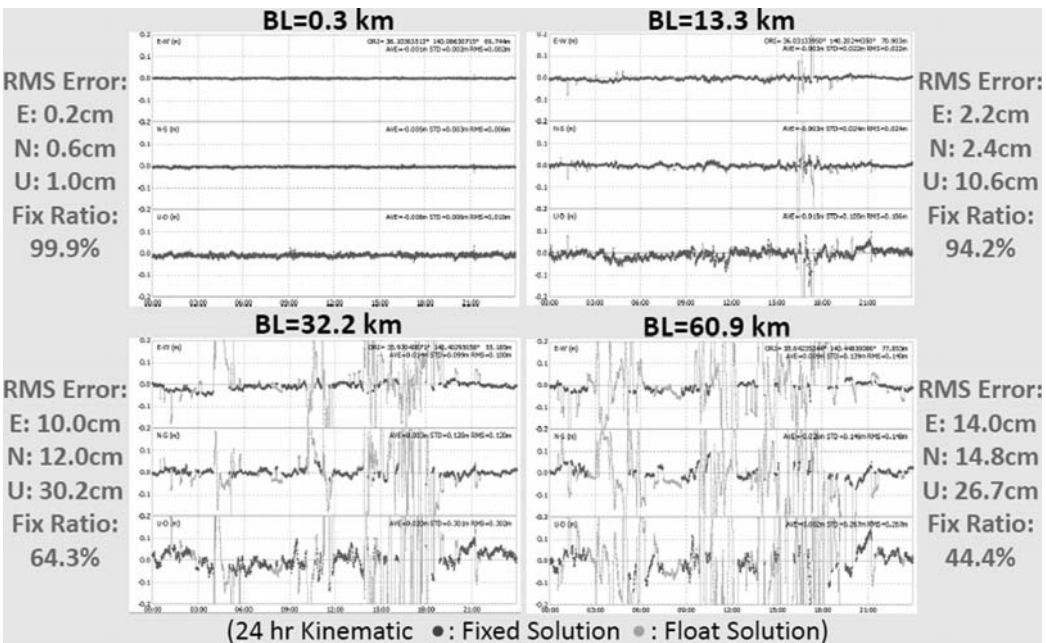


Figure 5-3. Example of the effect of baseline length (BL) on ambiguity resolution.

### **Equipment for Centimeter-Level (or Better) Positioning**

GPS receivers to be used for high-precision applications generally have the following features (Fig. 5-4):

- Able to measure carrier phase on at least one of the L-band carrier frequencies (L1, L2, L5), and preferably two frequencies (dual-frequency).
- Have the capability of tracking substantially more than the minimum four satellites simultaneously (using parallel multichannel tracking).
- Have the capability to record data for subsequent postmission analysis.
- Have a minimum data recording rate of 15 to 60 sec (preferably higher for RTK and kinematic applications).



**Figure 5-4.** Equipment for centimeter-level (or better) positioning. Clockwise from top left: geodetic antenna with radome antenna cover; geodetic antenna at a base station; geodetic receiver; antenna on tripod with receiver and a detached handheld controller.

- Antennas are chosen with stability and quality in mind in order to minimize phase center variations and sensitivity to multipath.

**Achieving High Precision Using Repeated Observations**

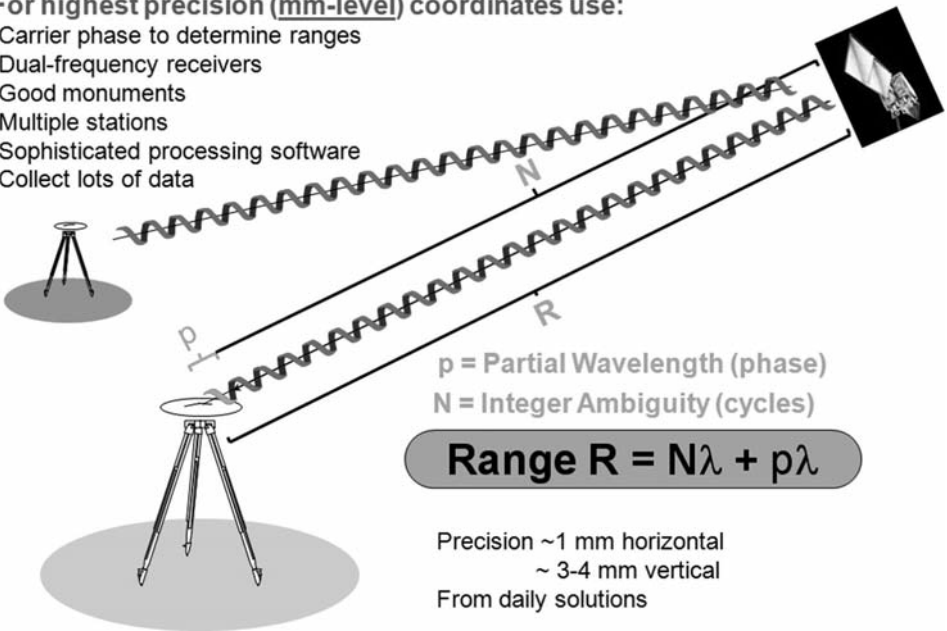
For highest precision, the relative or differential GPS positioning is applied based on carrier phase measurements between the receiver and the GPS satellites (Fig. 5-5). This mode of positioning is achievable by using geodetic-grade GPS receivers which are capable of producing centimeter- to millimeter-level accuracy. The highest precision (millimeter-level) is possible due to postprocessing using large volumes of data collected over a long period of time.

**Observing Multiple Epochs and Sessions**

When data are collected, the time interval at which every single measurement is recorded is called an *epoch*; for instance, data can be recorded at 1-sec (or longer) epochs. The time period during which multiple successive epochs are recorded continuously at two or more receivers observing a common set of satellites simultaneously is called an *observation session*. An observation session can be as short as 1 min. or as long as 2 hours or longer, but it cannot be shorter than the data-logging epoch. Usually the receiver operator has to configure these two parameters before taking measurements. However, in cases of continuous operation (e.g., at GPS CORS), the measurement systems are usually configured to continuously store data at short sessions of, say, 15 min. for postmission processing and analysis.

**For highest precision (mm-level) coordinates use:**

- Carrier phase to determine ranges
- Dual-frequency receivers
- Good monuments
- Multiple stations
- Sophisticated processing software
- Collect lots of data



**Figure 5-5.** Achieving highest precision (millimeter-level).

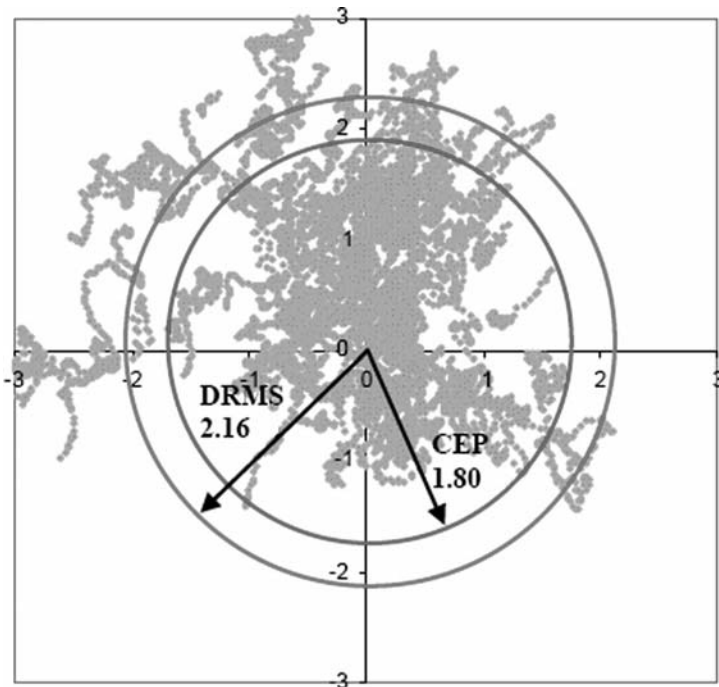


When GPS positions are logged over time, the positions are scattered over an area due to measurement errors. This dispersion of points is called a *scatter plot*, which GPS manufacturers use to characterize their equipment's accuracy. The area within which the measurements or estimated parameters are likely to be is called the *confidence region*. The confidence region is then analyzed to quantify the GPS performance statistically. The confidence region with a radius describes the probability that the solution will be within the specified accuracy. Two common GPS accuracy measures are the distance root mean square (DRMS) and the circular error probability (CEP). These two measures are illustrated in Fig. 5-6.

Root mean square (RMS) is the value of one standard deviation (68%) of the error in one, two, or three dimensions. DRMS is the radial or distance root mean square error, calculated using the RMS values for the separate X and Y directions according to the formula:

$$DRMS = \sqrt{RMS_x^2 + RMS_y^2} = \sqrt{\sigma_x^2 + \sigma_y^2} \quad (5-2)$$

The probabilities described by 1DRMS and 2DRMS are the typical 68% and 95% values, respectively. (2DRMS refers to twice the DRMS and 3DRMS refers to three times the DRMS. However, it should be noted that these measures are in



**Figure 5-6.** Scatter plot of repeated measurements. The center of the circle is the location of the mean estimate and the radii are measures of uncertainties in the estimate. CEP (the circular error probability) refers to the radius of a circle in which 50% of the measurements occur; DRMS is the distance root mean square.

two dimensions) In a 3-D case, mean radial spherical error (MRSE) corresponds to 1DRMS in the 2-D case, and is given by the formula:

$$MRSE = \sqrt{RMS_x^2 + RMS_y^2 + RMS_z^2} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} \quad (5-3)$$

CEP is the value of the radius of a circle, centered at the actual position that contains 50% of the position estimates. Values stated as CEP apply to horizontal accuracy only.

### Standard Deviation of Repeated Measurements

Although the highest precision is implied in static positioning, recorded GPS data can be postprocessed as kinematic measurements (especially if the measurements are recorded at 1-sec or shorter epochs). If the data are processed as kinematic measurements, each epoch is in effect a *measurement session*, the standard deviation of which can also be estimated.

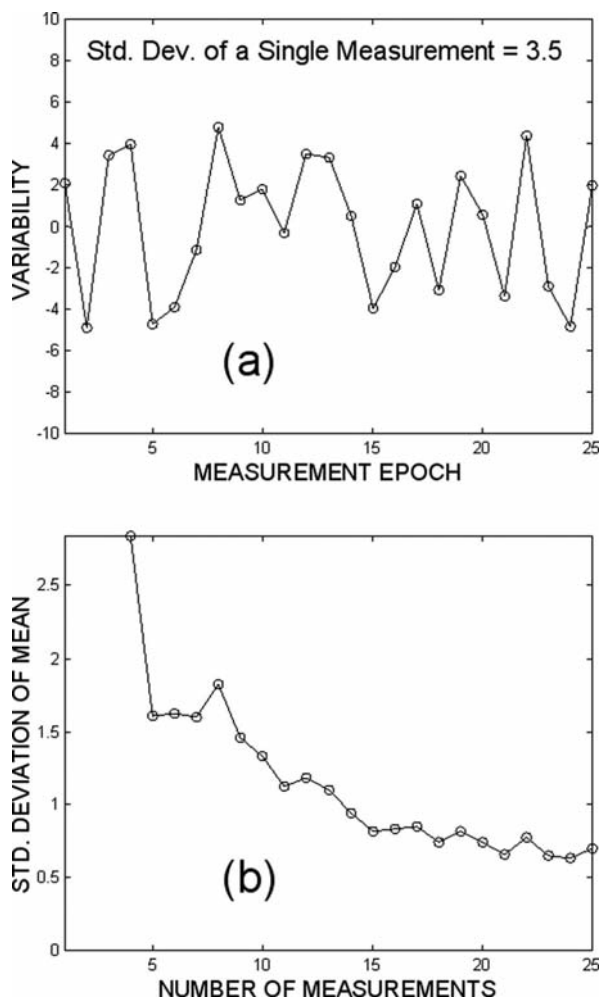
For highest precision, data are usually collected in hourly or daylong sessions. The session data are later postprocessed into a single static solution per session. For example, an hourly session will provide a single position solution for the rover, which is the mean of all the epochs observed within the hourly session. Thus, each session solution is based on a set of repeated observations. In geodetic applications, sessions can be archived into longer data sets spanning several days, weeks, months, or years depending on the intended use of the data. This process creates the time series data that can then be analyzed statistically. For instance, according to the error propagation laws defined earlier, the precision of a daylong solution should be higher than that of an hourly solution, and that of a week-long solution should be higher than that of a daylong solution, and so forth. Figure 5-7 illustrates this principle, in which the standard deviation of the mean improves as the number of repeated observations increases (i.e., as the time span increases). The presence of large errors, linear trends, or outliers in a set of repeated measurements may distort this relationship.

The primary advantage in GPS postprocessing is that the data can always be reprocessed, each time with the goal of improving the coordinate precision. For instance, when processing data 2 weeks after the observation, it is possible to incorporate precise orbits and precise clock parameters that are usually available from the websites of organizations such as IGS (International GNSS Service) and NASA. The acronym GNSS stands for Global Navigation Satellite Systems, which is further discussed in Chapter 8.

## Real-Time Kinematic (RTK) Systems

### Single-Base RTK Systems

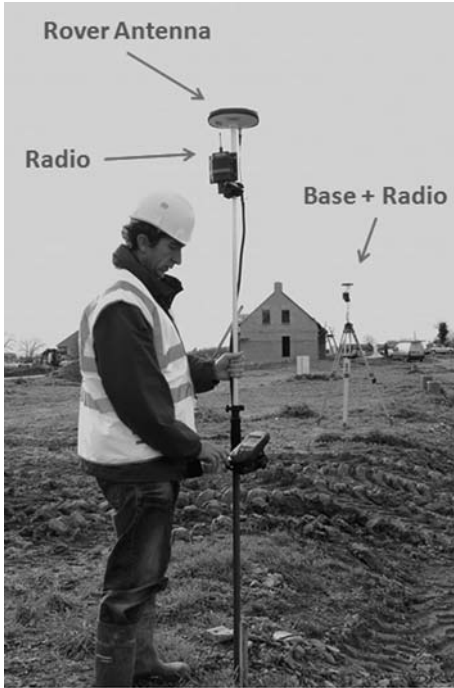
In practice, RTK systems use a single base station receiver. The base station broadcasts its measured carrier phase to the rover, and the rover unit compares its own phase measurements with the ones received from the base station. This



**Figure 5-7.** Standard deviations of repeated measurements. (a) A time series of repeated measurements; (b) the standard deviations of their respective means as a function of the number of measurements included in calculating the mean.

allows the rover to calculate its relative position to millimeters-level accuracy, although the absolute position is accurate only to the same accuracy as the position of the base station. The typical nominal accuracy for dual-frequency RTK systems is 1 cm in the horizontal and 2 cm in the vertical.

There are several ways to transmit a correction signal from the base station to the rover unit. The most popular way to achieve real-time, low-cost signal transmission is to use a radio modem, typically in the UHF band. In most countries, certain frequencies are allocated specifically for RTK purposes. Most modern RTK equipment have a built-in UHF band radio modem as a standard option (Figs. 5-8, 5-9, and 5-10).



*RTK with external radio connections*



*RTK with built-in radio & Bluetooth communication*

**Figure 5-8.** RTK radio systems.

### ***Initialization and Reinitialization***

RTK systems require some time for initialization, usually at the start of measurements. Once the base and rover have started tracking the same satellites, there is usually a short wait time required for initialization. However, initialization is also required whenever continuous tracking of satellites is inadvertently interrupted or if the tracking stops for even a short length of time. Dual-frequency RTK receivers are capable of reinitializing. Some receivers might require a return to a known coordinated position for reinitialization.

Many RTK systems resolve the integer ambiguity using OTF initialization (refer to “Real-Time versus Postprocessed Data” above). This standard function is a method of resolving the carrier phase ambiguity very quickly and can allow the system to initialize while the GPS unit is moving. The process can take less than 10 sec under the best circumstances, which are where the receivers are tracking a large number of satellites in a good geometry configuration [the position dilution of precision (PDOP) is small]; the receivers are dual-frequency; there is no multipath; and the receiver noise is low. It also helps if there is good correlation of atmospheric biases at both ends of the baseline. For this reason, RTK is best used when the distance between the base and rover is restricted to not more than 20 km (12 mi.).

## Leica Viva GNSS (GS15 Receiver)

**Manufacturer:** Leica Geosystems, AG, Switzerland

**Applications:** DGPS / RTCM, RTK, Network RTK

### PERFORMANCE SPECIFICATIONS

Number of Channels: 120

Very low noise GNSS carrier phase measurements with <math><0.5\text{ mm}</math> precision

Tracks the following satellite signals:

- GPS: L1, L2, L2C, L5
- GLONASS: L1, L2
- Galileo (Test): GIOVE-A, GIOVE-B
- Galileo: E1, E5a, E5b, Alt-BOC
- SBAS: WAAS, EGNOS, GAGAN, MSAS

### DGPS / RTCM

Code differential positioning accuracy..... typically 25 cm (RMS)

### RTK RapidStatic (phase)

Static mode after initialization

Horizontal.....  $\pm(5\text{ mm} + 0.5\text{ ppm RMS})$

Vertical.....  $\pm(10\text{ mm} + 0.5\text{ ppm RMS})$

### RTK Kinematic (phase)

Moving mode after initialization

Horizontal.....  $\pm(10\text{ mm} + 1\text{ ppm RMS})$

Vertical.....  $\pm(20\text{ mm} + 1\text{ ppm RMS})$

### On-The-Fly Initialization

Initialization time..... typically 8 seconds

Initialization reliability..... typically >99.99%

RTK baseline range..... up to 50 km

### Post Processing (phase)

Static with long observations

Horizontal.....  $\pm(3\text{ mm} + 0.1\text{ ppm RMS})$

Vertical.....  $\pm(3.5\text{ mm} + 0.4\text{ ppm RMS})$

### Rapid static mode

Horizontal.....  $\pm(5\text{ mm} + 0.5\text{ ppm RMS})$

Vertical.....  $\pm(10\text{ mm} + 0.5\text{ ppm RMS})$

### Kinematic

Horizontal.....  $\pm(10\text{ mm} + 1\text{ ppm RMS})$

Vertical.....  $\pm(20\text{ mm} + 1\text{ ppm RMS})$

### HARDWARE, POWER CONSUMPTION AND DATA COMMUNICATION

**Physical:** 196 mm x 198 mm; 1.34 kg (3.30 kg standard RTK rover including controller, batteries, pole & bracket)

**Power Consumption:** 3.2 W, 270 mA; Supply voltage (Nominal 12 V DC, Range 10.5 – 28 V DC)

**Internal Power Supply:** Recharge & removable Li-Ion battery, 2.6 Ah / 7.4 V, 2 batteries fit into receiver

**Operation time on internal battery:** 10 h receiving RTK data with standard radio, using 2 internal batteries

### Communication and Data Storage:

- Bluetooth® communication; Integrated Bluetooth® port v2.00 + EDR, class 2
- Serial RS232 Lemo, USB / RS232 Lemo; UART serial & USB (for removable internal RTK devices)
- RTK Transmission: Direct from GS15 (no data logger required)
- Removable SD Card (1 GB, sufficient for 280 days raw data logging at 15 s rate); Recording rate: up to 20 Hz
- Type of data: Leica GNSS raw data and RINEX data



**Figure 5-9.** A single-base/multiple-base RTK system.

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## Communication Link

RTK systems require a real-time telemetry link between the base station and the rover. This can be through a cable connection or a wireless connection, a telephone or computer network, an optical link, or other wired communications. Wireless telemetry is the most common, especially in portable RTK systems (Fig. 5-8) where

**TRIMBLE R8 GNSS SYSTEM**

**Manufacturer:** Trimble Navigation, Sunnyvale, California, USA  
**Applications:** GPS/GNSS precise surveying & positioning

**PERFORMANCE SPECIFICATIONS**

Advanced Trimble Maxwell 6 Custom Survey GNSS chip with 220 channels

Very low noise GNSS carrier phase measurements with <1 mm precision in a 1 Hz bandwidth

- Tracks the following satellite signals simultaneously:  
 – GPS: L1C/A, L2C, L2E (Trimble method for tracking L2P), L5  
 – GLONASS: L1C/A, L1P, L2C/A (GLONASS M only), L2P  
 – SBAS: L1C/A, L5  
 – Galileo GIOVE-A and GIOVE-B

**Code differential GNSS positioning**  
 Horizontal.....±(0.25 m + 1 ppm RMS)  
 Vertical.....±(0.50 m + 1 ppm RMS)  
 WAAS differential positioning accuracy..... typically <5 m 3DRMS

**Static and FastStatic GNSS surveying**  
 Horizontal.....±(3 mm + 0.1 ppm RMS)  
 Vertical.....±(3.5 mm + 0.4 ppm RMS)

**Kinematic Surveying**  
 Horizontal.....±(10 mm + 1 ppm RMS)  
 Vertical.....±(20 mm + 1 ppm RMS)  
 Initialization time..... typically <10 seconds  
 Initialization reliability..... typically >99.9%

**HARDWARE, POWER CONSUMPTION AND DATA COMMUNICATION**

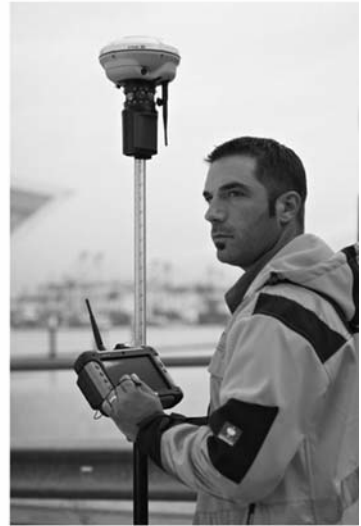
**Physical:**  
 19 cm × 11.2 cm (7.5 in x 4.4 in), including connectors; Weight: 1.34 kg (2.95 lb) with internal battery, internal radio, standard UHF antenna; 3.70 kg (8.16 lb) entire RTK rover including batteries, range pole, controller and bracket.

**Power Consumption:**  
 Power 11 to 28 V DC external power input with over-voltage protection on Port 1; Rechargeable, removable 7.4 V, 2.4 Ah Lithium-Ion battery in internal battery compartment; Power consumption is 3.2 W in RTK rover mode with internal radio. Operating times on internal battery:

- 450 MHz receive only option 5.8 hours
- 450 MHz receive/transmit option 3.7 hours
- GSM/GPRS 4.1 hours

**Communication and Data Storage:**

- 1 Hz, 2 Hz, 5 Hz, 10 Hz, and 20 Hz positioning
- Data storage on 57 MB internal memory: 40.7 days of raw observables (approx 1.4 MB /Day), based on recording every 15 seconds from an average of 14 satellites
- 3-wire serial (7-pin Lemo) on Port 1; Full RS-232 serial on Port 2 (Dsub 9 pin)
- Fully integrated, fully sealed internal 450 MHz receiver/transmitter option:
  - Transmit power: 0.5 W
  - Range: 3–5 km typical / 10 km optimal
- Fully integrated, fully sealed internal GSM/GPRS option
- Fully integrated, fully sealed 2.4 GHz communications port (Bluetooth®)
- External cellphone support for RTK and VRS operations
- 16 NMEA outputs, GSOFF, RT17 and RT27 outputs Supports BINEX



**Figure 5-10.** A single-base/multiple-base RTK system.

Courtesy of Trimble Navigation Limited © 2010.

users work in mobile mode. However, in some applications the wired connection is the most sensible form of communication between the RTK base and the rover. For instance, in dedicated RTK monitoring systems (on bridges, buildings, dams, etc.) a cable link is the most suitable telemetry for data communication.

**RTK Radio License**

Traditionally, a radio link is the most common type of telemetry in RTK systems. If a radio link is used, the modems at each end of the baseline must be tuned to the same frequency. The units communicate with each other along a direct line-of-sight. Most RTK radio equipment operates between UHF 400 to 475 MHz or

VHF 170 to 220 MHz. Voice communications also tend to operate in this same range, which can present problems from time to time.

In the United States, the Federal Communications Commission (FCC) requires cooperation among licensees that share frequencies. It is important for RTK users to know that voice communications have priority over data communications. Users should be aware of and avoid using typical community voice repeater frequencies. In addition, the FCC regulations require licensure of the radio spectrum for private use (i.e., an application is required for licensing a radio transmitter). Fortunately, when an RTK system is bought simultaneously with the radio units, the radio licensing and frequency selection are often prearranged by the GPS seller. Nevertheless, it is important to be aware of the licensing requirements in RTK operations and to avoid illegal operation without a proper license.

Elsewhere in the world, other international and national entities regulate frequencies and use of radio signals. In some countries certain bands are designated for public use (i.e., spread-spectrum communication) without any special licensing requirements—for example, the 900-MHz band in the United States and the 2.4-GHz band in Europe.

UHF spread-spectrum radio modems are the most popular for DGPS or RTK applications. The position of the transmitting antenna affects the performance of the system. It is usually best to place the transmitter antenna as high as practical. It is also best if the base has no overhead obstructions and is unlikely to be affected by multipath (e.g., away from activities at a construction site). The base should be within the line-of-sight of the rover but, if this is not practical, there should be as little obstruction as possible along the radio link.

As mentioned earlier, most RTK systems work best when limited to a baseline of less than 20 km (12 mi.). With a troublesome radio link, this distance could be limited even further. For example, in areas with high radio traffic (e.g., many RTK users at the same time), it can be difficult to find an open channel. For this reason, most RTK radio transmitters allow users several frequency options within the legal range.

### ***Single-Base RTK with Repeater Radios***

In certain circumstances, repeater radios can be used to extend the transmission range of the single-base radio RTK. Projects in small sites of, say, 3 to 5 km (1.8 to 3 mi.) can be done with or without repeater radios. Radio RTK operations covering larger areas might require use of repeater radio(s) that work in conjunction with the base radio transmitter. For example, a 35-watt Trimble 450 repeater radio can work in conjunction with a dual-purpose base/rover unit with a built-in 0.5-watt transmitter (Fig. 5-10). The repeater can be moved to a location from which it can still connect with the base in order to extend the base signal out farther. This can be done without affecting the base unit once it is operational. Typically, a maximum of two repeaters can be used in a single project. The second repeater is moved to its limits of connection with the first repeater and it retransmits the first repeater's signal farther out.

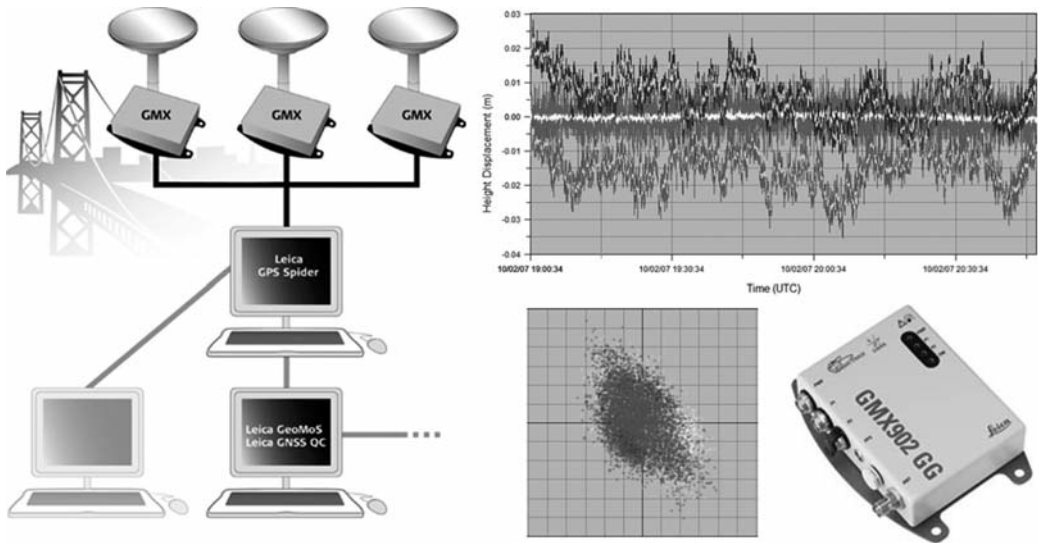
### RTK with Cell Phones

This approach uses a cell phone connection to the Internet to access corrections from the base or from multiple base stations. It is similar to a single-base RTK operation but allows operation over much longer distances from the base than is possible with radios. In addition, the cell phone connection tends to eliminate the signal interruptions that can occur over the radio link. On the other hand, data transmission delay (or *latency*), when it occurs on the Internet or due to poor cell phone reception, can be a source of low-quality RTK positioning. The single-base radio RTK requires setting up your own base. In most circumstances the base station must be guarded or set in protected areas due to possibilities of theft or vandalism of unattended equipment.

In comparison with the radio RTK, the cell phone-based method typically relies on permanent base stations scattered across a region. All that is required is to set up the rover and log in over the Internet with a cell phone. The amount of equipment that has to be carried is minimal and it is always with the operator in the field. The use of cell phones in this regard is typically a characteristic of real-time network solutions such as VRS (virtual reference stations), which are discussed in “Virtual Reference Stations” below.

### Dedicated RTK Systems

In addition to portable RTK systems, some RTK systems are designed specifically for dedicated continuous (24/7) measuring operations. For example, the Leica GMX902 (Fig. 5-11) is a dual-frequency GNSS receiver designed specifically for



**Figure 5-11.** Positioning with a dedicated RTK.

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monitoring applications. Given the nature of the application requirements (e.g., long-term use, sometimes in severe weather conditions), dedicated RTK systems are of rugged construction, weatherproof, robust, and portable. Most manufacturers design systems for integrated solutions with automated data archiving and high-speed, high-accuracy displacement calculation, with typical data measuring rates ranging from 1 Hz to 100 Hz for some models. They are the most expensive (can cost up to US\$50,000 or more apiece) but are the highest-precision RTK systems, for the most sensitive measurements. Additional key characteristics include low power consumption and durability. They do not necessarily require a radio or wireless communication link between the base and rovers. Instead, telephone line or a fiberoptic link is usually the most suitable form of data communication. In the case of centralized hub processing (mentioned in Chapter 3), data from all receivers are transmitted to a centralized control room for processing and analysis.

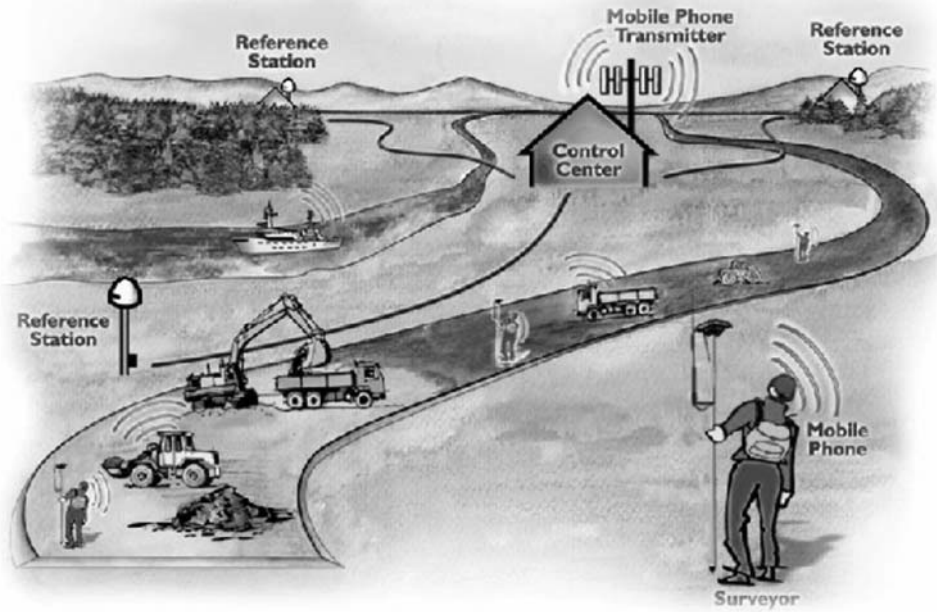
## Network RTK and CORS Networks Infrastructure

### ***Multi-Base Network RTK***

In the case of network RTK systems, observations of several reference stations are usually preprocessed in a central computing facility and network corrections are then made available to the user over the Internet using cell phone connections (Wegener and Wanninger 2010). The use of these systems, sometimes referred to as *real-time networks* (RTNs), have been on the rise worldwide as both government and commercial interests have led to proliferation of permanent GPS network infrastructures. They eliminate the need for setup of base stations when doing RTK operation and they extend the range of RTK coverage. In radio RTK systems, operations are usually restricted to within the radio range of a 3- to 5-km (1.8- to 3-mi.) radius. A network RTK system can operate anywhere inside the base station network covering an entire region. The cell phone network is used to maintain connection with the server and provides access to the nearest base stations in the network for position corrections (Figs. 5-12 and 5-13).

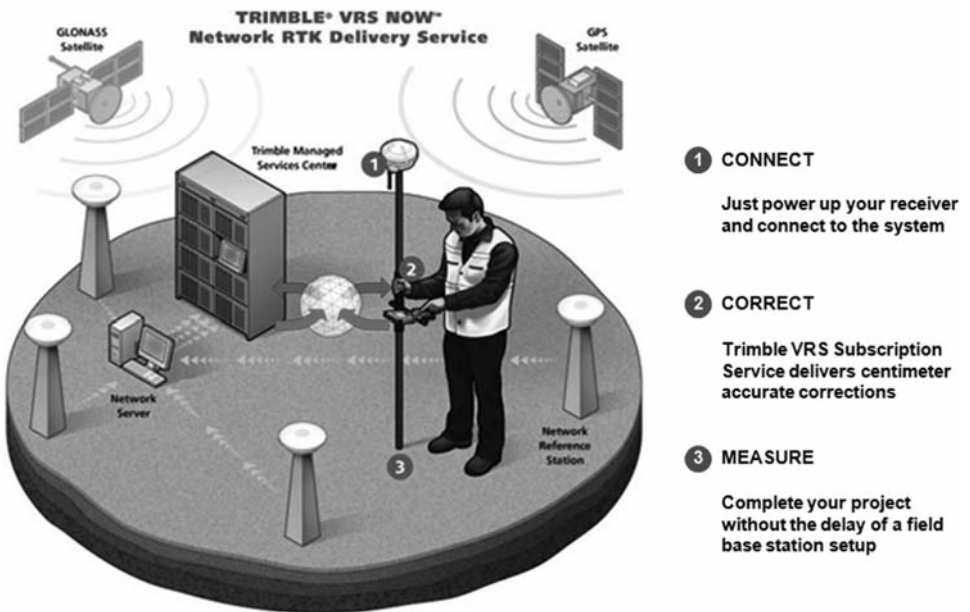
### ***Virtual Reference Stations (VRS)***

Corrections can be determined for a particular position within an RTN in several ways. One approach is the creation of a *virtual reference station* (VRS). As discussed in Chapter 3, VRS is a type of RTK system that requires a two-way communication link. Users send data and their approximate positions to the control and processing center. The control center returns corrections for an individual VRS via the Radio Technical Commission for Maritime Services (RTCM), and then the baseline processing software inside the rover calculates its position using the VRS. The VRS acts as a single nearby reference station. This concept of VRS is illustrated in Fig. 5-14.



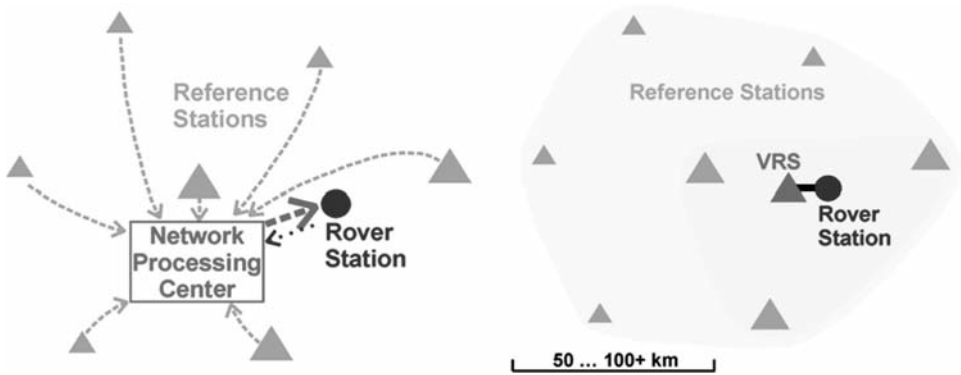
**Figure 5-12.** A VRS RTK setup.

Courtesy of Trimble Navigation Limited © 2010.



**Figure 5-13.** The VRS RTK rover function: connect, correct, measure.

Courtesy of Trimble Navigation Limited © 2010.



**Figure 5-14.** Network RTK using VRS. *Source:* Wanninger (2008).

### **Wide Area RTK (WARTK)**

Another approach involves sending RTK-type corrections or a broadcast of raw data for all the reference stations. *Wide area RTK (WARTK)* systems consist of a distributed network of reference stations communicating with a control center to calculate GPS error corrections over a wide area (similar to WADGPS discussed in Chapter 4). Real-time correction data are transmitted by radio or cellular modem to the rover within the network area. The system improves the reliability and operating range by reducing the systematic errors in the reference data. The distance at which the rover can be located from the reference base can be increased while improving OTF initialization times. Although in both single-base and multi-base network RTK the goal is to improve the rover position accuracy, the difference between the two methods is:

- In radio RTK a single base station, only a short distance from the rover, is used, which means that vertical positions tend to agree well with each other (Caution: Chapter 6, “The Vertical Component,” describes one of the limitations of GPS—it is weaker in the vertical component, especially in the RTK mode).
- In network RTK, multiple base stations are used to create an average correction for the rover. The base stations tend to be much farther away from the rover than in radio RTK. The vertical positions are much better over longer distances than what a single-base RTK can produce over longer distances.

### **Distance-Dependent Model**

The central idea underlying RTN corrections is the combination of observations from several base stations at precisely known positions. The data from the base stations are combined to produce a virtual model of the area of interest; from this model, distance-dependent biases such as ionospheric, tropospheric, and orbit errors are calculated. Several techniques have been developed to model (or interpo-

late) the distance-dependent biases between reference stations and user receivers (Dai et al. 2001). The data processing consists of real-time ambiguity resolution of the network carrier phase observations, and some quality control of the data. The network information is then transferred to the user, depending on selected communication links and data formats for transmitting the network data to the user.

VRS is the most widely used method. The user sends the rover's approximate position to the central computing facility and receives VRS observations in return, using the RTCM format (RTCM 2006), to be used for baseline positioning. In this method, an optimal set of reference observations are used, that is, the ones closest to the rover, and the precise correction models for distance-dependent biases are generated and transmitted. Based on the correction models and horizontal coordinate differences between the master reference position and approximate rover position, the reference observations are virtually shifted closer to the rover (Fig. 5-14). This results in VRS observations that are used by the rover to determine the precise position from the processing of the short "virtual" baseline between the VRS and the rover.

In calculating the distance-dependent biases, ionospheric and orbit biases are modeled individually for each satellite. Tropospheric corrections, however, may be estimated station by station. It is advantageous to separate the biases because ionospheric errors show much larger temporal variations as compared to the other distance-dependent biases.

### ***Subscription versus Free Services***

RTK dominates high-precision GPS applications, especially in areas that require centimeter-level accuracy in real time. In many regions worldwide, RTN services have been established by both governments and commercial interests to provide RTCM real-time corrections to RTK users. These services are sometimes free but often require subscription or fee payment before the user can access the broadcast corrections over a data link via a modem such as a cell phone. The requirement to set up base stations in the field can be avoided by using these RTN services (Fig. 5-13). In addition to extending the RTK range beyond the limitation of short baselines, these services alleviate the need to establish a radio frequency (RF) transmitter and relevant components before a single measurement can be made.

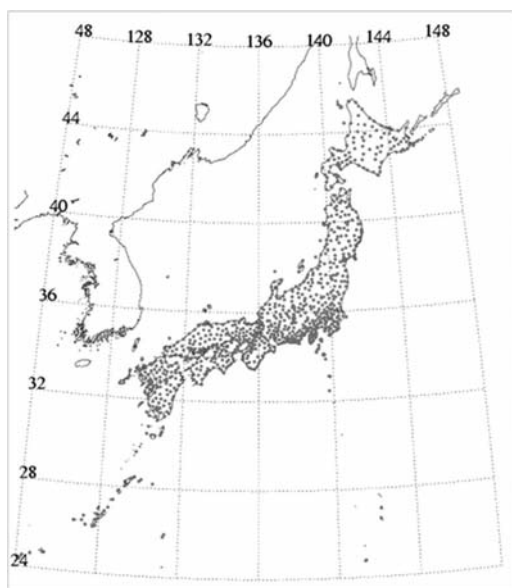
### ***CORS Infrastructure***

*Continuously operating reference stations* (CORS) are the backbone of many GPS networks and services that exist today in support of high-precision GPS positioning. While CORS can be configured to support differential GPS (DGPS) and RTK applications, their primary function is to collect GPS tracking data from known positions and archive the observations for subsequent downloads by users from the Internet. Most of these networks are administered by governmental and scientific organizations, although some are managed by public-private partnerships. Uses of CORS, especially by scientific organizations, include the establishment of

long-term time series of precise position coordinates and velocities of stations involved in the network. Such data are then used to predict precise positions of the stations at any other desired time. However, the most important benefit of CORS is the user's ability to do relative positioning without having to set up their own base station.

The original motivation for setting up a network of CORS was for geodynamic applications such as long-term monitoring of plate tectonics and earthquakes. In Japan, for example, the GPS Earth Observation Network (GEONET) was established by the Geographical Survey Institute (GSI) after the Kobe earthquake in 1994. Today, GEONET comprises more than 1,000 stations around Japan (Fig. 5-15). Networks that support the establishment and monitoring of the International Terrestrial Reference System (ITRS) for geodetic applications have been created around the world by the International GNSS Service (IGS). Users in the United States can take advantage of the CORS network administered by the National Geodetic Survey (NGS). The continental NGS system has two components, the Cooperative CORS and the National CORS (Fig. 5-16). Together, they comprise a network of hundreds of stations that constantly log dual-frequency GPS data, available for download in the *Receiver INdependent EXchange* (RINEX) format.

Other CORS have been established regionally, such as through government–university partnerships. Examples include the Southern California Integrated GPS Network (SCIGN), GPSnet in the state of Victoria in Australia, EarthScope [funded by the (U.S.) National Science Foundation], and NASA's Global Differential GPS (GDGPS) Service.

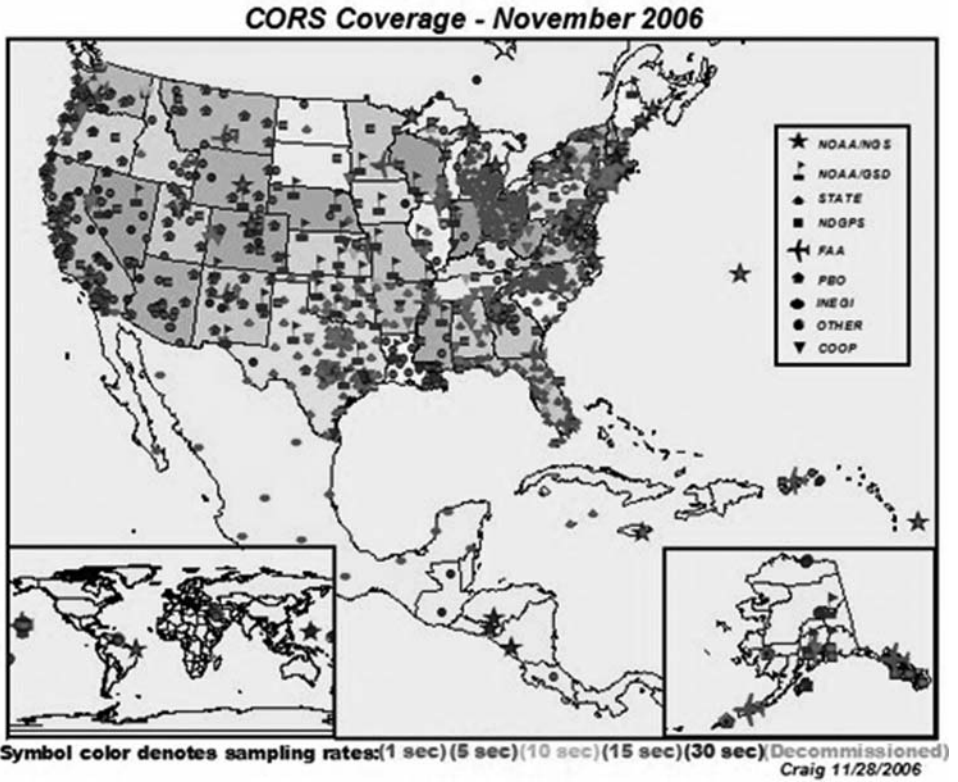


Japan National CORS network--GEONET



GEONET Station in Komatsu, Japan

**Figure 5-15.** GPS CORS in Japan.



**Figure 5-16.** The U.S. national CORS network.

Courtesy of NOAA (2006).

**Online CORS User Services**

The greatest benefit of GPS CORS is the capability to execute differential GPS positioning even if the user has only one receiver. The existence of online CORS-based GPS processing services that are freely available and remotely accessible from any location is an important element of that capability. The online GPS processing services allow remote processing of GPS data files submitted via the Internet. This reduces project costs significantly, especially for projects that require external control. During remote processing, CORS data are either applied as an external control or to estimate and remove some of the GPS errors that degrade the position coordinates. Here is a list of some of these services:

- *OPUS*. An NGS utility that allows for processing of GPS receiver data for rapid-static and static surveying methods. It computes an accurate position for submitted data file and ties the coordinate results to any three closest NGS CORS (NGS 2011).
- *CSRS*. The Canadian Spatial Reference System (CSRS) online database allows users direct access to the primary horizontal and vertical control networks

archived on the Canadian Geodetic Information System (CGIS) and the CSRS-Precise Point Positioning (PPP) online GPS processing system (NRCan 2011).

- *AUSPOS*. AUSPOS provides users with the facility to submit dual-frequency, geodetic-quality RINEX data, observed in a static mode, to a GPS processing system and receive rapid turnaround Geocentric Datum of Australia (GDA) and International Terrestrial Reference Frame (ITRF) coordinates. This service takes advantage of both the IGS stations network and the IGS product range, and works with data collected anywhere on Earth (GeoSciAust 2011).
- *GDGPS (Global Differential GPS Service)* and *APPS (Automatic Precise Positioning Service)*. GDGPS and APPS accept GPS measurement files and apply the most advanced GPS positioning technology from NASA's Jet propulsion Laboratory (JPL) to estimate the position of GPS receivers, whether they are static, in motion, on the ground, or in the air. The APPS accepts measurement rates of up to 1 sec and all coordinate outputs are in an ITRF frame (XYZ and LLH files). The other output formats include the Google Earth URL with the plotted trajectory or site and instant positioning for web users (JPL 2011).
- *SCOUT (Scripps Coordinate Update Tool)*. SCOUT, which is administered by the California Spatial Reference Center (CSRC) processes RINEX files to calculate precise coordinates and also allows users to obtain input files for their processing software. It gives the option to select up to four reference CORS to be used in the processing (CSRC 2011).

Although these services are available for use worldwide, the mode of application may be limited for project locations where CORS network sites are few and far between. In reality, many parts of the world still have no (or very few) control networks established, limiting the use of online services. Nevertheless, some of the services, such as AUSPOS and GDGPS, may still suffice for those locations, especially in applications requiring centimeter-level precision.

## PART 2

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# **Applications in Engineering and Megaprojects**



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# Utilizing GPS in Engineering and Project Management

## Considerations for Using GPS

Before beginning a project in which GPS is to be used, it is vital to be aware of a number of issues associated with the system and equipment capabilities. Using GPS effectively requires some appreciation of the capabilities of the technology, as well as its limitations and challenges: Is it a suitable tool for the goals and objectives of the project? Is it the only option for its purpose, or is there an alternative solution to the problem? Are there cost-effective advantages of applying GPS to the problem at hand? What are the limitations? All these questions are important to consider at the onset without blindly applying the technology.

One decision that must be made is the selection of the GPS system(s) to be used. Questions of cost, features, and functionality must be asked. It is also vital to know whether or what additional equipment is needed. Why do some units have the capability to collect more accurate data than others? Are there ways to increase the accuracy of the data?

Most of these issues are addressed in previous chapters. Chapters 2 and 3 discussed the sources of error that contribute to lower accuracy and how the various errors can be countered to increase accuracy. Chapters 4 and 5 discussed features of different receiver systems, including accuracy levels and error correction methods.

Every application requires certain receiver characteristics and functionality. Table 6-1 gives a generic example of considerations for selecting a GPS system. Every user will have to determine the specifics for their application, and ultimately every application will benefit from the most viable and cost-effective solution that will fulfill the requirements.

## ***Case Example: Considerations for Structural Monitoring***

Figure 6-1 and Box 6-1 illustrate the decision-making process for utilizing GPS in structural monitoring (Kijewski-Correa 2005). In this case, the selection of GPS as one of the sensors for structural monitoring is dependent on the need to observe both static and dynamic displacements of a structure. GPS has an advantage over accelerometers, which can observe only the dynamic displacements (Table 6-2). The selection of GPS also depends on the feasibility of the technology. For

**Table 6-1.** Example of Specifics for Selection of a GPS System for an Application

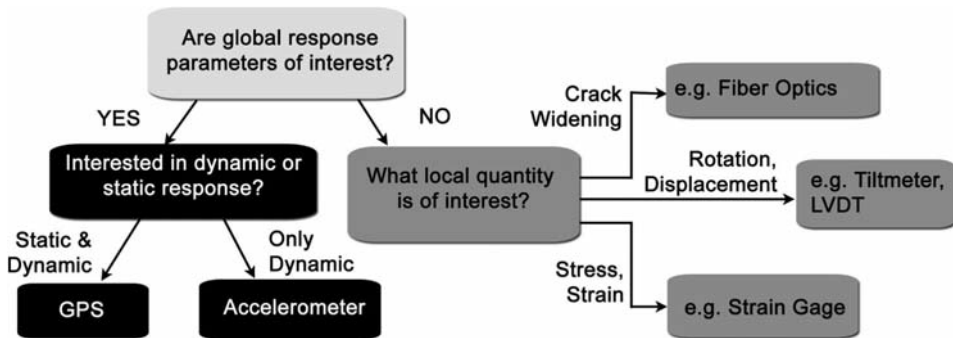
<i>Application</i>	<i>Horizontal Precision</i>	<i>Vertical Precision</i>	<i>Reliability</i>	<i>Availability</i>	<i>Timing</i>
Car navigation	–	–	±	±	–
GIS	±	±	±	±	–
Tracking	±	–	±	+	–
Aviation	±	±	+	+	–
Monitoring	+	+	+	±	–
Construction	+	+	+	+	–
Land survey	+	+	+	±	–
Timing	–	–	–	+	+

–, less important; +, important; ±, may or may not be important.

instance, if the structure is not expected to move at least 1 cm, the resolutions of existing GPS technology [i.e., RMS positioning errors of, say, 3 mm + 0.5 ppm (static) and 5 mm + 2.0 ppm (dynamic)] will likely be insufficient. For this reason, GPS is more suitable to monitoring taller structures of 30 or more stories that are generally flexible, though it can be applied to any structure provided the levels of expected motion are 1 cm or more.

The selection of GPS also depends on budget constraints. The cost-effectiveness of using GPS (a unit could cost tens of thousands of dollars) versus the cost of traditional sensors—depending on the number of sensors deployed—is another important consideration. For example, the cost of using GPS might be warranted only if significant leaning, tilting, or settling of the structure is suspected. Once the determination is made that GPS technology is needed, any number of GPS vendors can be contacted for consultation.

Many vendors have technical staff (applications specialists) who will oversee configuration and deployment of the system. In addition, the GPS manufacturers



**Figure 6-1.** Decision-making process in sensor selection for structural monitoring. Source: Kijewski-Correa (2005, Fig. 7).

Courtesy of Dr. Tracy L. Kijewski-Correa, University of Notre Dame. Used with permission.

**Box 6-1. Decision-Making Process in Sensor Selection for Structural Monitoring**

Kijewski-Correa (2005, Fig. 7) presented a decision-making process in sensor selection for structural monitoring (presented here in Fig. 6-1). In that discussion, the question was posed regarding the role of GPS and other monitoring technologies in the assessment of historic structures. Kijewski-Correa stated, “The technology-selection process begins with the decision of whether static vs. dynamic motions are of interest . . .” and is subsequently guided by the following considerations:

- If it is not suspected that the structure is settling, leaning, or tilting (all examples of static displacements) and if the investigator is interested simply in seeing the structure’s relative motion under ambient vibrations, accelerometers should be sufficient. This process would be regarded as dynamic-motion tracking.
- If both static and dynamic motions are of interest, a GPS system would be a more appropriate choice. Accelerometers and GPS provide “global monitoring” that does not require specific knowledge of where a potential structural problem may be occurring but investigates the motions of the building as a whole.
- If there is knowledge of existing damage (e.g., cracks) or some critical component that needs to be investigated (e.g., a brace or connection), then a more localized approach may be required, since it can focus on quantities such as stresses, strain, or widening of cracks. If multiple-response sensors, both local and global, are desired, the technologies can be integrated into one comprehensive solution. (Kijewski-Correa 2005)

may know of existing nearby reference networks established for surveying and navigation. The use of such existing infrastructure would relieve the burden (in both cost and effort) of setting up a new reference station for the structural monitoring project.

**Table 6-2.** Complementary Features of GPS and an Accelerometer

	<i>GPS</i>	<i>Accelerometer</i>
Frequency = 0 Hz	+	-
Frequency ≥ 1 Hz	±	+
0 < Frequency < 1 Hz	+	-
Continuous and unattended operation	+	+
Δ < 1 cm	±	+
Δ ≥ 1 cm	+	+
Cost	\$\$\$	\$

+, sensor performs well; ±, sensor performs average; -, sensor unable to perform.

Additional important considerations include the fact that GPS can provide a measure of total structural displacement, performing best at low frequencies ( $f < 1$  Hz) and large amplitudes ( $\sigma \geq 1$  cm). The technology has real-time capability and can be operated unattended and continuously. A significant drawback, though, is its reliance on satellite orientation, resulting in degraded accuracy in high position dilution of precision (PDOP) conditions. However, it is envisioned that the global satellite availability will increase due to revitalization of GLONASS (*GLOBAL'naya NAVigatsionnaya Sputnikovaya Sistema*, a radio-based satellite navigation system similar to GPS, operated for the Russian government by the Russian Space Forces) and new signals by other systems such as the European GALILEO satellite system. More satellites in space mean more signals, and perhaps better performance, in obstructed environments, which should help to eventually diminish inherent PDOP errors. Some of the latest receiver models are now capable of tracking these new signals (*GPS World* 2010).

## Considerations for Selecting a GPS Receiver or System

Selection of the right GPS receiver for a particular project is critical to its success. Receiver selection must be based on a sound analysis of the following criteria:

- Applications for which the receiver is to be used (e.g., static or dynamic, code phase or carrier phase)
- Accuracy requirements
- Power consumption requirements
- Operational environment
- Signal processing requirements
- Cost

As previously discussed, GPS receivers range from high-end, high-cost, high-accuracy geodetic-quality to low-end, low-cost, low-accuracy recreational models. Moderate-cost, meter-level accuracy, mapping-grade receivers are also available. Dozens of vendors produce GPS receivers and there are hundreds of models and options available. Current comparative information on GPS receivers and options is readily available in various trade magazines, such as *GPS World*, *POB (Point of Beginning)*, and *Professional Surveyor*. The following factors and features should be reviewed when purchasing or selecting a GPS receiver or system for a project.

### **Intended Application**

In a much broader perspective, GPS applications include land-based, water-based, and airborne positioning, with a wide range of accuracy requirements. Land applications include real-time topographic surveying, geodetic control, resource mapping, navigation, survey control, boundary determination, structural deformation monitoring, and transportation. Most of these applications require carrier-phase,

geodetic-quality receivers. Water or marine applications include navigation and positioning of hydrographic surveys, ships, dredges, and drill rigs, typically using meter-level differential code-phase positioning techniques. GIS development applications are commonly performed with low-cost recreational or mapping-grade handheld GPS receivers, using either absolute point positioning or code differential techniques. Airborne applications include navigation and positioning of aircraft (e.g., for photogrammetric-based mapping) and require high-end, geodetic-grade receivers along with inertial measurement units (IMUs). Some receivers can be used for all types of applications and accuracies; for example, a GPS receiver may contain capabilities for performing code, carrier, RTK, WAAS, GLONASS, or GALILEO positioning. Generally, the more applications a receiver must fulfill, the more it will cost. It is important for the receiver's potential project applications be defined in order to select the proper receiver and the necessary options, and to avoid a purchase of a US\$50,000 GPS system when a US\$10,000 system would have sufficed.

### ***Accuracy Requirements***

Knowledge of the point positioning accuracy requirements is essential when deciding on the type of GPS receiver that will be required. Receiver cost typically increases as accuracy is increased. For example, a geodetic-grade receiver is usually specified for high-quality project control work, particularly when precise vertical control is being established. Accuracy requirements will further define procedural requirements (static or kinematic), signal reception requirements (whether use of either C/A- or L1/L2 P-codes is appropriate), and the type of measurement required (pseudorange or carrier-phase measurements). If only meter-level positioning or mapping is involved, inexpensive single-frequency GPS receivers are adequate, especially if sometimes combined with differential correction services.

### ***Power Requirements***

The receiver power requirements are an important factor in the determination of receiver type. As seen in Chapters 4 and 5, receivers typically run on a variety of internal and external power sources. Most systems operate on small rechargeable internal batteries (e.g., drawing some 1 to 5 watts). A high-end GPS receiver can operate for only a few hours on its internal battery, whereas a low-end, recreational-grade receiver that draws less power may operate for 1 to 2 days on a set of AA batteries. Use of external rechargeable batteries can also be considered as a power source. If continuous operation, such as structural monitoring or navigation, is performed, then an external power option is desirable.

### ***Operational Environment***

The operational environment is also an important factor in the selection of antenna type, antenna and receiver mounting device, receiver dimension and

weight, and durability of design. For example, the harsher the environment (high temperature and humidity variability, dirty or muddy work area, etc.), the sturdier the receiver and mount must be. Most receivers are designed to operate over wide temperature ranges and in 100% humidity conditions. The operational environment will also affect the type of power source to be used.

### ***Baseline Range***

For static control surveys, the typical baseline lengths encountered will determine the type of receiver that is required. Single-frequency receivers are usually adequate for baseline lengths of less than 20 km (12 mi.). Beyond 20-km lengths, dual-frequency receivers are needed. RTK operations require geodetic-quality, dual-frequency receivers over all baseline lengths. Precise vertical control surveys would also require dual-frequency receivers over all baseline lengths.

### ***Data Logging***

Most receivers can log data to an external logging device, such as a survey controller, or directly to a laptop computer. Some mapping- and geodetic-grade receivers can also log data internally for later download through a communications port. Recreational-grade, handheld-type receivers can collect, process, and display data internally. The amount of storage required is a function of the project needs and the data logging rate: 1-sec, 5-sec, etc. Most high-end units use memory cards for additional storage requirements. Quality receivers will have two to four or more RS-232 ports, with high data transfer rates (e.g., 9,600 to 115,200 baud rate).

### ***Operator Display***

For some projects it will be necessary that the selected GPS receiver system has a display unit. Most modern receivers and controllers contain simple icon-based displays for selecting GPS survey modes and data-logging options. Costs and options will vary with the size of the LCD display on the receiver or controller. Quality receivers provide audible and visual warnings when the data quality is poor.

### ***Satellites and Channels Tracked***

Many receivers can track 12 or more satellites. Some can track “all-in-view.” The ability to acquire more than one satellite system (e.g., GPS+GLONASS+GALILEO) would be advantageous in mountainous or urban areas where GPS satellites are partially blocked.

### ***Size and Weight***

Size and weight are important if receivers are used for RTK or mapping type of projects where the operators will have to carry the unit as they move from one

project location to another. It is also an important factor in applications such as tracking, where concealment of the GPS unit is desired.

### ***Free and Commercial DGPS Capability***

Receivers with varied code DGPS capabilities are needed in some remote or mountainous areas, especially for cases where one of the DGPS service provider signals is poor or out. Some receivers are designed to acquire commercial and free DGPS pseudorange corrections.

### ***Antenna Type***

A wide variety of antennas are available from GPS receiver manufacturers. In addition, optional antenna types can be ordered with the same receiver. Some antennas are built into the receiver and others are external. Multipath minimization will require more expensive antennas, especially for static control surveys. These include antennas configured with ground planes and choke rings. For high-accuracy work, antenna reference points should be modeled.

### ***Processing Requirements***

Operational procedures required before, during, and after an observation session are manufacturer-dependent and should be thoughtfully considered (and tested) before purchase of a receiver. A receiver may be easy to operate in the field, requiring very little user interface, but a tremendous amount of time and effort may be required to download and process the data. Another determining factor in the receiver selection process is whether a postprocessed or real-time solution is required.

### ***Cost***

Receiver hardware and software costs are a function of development costs, competition among manufacturers, and product demand. Historically, costs for procurement of GPS equipment have fallen steadily and the trend continues. Cost estimates must include full GPS systems along with auxiliary equipment, software, training, and so forth.

### ***Data Exchange Formats***

In order to transfer data, a common exchange format is required. GPS vendors usually have their own proprietary formats. However, most GPS receiver data can be converted into a common text format, such as the Receiver Independent Exchange (RINEX) format, which is commonly used for postprocessed data. Real-time data exchange, such as in RTK positioning, is typically handled using the Radio Technical Commission for Maritime Services (RTCM) standard. Vendors



often allow for optional outputs such as ASCII, DXF, ArcInfo, DGN, NMEA 0183, and so forth.

## **Planning and Installing a GPS Measurement System**

Due to variability in GPS projects, it is impossible to discuss details that address the needs of every project. The specifics of a GPS project will vary depending on its purpose and requirements. Some projects are easily executed by one person. Most large-scale projects need a multiskilled team effort, while for smaller projects with fewer personnel, many of the tasks being handled by multiple people in a large-scale project can be accomplished by one person.

Because of the simplicity of many types of GPS receivers, it may be tempting to assume that incorporating the technology means handing out a receiver and noting down the coordinates. This couldn't be further from the truth. GPS may be a simple tool but using it effectively in a project requires insight, planning, and forethought. The following topics are presented assuming a full-scale GPS measurement system (refer to the project scale definitions in "What Does a GPS Measurement System Entail?" in Chapter 1).

### ***System Design and Work Flow***

It is vital to thoroughly understand what the complete GPS measurement system is going to entail. On that basis, the planning and layout of the measurement system will facilitate a work plan. It is necessary to visualize procedures that must be accomplished and in what order the tasks are to be performed. But first there must be a concept—mental or written—as to what is required to complete the project. These typical questions can help address the various components of the planning process:

- How many receivers are needed and for what locations or measurement points?
- What types of receivers are needed? Are they mixed grade or the same types of receivers?
- What are the data communication options?
- Is the work going to involve installation of permanent GPS monument(s) on the ground?
- What will be used as the power source for the measurement system?
- What about security? Will the system be safe from theft or vandalism or is there no such concern for the project?
- Is it going to be necessary to test or calibrate the equipment before installation or during use?
- Are the GPS data to be recorded and/or displayed for human analysis or are they part of a "black box" sensor system?

While for some projects a schematic block diagram is essential for designing the GPS measurement points and data communication systems such as cable layout

plans, a work flow plan may suffice in other cases. Existing information about the project (e.g., as-built plans or scaled models) can be the basis for such design. Block diagrams are especially important in full-scale projects such as buildings or bridge systems, or if integrating a GPS measurement system with other systems requires such knowledge about the system being studied.

### ***Equipment and Resources***

Specific equipment and material will vary from one application to another. Based on factors such as size of the project, number and location of measurement points or target features, time available to complete the work, and the specifics of the data collection methodology, it is necessary to determine and acquire the relevant types and quantities of equipment (Fig. 6-2), personnel, and other instruments needed to successfully complete the project. If field trips are involved, the project may require additional items such as computers and accessories, photographic and communication devices, instruction manuals, field data sheets with pens or pencils, tape or measuring devices, and personal gear.

### ***Installation***

In a full-scale project, installing a GPS measurement system may span several weeks or months. Consider the installation of a GPS measurement system on a “mega-bridge” system. The project may need several dozens of receivers, laying of ground cables spanning several kilometers, installing a complex cable system on bridge decks and towers, and building a control room for the measurement system. If the project owners are interested in a fully independent system with both base stations and rovers, then new reference stations must be established in the vicinity of the project area (Fig. 6-3). All these tasks combined cannot be done in a day or two.

Given the magnitude of such a project, all project personnel must be properly trained for the tasks at hand. Most importantly, the personnel must be well-trained



GPS Delivery



Reference Station

**Figure 6-2.** GPS equipment in a full-scale project.

Copyright by Leica Geosystems AG. Used with permission.



**Figure 6-3.** Building a reference station.

Copyright by Leica Geosystems AG. Used with permission.

regarding occupational health and safety issues. There must be strong management interaction with field and office personnel throughout the entire conduct of the project.

## Developing a GPS Project

### *Identify Project Goals and Objectives*

Any project requires taking time to plan according to the goals and objectives. A key component in a GPS project is the level of data accuracy and what information the data are intended to supply, such as position, velocity, or time.

- Is GPS going to be applied as a standalone solution or an integrated solution with other systems?
- What methods, equipment, and resources will be used to collect the data or install the GPS system?
- How will the GPS data be processed or applied?

The answers to these questions will relate to the goals and objectives of the project; without a strong link between the project questions and GPS data collection effort, there is an increased possibility that the GPS system or the data collected will not be useful.

### *Determine Accuracy Needs*

A review of the goals and objectives will help determine the project's data needs, especially the level of accuracy. For instance, is it necessary to know the position of point(s) of interest to the centimeter level, or will being within 5 to 20 m be sufficient? The answer to this question has implications for what type of GPS receiver to use or buy, and what data communication protocols and error correction methods or services to use, if needed.

Accuracy is the most important user element of GPS, and obviously an important feature to consider when deciding which type of receiver to use. As illustrated in Chapter 5, “The Concept of Precision,” *accuracy* is the amount by which a measurement or quantity differs from the actual, real-world value that it represents. *Precision* indicates the magnitude of the difference between a measurement and the mean, that is, the dispersion among different measurements. A GPS receiver can record coordinates with almost infinite precision but that does not mean the GPS coordinates are always highly accurate. Both the type of receiver and method of data collection can affect accuracy and precision in different ways.

A professional user, such as a surveyor or engineer, cannot use a recreational-grade receiver to obtain centimeter-level accuracy, and a novice user cannot produce centimeter-level accuracy with a professional geodetic-grade receiver. While it is possible to simply turn on the receiver outdoors and let it begin calculating coordinates, that is not enough to ensure a high level of accuracy. Many error sources can degrade the accuracy of a GPS position and there are various correction methods to mitigate those errors. These are discussed in detail in Chapter 3.

### **Select Data Collection Methods**

Once the accuracy requirements are established, the next step is to determine the data collection methods, that is, how the GPS positions are recorded and/or utilized. For a real-time project where the object being measured or monitored is mobile or quasidynamic, the *measurement (or position) update rate* is important. If a GIS survey is being administered, then perhaps it is cost-effective to have the field crew capture the GPS coordinates along with recorded features at the same time the survey is administered. In other cases, a dedicated team may be charged with collecting GPS points for postprocessing. If data storage is needed (e.g., for later processing or as evidence), then the *data-logging rate* will influence decisions about what additional equipment is needed, if any. Alternatively, on the basis of GPS receiver *storage capacity*, decisions will be made about how long each data collection session should be. In the case of an installed dedicated GPS system for continuous measurement, a carefully planned data management system is paramount. As with the data accuracy needs, these factors will have implications on what type of GPS receiver(s) to use.

### **Budget for Resources**

Closely linked to the GPS data needs is the development of the equipment, material, and personnel (man-hour) budget. Decisions will be made about what type(s) of GPS receiver(s) to use or purchase, how many will be needed, GPS vendor selection, and so forth. But even if the equipment to be used is already procured and available in-house, it is good practice to cost such items according to the duration of use. Other ongoing costs such as GPS networks subscription fees, if applicable, should be incorporated into the budget as well.

### **Identify Logistics**

Questions concerning logistics, such as transportation or deployment of people and/or equipment, should also be addressed beforehand. Prior to the GPS equipment being used, deployed, or installed, some training may be necessary on how to use the equipment and materials, especially if the project involves multiple people. In most cases the GPS equipment will be used to record coordinates and pertinent information. Vendor-supplied manuals could be part of the training material; the training should not only focus on the specifics of the project but also provide an overview of what GPS is and how it works.

## **Understanding the Limitations**

### **The Vertical Component**

GPS is weaker in the vertical component, which is less accurate compared to horizontal components, especially in the RTK mode. The precision will improve with the length of observation time but it is critical to understand that a GPS vertical component is not the same as that provided by optical surveying, such as using an electronic distance meter (EDM) or a level. The GPS height results can be immediate and of similar relative accuracy, but it is not a good idea to consider the methods equivalent. GPS offers some advantages and disadvantages when compared with conventional height measurement techniques. For example, RTK can be much more productive since it is available 24 hours a day and is not affected by weather conditions. However, when it comes to the vertical component, RTK and the level are certainly not equal.

GPS measures heights relative to an *ellipsoid* (a mathematical figure). In contrast, the height differences obtained through conventional optical methods are relative to the *geoid*, which is an equipotential surface at the sea level. An *equipotential surface* is a level surface of equal gravity potential everywhere (Elithorp and Findorff 2009). The height of a point obtained by optical leveling is known as the *orthometric height* ( $H$ ), whereas that obtained by GPS positioning is called the *ellipsoidal height* ( $h$ ). The two are not the same and the mathematical difference between them is called the *geoid height* ( $N$ ).

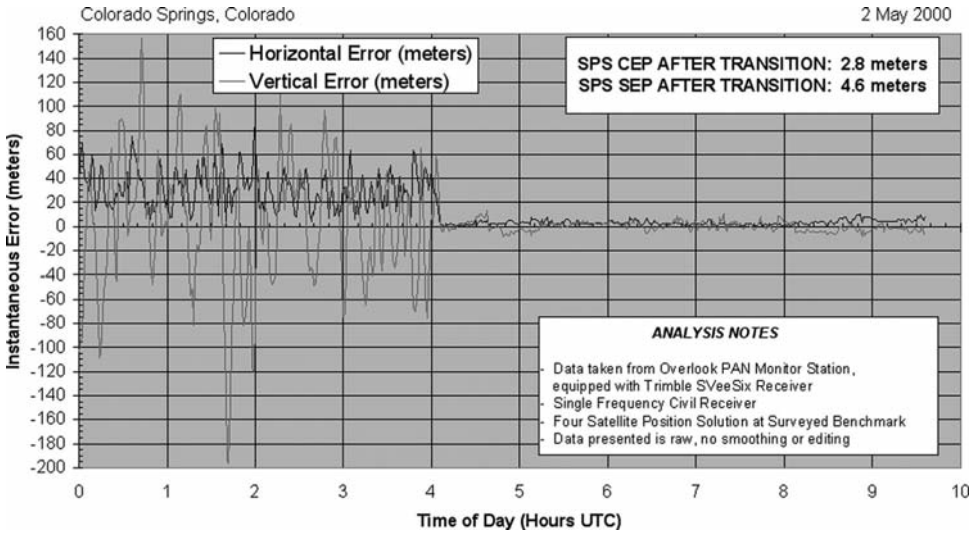
GPS can be used to measure differences in ellipsoidal height between points with good accuracy. However, unlike a level, unaided GPS cannot be used to measure differences in orthometric height. Stated in another way, “orthometric elevations are not directly available from the geocentric position vectors derived from GPS measurements” (Van Sickle 2008, Ch. 5). However, from GPS measurements of ellipsoidal heights, orthometric heights (which are mostly used in engineering applications) can be derived when a geoid model for the measured point is available. In the past these calculations were done exclusively in a postprocessed mode, but nowadays many manufacturers include a geoid model in their RTK systems. Without a geoid model, GPS will only provide differences in ellipsoid heights between the base station and the rover. It is not recommended to presume that

the ellipsoid surface is parallel to the geoid surface between the base and the rover and ignore the deviation between the two. They may depart from one another by as much as 1 m in a distance of 4 to 5 km (2.5 to 3 mi.).

**“Without Warning”**

In some sectors such as aviation, the GPS system integrity is critical—there must be a way to issue a warning if the system accuracy is degraded. However, there is no universal system in place to let the everyday civilian user know if the system accuracy is compromised or degraded, and other GNSS systems that are currently under development will complement GPS in this regard. At the same time, the United States has no intention of applying a blanket policy without notice, like the selective availability (SA) that was imposed prior to May 2000 (Fig. 6-4). That feature is no longer implemented in the new-generation satellites. However, GPS is still primarily a military system, although civilian users far outnumber the military users.

To put things into perspective, if the system accuracy is inadvertently compromised, the user might blindly rely on the coordinates—with possibly tragic consequences. For instance, given the heavy reliance nowadays on the system, it can make the difference between an ambulance arriving at the correct address and



**Figure 6-4.** The end of selective availability (SA) on May 2, 2000. SA was a technique to reduce the accuracy of unaugmented, single-receiver GPS measurements. Initially, the highest-quality signal was reserved for military use and the signal available for civilian use was intentionally degraded by SA. This changed with U.S. President Bill Clinton ordering SA turned off at midnight May 1, 2000, improving the precision of civilian GPS from 100 m (about 300 ft) to 20 m (about 65 ft). The U.S. military by then had the ability to deny GPS service to potential adversaries on a regional basis (NGS 2010).

saving a life or ending up the wrong address and failing to save it. Similarly, it could make the difference between a dispatched GPS-aided building demolition unit arriving at the wrong house across the street, or getting to the correct address.

### ***Unobstructed Line-of-Sight***

Due to the line-of-sight (LOS) requirement between the antenna and satellites, *unaided GPS* is not effective for “concealed” positioning. Although miniaturization makes it possible to use the GPS technology in a nearly nonintrusive and/or concealed manner, using it effectively in obstructed environments is still a challenge. The antenna portion of a GPS receiver, whether external to or embedded within the receiver (and no matter how small it is), must be placed in such a way that there is a direct LOS between the antenna and the spaceborne satellites. For this reason it is almost impossible to use unaided GPS as a concealed device wherein both the receiver and the antenna are completely concealed inside the object being positioned. If needed, the solution might be to design the antenna as part of the body of an object while still meeting the LOS requirement. Alternative methods using assisted-GPS (A-GPS) and wireless networks (discussed in Chapter 7, “Integrations and Wireless Communications” and “Wireless Trilateration Technologies”) can aid tracking in situations in which GPS alone cannot work.

### ***Satellite Geometry***

Another issue closely related to the LOS requirement is the PDOP at the location of the GPS receiver (see Chapter 2, “Position Dilution of Precision (PDOP)” and Fig. 2-18). This is mostly relevant in static GPS surveys for high-precision applications where observing a sufficient number of healthy satellites is critical to obtaining high accuracy. Obstructed environments such as urban canyons or deep gorges are not good candidates for good satellite geometry. However, in some situations observing data for a longer period may help improve the results due to the changing satellite geometry.

### ***Susceptibility to Interference and Jamming***

GPS is based on radio signals that are transmitted from the spaceborne satellites to a receiver on or near the Earth’s surface. The GPS “carrier” radio signals have known frequencies within the microwave L-band of the electromagnetic spectrum. Radio waves are known to be susceptible to interference and jamming. Due to considerations of interference, integrated solutions such as inertial navigation system (INS)/GPS systems are routinely used in applications involving safety and security, such as in military and civil aviation.

GPS signals are so “weak” that they are easily swamped by the smallest of interfering signals. The GPS signals reaching the Earth’s surface are around  $-163$  dBW ( $50 \times 10^{-18}$  watts), which is well below the receiver noise floor. In “The Civilian Battlefield” (*Inside GNSS* 2011a), the author details some of the ways to

counter the threats of interference, jamming, and spoofing of GNSS receivers. According to the article, a 10-mW jammer will prevent a receiver from acquiring the C/A code at a distance of 10 km, and a receiver already tracking the C/A code will lose lock about 1 km from the jammer. While jamming denies the availability of a service, spoofing fools the GPS receiver into thinking it is still tracking satellites, when in reality it is processing fake GPS signals.

Combining GPS with INS is one of the well known solutions to this problem, as the two systems are highly complementary. For example, although INS typically provides very good short-term accuracy, it drifts and loses accuracy over time as errors accumulate. However, INS cannot be jammed. GPS, on the other hand, provides exceptional long-term accuracy but is highly susceptible to jamming and spoofing. Antenna and receiver design options can also mitigate or eliminate the problem of jamming and spoofing.

Spectrum allocation for bandwidth use (e.g., for smart phones and other devices) is yet another challenge facing the GPS system. For example, on January 26, 2011, the Federal Communications Commission gave conditional approval to LightSquared, a multi-billion dollar venture backed by Harbinger Capital Partners and other hedge funds, to build a new broadband network that has the potential to overwhelm GPS receivers across the country (*Inside GNSS* 2011b). LightSquared planned to provide nationwide 4G (fourth generation) mobile broadband service using two geostationary satellites and a new network of around 40,000 ground stations called *ancillary terrestrial components* (ATCs). The company planned to offer its expanded service in the frequency band ranging from 1525 to 1559 MHz. Most GNSS systems (GPS included) and related augmentation and regional services use (or plan to use) the adjacent band ranging from 1559 to 1610 MHz. For example, the GPS L1 C/A code is a 20.46 MHz signal centered at 1575.42 MHz. The L1C signal planned for GPS Block III satellites will be more than 24 MHz wide, coming even closer to the proposed LightSquared spectrum. Each of the planned ATCs' ground stations would transmit a signal roughly 1 billion times more powerful than a GPS signal. This could potentially overload and crash GPS receivers.

The above scenario clearly demonstrates a major contemporary issue facing the GPS community at the time this book is being written. The FCC “. . . conditioned final approval of LightSquared's operations on the company finding a way, in cooperation with the GPS community, to address the overload problem” (*Inside GNSS* 2011b, p. 20).



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# Application Examples

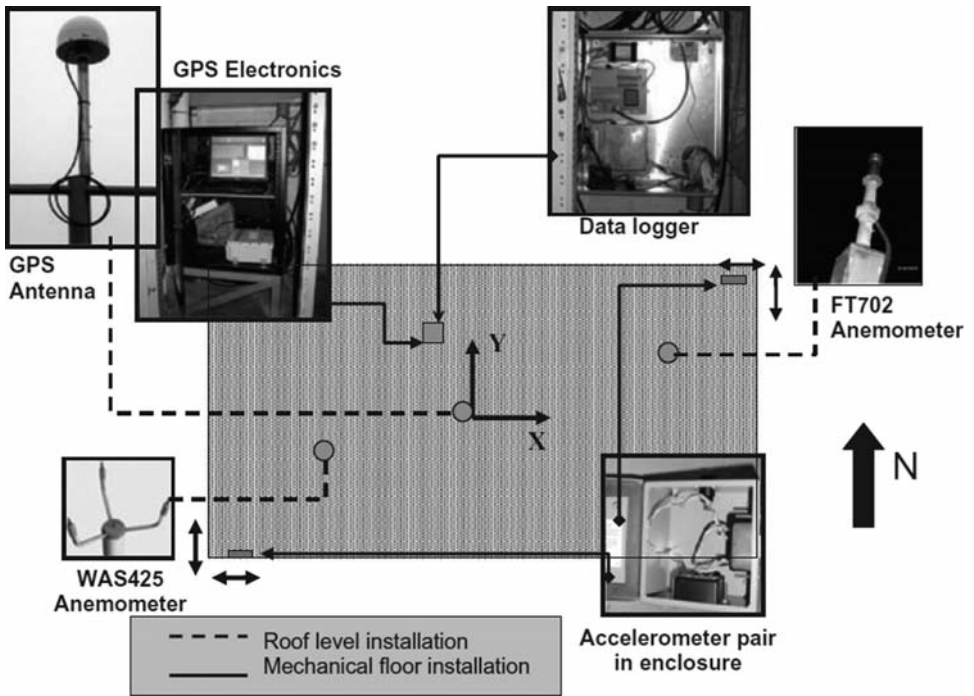
## Structural Health Monitoring

The early work in GPS monitoring of civil engineering structures can be traced to monitoring of settlements, thermal expansion, and other long-period displacement trends in bridges and dams. Since GPS displacements showed excellent correlation against measurements by traditional accelerometers, the technology was deployed for dynamic monitoring of a number of bridges: the Akashi-Kaikyo Bridge, . . . the Tsing Ma, . . . and Ting Kau Bridges in Hong Kong. The Di Wang Building in China, two buildings in California, and another in Singapore have been monitored by GPS. (Kijewski-Correa 2005)

Structural health monitoring (SHM) is becoming increasingly important due to the large network of aging infrastructures worldwide. Monitoring of built structures is traditionally accomplished using accelerometers or strain gages, which are unable to resolve the global displacements of the structure, including static, quasi-static, and dynamic components. Given the need to observe these various response components, GPS has become a viable alternative for SHM. The technology has been successfully applied in full-scale deployments worldwide.

Through ongoing monitoring programs, the responses of structures are measured under a wide range of conditions with the aim of improving the understanding and techniques for their design. The measurements are correlated against the predictions of finite-element models and wind-tunnel tests used in their designs. The data gathered from these projects also serve as metrics for performance assessment. GPS and accelerometer systems provide valuable information on the in-situ behavior of structures so that the next generation of structures can benefit from the experiences of their predecessors.

Figures 7-1 and 7-2 are two case examples of full-scale structure monitoring projects incorporating the use of permanently deployed GPS alongside other measurement technologies. The first example is a schematic overview of the sensor array deployed on tall buildings in downtown Chicago to measure the wind-induced response (Kijewski-Correa et al. 2006). The second example is a project in



**Figure 7-1.** Schematic overview of generalized sensor array in a Chicago full-scale building monitoring program.

Source: Kijewski-Correa et al. (2006, Fig. 1).

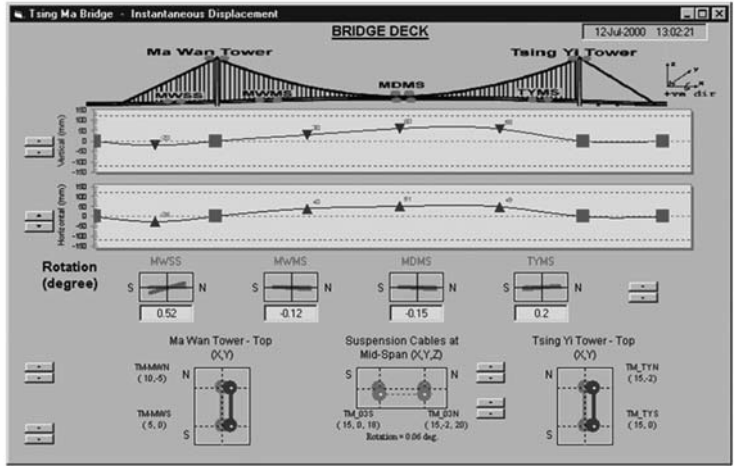
Hong Kong for measuring the wind-, traffic-, and temperature-induced responses of suspension bridges.

In the first example (Fig. 7-1) the sensors shown with the dashed lines are deployed at the floor level (inside the building), while those shown with the solid lines are installed at the roof level. Notably, the GPS antenna is installed at the roof level due to the requirement for a clear view of the sky, to observe the satellites; the other GPS electronic hardware components are installed at the floor level. The communication data cables provide the connection between the roof-level and the floor-level components. The schematic also indicates two orthogonal pairs of accelerometers at two opposite corners of the highest floor of the building. These are meant to capture the sway and torsional motions during significant wind events. In contrast, one GPS antenna is sufficient to capture the sway, but two antennas are still needed to capture the torsional response. The system is supplemented by a pair of ultrasonic anemometers at the opposite corners of the building rooftop, several meters above roof level, to provide a measure of the wind speeds above downtown Chicago.

As mentioned in previous chapters, the true benefit of using GPS in such monitoring programs is in being able to resolve both static (permanent) and



(b)



(c)

**Figure 7-2.** Full-scale bridge monitoring program in Hong Kong. (a) Tsing Ma Control Area (TMCA), Hong Kong; (b) GPS antenna on the bridge tower; (c) sample instantaneous displacements.

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dynamic (periodic) movements in a global spatial reference frame. This is possible because of the position of the antenna (the “rover”) on the roof level being relative to another reference antenna (the “base”) firmly mounted on a solid foundation elsewhere or on a nearby low-rise building. The evolution of the relative baseline between the rover and the base over time will capture both the trend (of permanent displacement, if any) and the periodic behavior of the whole building

in response to wind loading. In contrast, an accelerometer cannot capture the static deformation of the structure.

In addition to its application for monitoring wind-induced motions, GPS has also gained much recognition for its performance in seismic regions. Thus, while these case examples are primarily concerned with wind and/or traffic-sensitive structures, the application extends to seismic-induced motions (Çelebi and Sanli 2002).

In bridge monitoring, the rover antennas are placed at strategic locations on the deck and towers. While in the case of tall building monitoring the number of antennas may be limited by the space on the roof level, several receivers—up to a dozen or more—may be placed in pairs on the deck and towers of a long-span suspension bridge (Fig. 7-2). Such a configuration will allow for the full deformation mode (rotations and displacements) of the bridge to be resolved by the GPS measurement system. However, in addition to the GPS component, the full measurement array may consist of other localized sensors to measure the deformation of structural components (e.g., cables, towers, and deck sections), cable force, deck strain and stresses, and accelerations of the bridge deck:

. . . the WASHMS for Tsing Ma Bridge (TMB), Kap Shui Mun Bridge (KSMB) and Ting Kau Bridge (TKB) consisted of 774 sensors in seven major types: anemometers, temperature sensors, dynamic weigh-in-motion sensors, accelerometers, displacement transducers, level sensing stations, and strain gauges. The commissioning of GPS-OSIS in January, 2001, brought an additional 29 sensors into the overall system. (Wong et al. 2001)

## Robotics and Machine Control

### ***Automated Machine Guidance with GPS***

GPS robotics and machine control are used to guide heavy machinery in many types of construction. It complements the historical stakeout for earthwork and large-scale construction that has relied on effective but slow technologies and processes. The real benefit of using GPS in these applications is in terms of productivity and cost reductions. It is also highly desirable to automatically guide machines to work in extreme environments (Fig. 7-3).

The two types of automated machine guidance (AMG) systems that use GPS (Bennett 2010) are *indicate* and *automatic*. Indicate machines use lights, tones, or in-the-cab display systems to guide the operator (Fig. 7-4a). The operator manually moves the blade or bucket to a particular grade or elevation using constant feedback from the system without ever having to interpret the grade stakes. The indicate systems are relatively inexpensive and allow the operator to maintain full control of the equipment. Automatic systems use onboard computers and servo-like mechanicals to operate semiautonomously. The operator still drives the machine but the GPS machine control system automatically interprets the design model and controls the actual movement of the blade or bucket.



**Figure 7-3.** A GPS-controlled machine hard at work.

### **Site Calibration**

By default, the GPS rovers on an AMG system output latitude, longitude, and ellipsoidal height, or Cartesian (X, Y, Z) coordinates, based on the WGS-84 reference ellipsoid. However, most engineering projects are designed to work with



(a)



(b)

**Figure 7-4.** (a) A machine operator from MACTEC Development Corp. watches the in-cab AMG display while grading ball fields at the Lyndhurst Recreation Complex in Lyndhurst, N.J.; (b) checking AMG grading progress at the Kingsland Landfill in Lyndhurst, N.J. with RTK GPS.

Courtesy of Joseph Priestner, LandMarker Geospatial © 2010.

plane coordinate systems only. Because of this requirement, some GPS systems have the option to select from certain preinstalled standard plane coordinate systems. In the absence of such options, a site calibration is required to carry out a transformation between the computed coordinates and the local survey control to achieve a tight correlation such that all positions reported by the AMG system are relative to the on-site survey control used by others involved in the project.

A calibration of the GPS system is needed in order to relate GPS positions that are measured in terms of the global WGS-84 system to local grid coordinate projections, such as the State Plane Coordinate System (SPCS), the Universal Transverse Mercator (UTM), or a local elevation system (Appendix 6). In addition, a vertical calibration is needed to adjust the observed GPS ellipsoidal elevations to a local vertical datum and account for undulations in the local geoid over the project area.

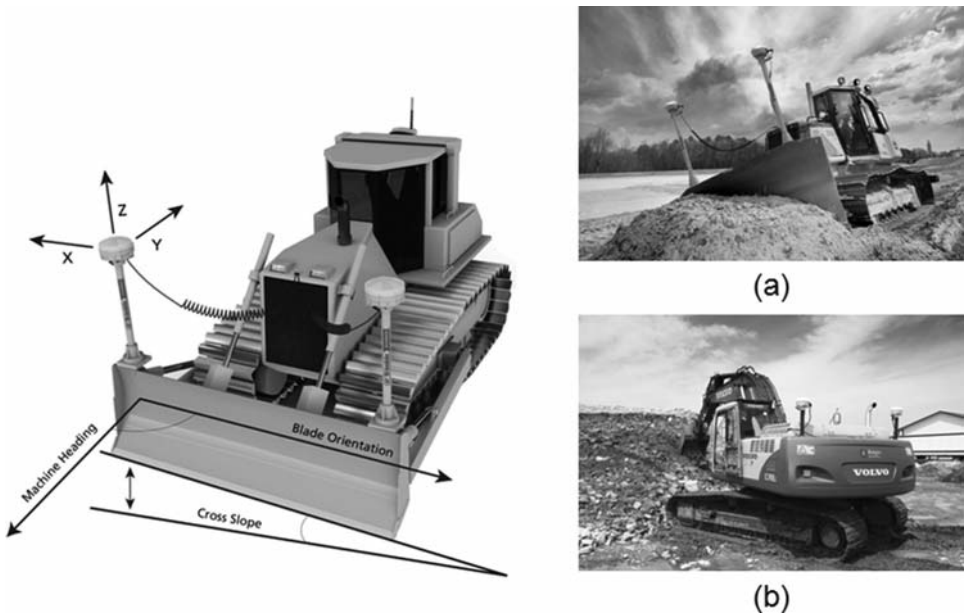
A calibration should be done on a project area whenever new points are to be established. It is based on a set of points that have 3-D coordinates in both WGS-84 and the local grid coordinate projection system. The number of points that can be used in a calibration is manufacturer- and software-dependent. Smaller-sized projects may be calibrated by one 3-D point; however, for larger-sized projects three or four 3-D points are recommended. Calibration points should be well distributed around the project exterior. The calibration results should be carefully examined for reasonable horizontal and vertical residuals.

For example, in performing a site localization using coordinates and elevation values supplied by a contractor, the project surveyor can, by default, tie into four or more control points around the project by holding them fixed. However, there is a need to also verify the local control data supplied by the contractor since site localization can warp data enough to fit bad survey control data. Different approaches can be tried. For example, as a check, the surveyor can hold only one point fixed and perform a quick, minimally constrained adjustment. This could detect any problems with the local control data supplied by the contractor (Priestner 2010, p. 14). In addition, the professional surveyor can also perform independent calibration checks of the GPS system periodically during construction.

### ***Orientation, Slope, and Height Guidance***

GPS rovers triangulate the exact location of a constantly moving machine by using error corrections from a base receiver or a reference network (refer to Chapter 5, “Real-Time Kinematic (RTK) Systems”). Using the error corrections and data from its onboard GPS rovers, the machine constantly generates coordinates that its computer can use as reference against the design model, and manipulate the vehicle’s blade and bucket accurately. Dual-antenna systems integrated with other sensors allow for the slope and orientation computations (Fig. 7-5), for which it is also necessary to have the computed GPS coordinates converted into a local horizon system (refer to Fig. 2-4).

GPS machine control yields levels of horizontal accuracy to within a single centimeter; this accuracy level is not sufficient for complex 3-D highway and site



**Figure 7-5.** Dual-antenna system for (a) slope and (b) orientation guidance.

Courtesy of Trimble Navigation Limited © 2010.

construction projects which also require a precise elevation component. Because of the inherent inaccuracy in the height component (refer to Chapter 6, “The Vertical Component”), the GPS machine control systems are also integrated with laser control systems. For instance, tripod-mounted lasers send out a horizontal beam in a 360-deg arc within the construction site. Receiving prisms on the excavator or bulldozer automatically notify operators when they have reached the desired elevation, thereby enabling a millimeter-level vertical accuracy. Thus, the vital role of GPS in machine control is automation, in terms of orientation and cross-slope, despite the weakness in vertical component.

### ***The Benefits of Using GPS***

With GPS machine control the entire grading process proceeds faster, more efficiently, and more accurately. Traditionally, civil engineers create designs, drafters convert them into 2-D paper documents, and technicians, surveyors, and contractors interpret these documents to produce lists of cuts, fills, and staking coordinates. According to Timothy Bennett of Bennett Engineering & Land Surveying (Sagamore Beach, Massachusetts), “During grading, every time the equipment operator bumped a stake or completed a couple of passes, the field team would have to repeat the entire process. . . . GPS machine control eliminates these and other factors that can slow project completion and increase costs” (Bennett 2010, p. 19).



## Maritime Operations

### *Ship Navigation at Large Ports and Harbors*

In offshore navigation, GPS is a tool for any phase of maritime navigation, such as ocean, coastal, port approach, and port maneuvers, in any weather conditions. Among the most difficult maneuvers for vessels (Fig. 7-6) is the approach to port and precision docking, particularly under poor weather conditions. In such conditions, locally assisted satellite navigation is a fundamental tool for all kinds of harbor operations and precision docking. The increased availability of satellites (as discussed in Chapter 8) will help to provide the service even in an environment with limited sky visibility.

In relation to Table 6-1 in Chapter 6, the considerations for using GPS in ship navigation are similar to those of tracking, with “GPS signal availability” being the top priority. Satellite navigation provides a means for implementing the regulations on automatic identification systems (AIS) and vessel traffic management systems, increasing navigation safety and collision prevention as regulated by the International Maritime Organization. In the future, additional satellite systems such as GALILEO will add to the signal availability, high accuracy, and integrity needed for navigation at open sea. These will enhance confidence in the calculated position of a vessel. GALILEO will also be an additional means for implementing the AIS regulations and thus contribute to improved AIS reliability, increased safety, and vessel traceability.



**Figure 7-6.** A shipping vessel loaded with containers.

GPS satellites also enable precise navigation along inland waterways, especially in critical geographical environments or meteorological conditions. With the help of GPS systems and infrastructure, the vessels navigate through rivers and canals where the accuracy and integrity of navigation data are essential to automate accurate maneuvers in narrow waterways. However, as is the case in aircraft navigation, GPS is not to be used as the sole means of navigation for marine vessels. Backup systems such as radar and compass or direction finder and distance measuring equipment are still necessary.

### ***Container Tracking***

Cargo shippers want to be able to give their clients accurate information on the whereabouts of their containers (Fig. 7-7), anywhere en route (over the ocean and over land), in a seamless and efficient way. Governments want to ensure that cargo arriving on land is properly taxed and that no leakage is occurring during transit. They also want to know that dangerous goods aren't being smuggled into their country. Importers want to ensure that the goods they are bringing into a country will arrive securely, complete and intact. They also want to know when those goods will arrive and be ready for pick-up.

Container tracking can be accomplished in a number of ways, most notably today by associating the container with the carrier—whether a cargo vessel, tractor/trailer, or rail car. In many cases it is possible for shippers or consignees to access carrier information about the location of the transport to track the container.

The key to many of the potential benefits of container tracking and monitoring is sensor technology. Sensors that monitor temperature, humidity, shock, vibration, and so forth provide cargo owners with important information about



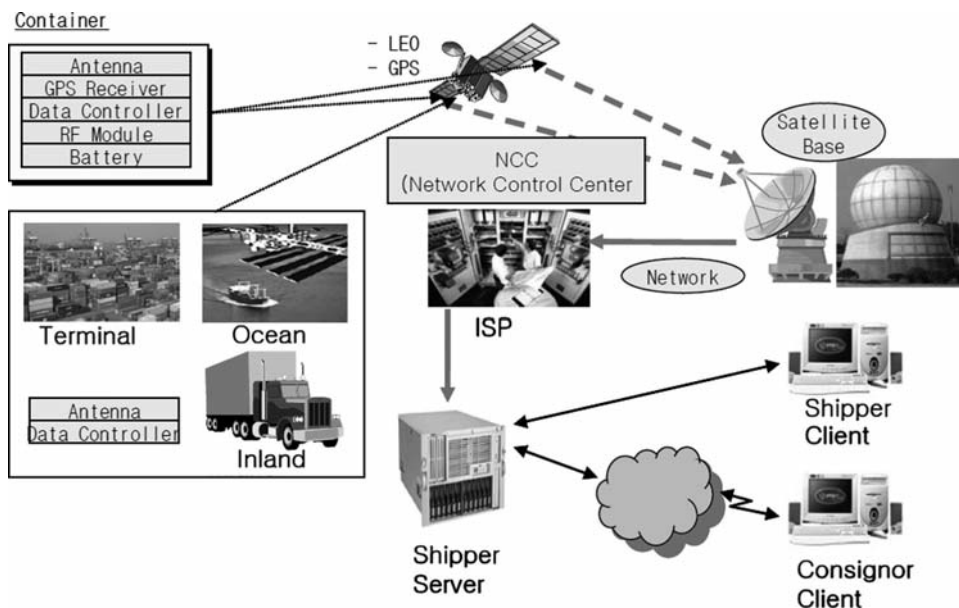
**Figure 7-7.** Shipping containers awaiting transportation at a container terminal.

the condition of their goods. Using GPS technology, positions of containers and ships can be plotted to within about 10 m.

Figure 7-8 shows a schematic example of container tracking service using GPS (Ahn 2005). When GPS is used as one of the key elements of tracking, containers equipped with GPS antennas and receivers are carried by ship through the ocean. When they reach the next terminal of container yards, they are unloaded and directed to the final inland destination. Throughout the journey, all activities and the status of the containers, including the GPS positions, are reported via a suitable communication link such as low Earth orbit (LEO) satellites. (Satellite communication is most suitable in this kind of application since it is global, covering many countries and oceans. Other alternatives such as cellular communications have limitations in wide-area coverage and would require roaming services to cover many countries.) The information can be relayed on to the stakeholders over the Internet from a network control center.

As noted earlier, one of the constraints in using GPS in this kind of application is that the antenna should be exposed to provide a line-of-sight to the GPS satellites, and larger position errors can be expected in obstructed regions. Other elements of a GPS receiver such as the data controller, the RF module, and the battery can be concealed inside the container without affecting the reception of the satellite signals.

Since in most instances it takes more than 3 months for the container to be reclaimed, the battery life should be able to last longer than 3 months without recharging. A solar battery could be a solution but weather does not always allow the container to be exposed to the sun at all times. Other considerations for power



**Figure 7-8.** A schematic of container tracking using GPS.

requirements may include the expected number of data or message transmissions during the shipment period.

## Material Tracking in Large Construction Sites

Construction-site theft is a concern for the construction industry, particularly when a project is in the early stages and most of the materials are unsecured. Hundreds of millions of dollars in heavy construction and farm equipment are stolen annually throughout North America, according to the National Equipment Register (NER 2011).

Two factors can contribute to construction-site theft: (1) the rising costs of building materials, which are becoming harder to afford but easy to sell for fast money, and (2) the isolation of new developments, especially when there are no security procedures for monitoring the area. But stealing can also be an inside job. Furthermore, one construction site can have multiple subcontractors, adding to the complexity of the problem.

In a constant battle to stay ahead of the thieves, construction companies are increasingly relying on technology to safeguard their equipment. They count on technology tools such as cameras, GPS, and alarm systems. Individual item costs can range from US\$5 to US\$50,000 or more, and the technology applied should be effective both in terms of the cost and application. Most importantly, companies don't want to tip off thieves by letting them know how they protect the equipment. Thus, it is necessary that the technology applied should be as small as possible and concealable so that the thieves cannot easily detect it.

A miniature GPS tracking device should be able to track equipment anywhere except in obstructed areas such as within tunnels or inside buildings. However, most of the GPS tracking devices are nowadays based on assisted-GPS (A-GPS) complemented with wireless positioning technologies (further discussed in "Integrations and Wireless Communications," below) that enable them to circumvent the signal outage problem.

If thieves broke into a site where a home was being built and took valuable appliances, and the builder had concealed a GPS device in one of them, it may be possible to track and recover all of the appliances and find the people responsible for the theft. The GPS tracking concept is similar to that illustrated in Fig. 7-8, except for the short-range communication links typically used to relay the information from the GPS device to the user.

## Site Control and Design

Surveys of built structures, facilities, utilities, or terrain must be controlled to some reference framework, both horizontally and vertically. The reference framework should consist of control points and/or benchmarks located in the vicinity of the project. Those control points can then be used to perform supplemental surveys and control of the project.

Control by GPS methods, where applicable, is increasingly common given the worldwide proliferation of continuously operating reference stations (CORS) networks and related services (refer to Chapter 5, “Network RTK and CORS Networks Infrastructure” for more information). With the ease of extending control with GPS, it is fairly simple to establish some form of project control with reference to the WGS-84 ellipsoid. Control can be brought in from existing points using static GPS observations. From these points, subsequent details can be surveyed using real-time kinematic (RTK) GPS methods. Although the control would be simply referenced to the satellite-based WGS-84 system, connections to local reference frameworks such as the Universal Transverse Mercator System (UTM) grid can be made. Figure 7-9 is one of the worldwide examples in which RTK GPS has been used to control megaprojects.

Bringing distant horizontal and vertical control to a project site using traditional methods can be costly and may exceed the cost of performing the local site survey itself. In particular, a distant benchmark may require a lengthy level line to bring in accurate vertical control. More options are available for bringing in horizontal control to a project site by using GPS methods, such as GPS static options using CORS networks.

Permanent networks of CORS can be used to establish control at virtually any place. The use of CORS stations eliminates the need to occupy full baselines with



**Figure 7-9.** GPS/RTK technology was used in the construction of the Øresund Bridge between Denmark and Sweden.

two receivers. A single GPS receiver is set up at a primary control point in the project site, and 1- to 2-hour static GPS observations are recorded. These observations become the end of any number of selected baselines using stations in the CORS network. Azimuth orientation at the project site is easily performed as part of the process of bringing in CORS control. A second GPS receiver is set up at a marked point, hundreds of feet away from the first GPS point. GPS observations over the short baseline are made concurrently with the CORS baseline connections. The fixed solution over this short baseline will provide adequate azimuth orientation for subsequent control work at the project site. An absolute accuracy of 10 to 30 sec over a 1,000-ft baseline would be adequate for small sites in which no real property connections are required. If the site has deeded boundary alignments (e.g., bearings shown along a road or boundary), then these deeded bearings may be used for azimuth reference. GPS-derived azimuths would have to be corrected to fit the local orientation.

### ***Nongeoreferenced Control***

“Georeferenced” control is rarely required for construction projects. To georeference a control means to define the coordinates of its points in an absolute framework such as WGS-84 (refer to Chapter 2, “World Geodetic System 1984 (WGS-84)”). An arbitrary control network would be adequate for all design, stake-out, and construction. Maintaining a good relative accuracy with an adjoining project or control network is far more important than accurate connections to distant networks. Likewise, connections to adjoining property boundary monuments are significantly more critical than connections to distant networks. Surveys involving real property boundaries must always be connected to established property corners or adjoining right-of-way boundaries. Locations of structures, buildings, roads, utilities, and so forth are surveyed and mapped relative to the property boundaries. Likewise, stakeout of planned construction must be performed relative to the boundaries. Control framework coordinates may be placed on property corner marks, and subsequent stakeout work should not be performed relative to distant control.

In such cases, an arbitrary grid system can be established in minutes. The baseline is quickly marked with stakes, hubs, rebar, or nails at each end. Detail surveys using RTK GPS can then be conducted, using the arbitrary baseline. If needed, supplemental control traverses can be run to set additional marked control points around the project site. Optionally, RTK radial control points can also be set relative to the baseline.

### ***Approximately Georeferenced Control***

If georeferenced control is required on an isolated project, autonomous GPS positioning could be used to establish approximately georeferenced coordinates at the primary control point. All data observed on the arbitrary grid system can then be later translated and rotated to a georeferenced coordinate system. If only

approximate georeferenced control is required, a handheld GPS receiver is adequate; in that case it should be noted on project records that the resultant coordinates are approximate. A brief visual recording of the position is sufficient. A quick, autonomous GPS position on the other end of the baseline can be used to establish a rough geodetic azimuth ( $\pm 1$  deg at best) of the baseline.

### ***Precisely Georeferenced Control***

If more precise georeferencing is required, long-term (1- to 2-hour or longer) static GPS observations can be made at the primary control point. With geodetic-quality receivers a high accuracy will be obtained. If two geodetic receivers are available, a fixed solution is possible over a short baseline with only a few minutes of static observations.

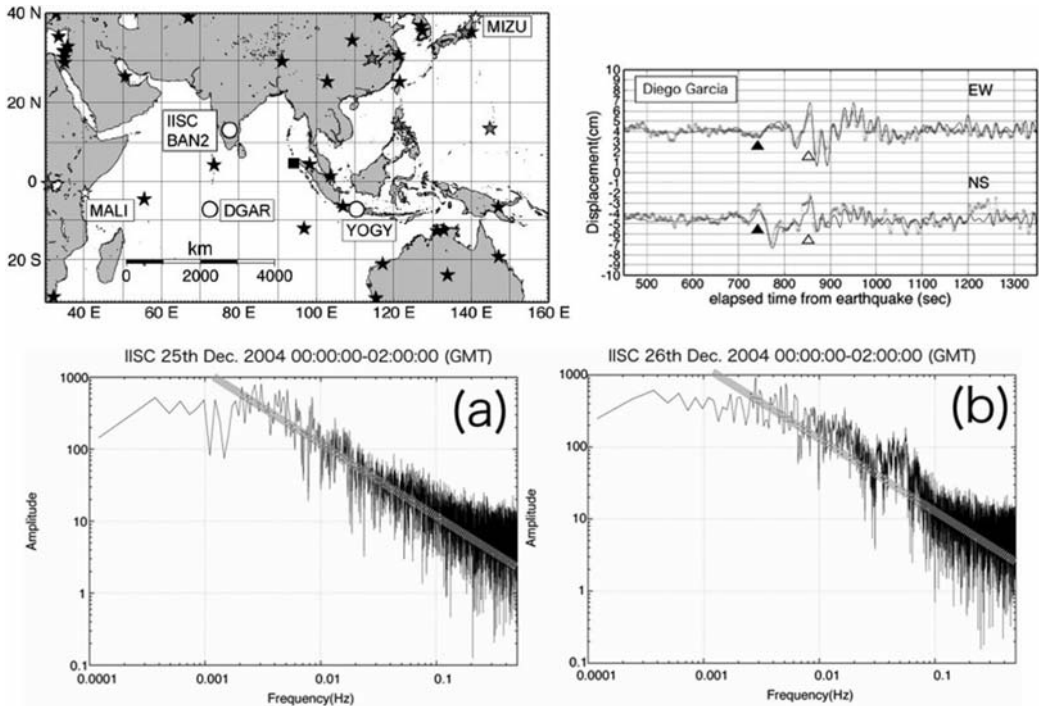
## **Geohazards Monitoring**

### ***High-Rate GPS***

*High-rate GPS* is a technique whereby positions are estimated at a rate of once per second or higher, using high-precision GPS phase observations. Today, the highest GPS receiver sampling rate is 100 Hz (100 samples per second), according to the annual GPS receiver surveys by the *GPS World* magazine. However, this might change in the future. Developed only in the last few years, high-rate GPS was used to determine the time-dependent surface displacements caused by the 2002 Denali earthquake, the 2003 San Simeon earthquake, the 2003 Tokachi-Oki earthquake, the 2003 explosive activity of the Stromboli volcano, and the tsunamis induced by the 2004 Kii peninsula earthquake and the 2004 Tsumatra earthquake (Fig. 7-10). Other examples include high-frequency bridge and building displacement monitoring (see earlier examples in Figs. 7-1 and 7-2).

### ***GPS "Seismometer"***

The recent recordings of earthquakes with 1-Hz GPS show a great promise for using GPS as a new type of seismometer. Lack of independent direct measurements of the surface displacements limits an assessment of the accuracy of high-rate GPS. The most obvious possibility is to compare high-rate GPS data to seismic measurements, but seismic instruments record either velocity (seismometers) or acceleration (accelerometers) and thus require an integration (or double-integration) process for displacement, whereas GPS naturally produces position estimates. Seismometers suffer drift ratio or bias instability while GPS is stable over the whole measurement time. However, GPS has certain weaknesses, too. For instance, receiver background noise is prevalent in the high-frequency (short-period) range where seismometers tend to perform better. GPS requires sky visibility and the antenna must be visible to the satellites being observed. There is no

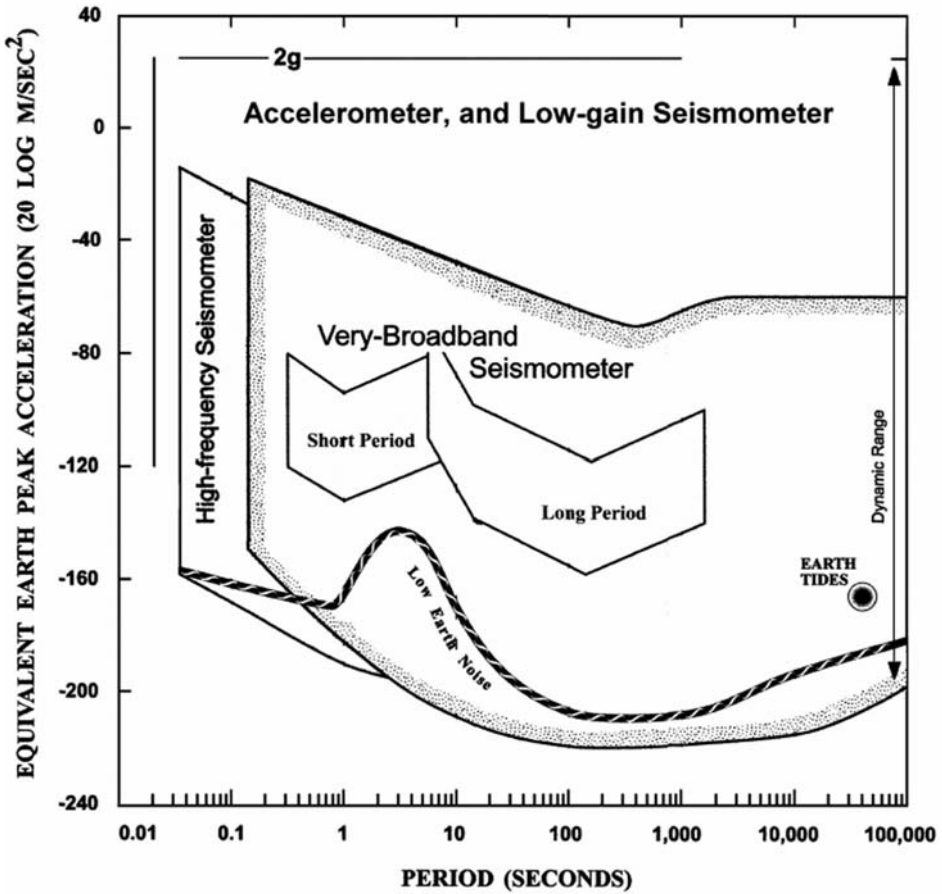


**Figure 7-10.** Tsunami detection with long-baseline, 1-Hz GPS. *Source:* Ohta et al. (2006) with permission.

such requirement with the seismometers as they can be deployed indoors or outdoors. These are some of the strengths and weaknesses of each independent system. However, rather than focus on the weaknesses, what are their complementary benefits? The technical considerations for measuring seismic events (Lee and Wu 2009) are introduced here to provide a frame of reference for that discussion.

To record seismic waves, both the available technology and the nature of the Earth's background noise are important. The Earth is constantly in motion and the planet's background noise is usually classified as either *microseisms* or *micro-tremors*. Microseisms have frequencies below about 1 Hz, are often the largest background signals, and are usually caused by natural disturbances (largely caused by ocean waves near shorelines). Microtremors have frequencies higher than about 1 Hz and are due to human activities (such as traffic and machinery) and local natural sources (such as wind and moving vegetation). Ground motions from earthquakes vary by more than ten orders of magnitude in amplitude and six orders of magnitude in frequency, depending on the size of the earthquake and the distance at which it is recorded. Figure 7-11 illustrates the relative dynamic range of some common seismometers for global earthquake monitoring. A “low Earth noise” model is the lower limit of Earth's natural noise in its quietest locations—it is desirable to have instruments that are sensitive enough to detect this minimal background Earth signal.





**Figure 7-11.** Relative dynamic range of some common seismometers for global earthquake monitoring. The Y-axis is marked in decibels (dB) where  $\text{dB} = 20 \log (A/A_0)$ ;  $A$  is the signal amplitude and  $A_0$  is the reference signal amplitude.

Modified from Hutt et al. (2002, Fig. 1), with permission.

In the analog instrument era (prior to about 1980), short-period and long-period seismometers were designed separately to avoid microseisms, which have predominant periods of about 6 sec. Short-period seismometers were designed to detect tiny ground motions from smaller, nearby earthquakes, while long-period instruments were designed to recover the motions of distant, larger earthquakes (“teleseisms”). Additionally, strong-motion accelerometers, generally recording directly onto 70-mm-wide film strips, were used to measure large motions from nearby earthquakes. In today’s much more capable digital instrumentation, two major types of instruments are deployed: (1) *broadband seismometers*, which replace and improve upon both short-period and long-period seismometers, and (2) *strong-motion accelerometers* for high-amplitude, high-frequency seismic waves from local

earthquakes, which often drive broadband seismometers off scale. In addition to having large variations in amplitudes and frequencies, seismic waves from earthquakes also attenuate rapidly with distance, that is, they lose energy as they travel, particularly at higher frequencies. These effects must be considered in order to monitor seismic waves effectively.

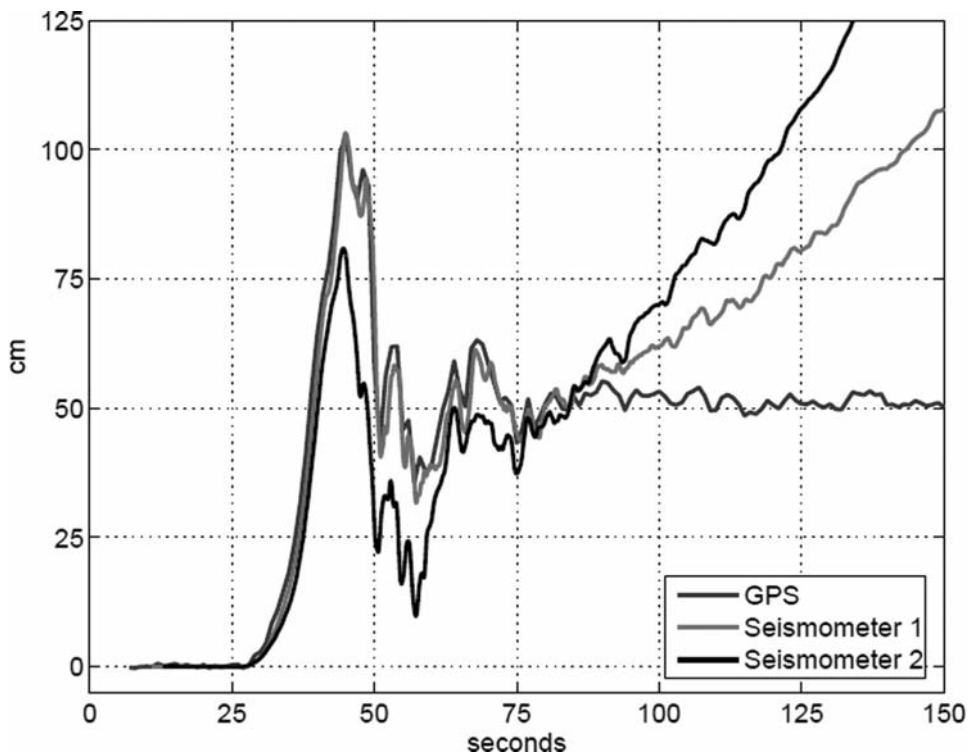
Seismometers are sensitive enough to detect the minimal background Earth signal in the range where the GPS receiver signal is typically too noisy [seismometers and accelerometers have larger-frequency bandwidth and are very accurate ( $\pm 0.03$ – $0.5 \text{ m/s}^2$ )]. However, since strong-motion seismometers measure acceleration, one way that high-rate GPS can contribute to the field of seismology is by providing accurate measurements of displacement as a *strong-motion instrument* (Larson 2009). Such instruments are used to study large-amplitude ground motions and the response of engineered structures to such motions. While GPS is a much less precise accelerometer, it has been shown that it more accurately measures displacement caused by very large earthquakes. Through recent recordings of earthquakes, real-time regional GPS networks have been shown to be essential to medium to large earthquake response. The Southern California Integrated GPS Network (SCIGN) mentioned in Chapter 5 is one example.

Here are some of the reasons to look at high-rate GPS as a complement to broadband seismometers and accelerometers:

- *GPS directly measures displacement (not velocity or acceleration).* GPS can provide direct, instantaneous 3-D displacement and absolute position on a well-defined global reference frame, WGS-84. The connection to the WGS-84 frame makes it easier to assess how an object or a built structure might have moved with respect to the surrounding bedrock, for example, after a shock such as an earthquake. The GPS constellation can be considered an “ideal pendulum” since GPS satellites are not affected by earthquakes (Ge et al. 2000).
- *GPS does not incur sensor drifts that are common with seismometers and accelerometers.* Typically, after integrating strong-motion accelerations to displacement, large drifts are visible (Fig. 7-12).
- *GPS does not clip.* Although considerably less sensitive than a seismometer, GPS detects displacements that would otherwise cause seismometers to clip (i.e., “cut off” signals with large amplitudes). This is illustrated in Figs. 7-13 and 7-14, using plots of teleseismic waves captured from the April 4, 2010  $M_w$  7.2 Baja California earthquake in Mexico. Most of the broadband seismometers in southern California clipped during this earthquake, and on-the-fly 1-Hz GPS provided the only direct measurements of dynamic and static (i.e., total) displacements. Note that even at the Piñon Flat Observatory, 180 km (112 mi.) from the epicenter, the broadband seismometer clipped.

### **“Earthquake Simulators”**

Many researchers have proposed higher-rate-sampled [10-sample-per-sec (Hz) or even higher] GPS data for GPS seismology as well as engineering. It is important



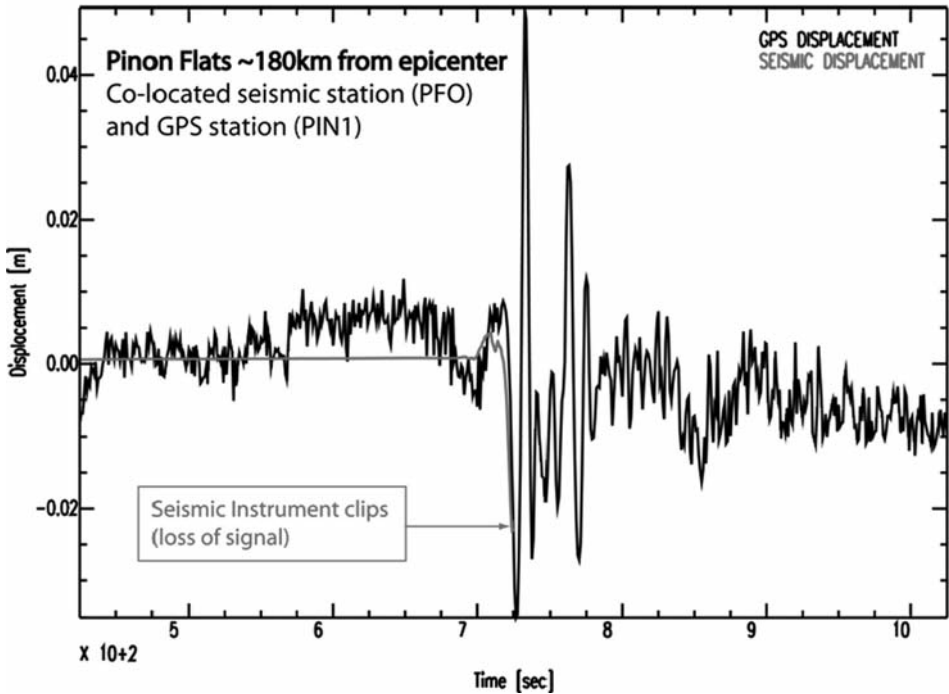
**Figure 7-12.** Seismometer sensor drift. *Source:* Miyazaki et al. (2004).

to be able to assess the accuracy of such high-rate GPS seismometers (Elósegui et al. 2006). There are no 10-Hz GPS data from large natural earthquakes available and there are no direct, independent measurements from a similar technology. To circumvent this problem, so-called earthquake simulators have been routinely used to enable the movement of a GPS antenna in a known manner with a temporal spectrum similar to a real seismic event. The difference between the antenna position inferred from GPS observations and the known “true” antenna position will directly yield the time-dependent error in the GPS measurements. According to Dr. Guoquan Wang of the Puerto Rico Seismic Network at the University of Puerto Rico at Mayaguez, Puerto Rico, “The accuracy of high-rate kinematic GPS is independent of the sampling rate of the receiver, while it depends on the motions of the antenna” (Wang 2011). The RMS errors during antenna movement can be considerably larger (e.g., two to three times larger) than those during nonmovement.

## Miniaturized GPS Systems

GPS receivers have been miniaturized to just a few integrated circuits, making the technology very economical and accessible to virtually everyone. These days GPS

## Comparison of Seismic and GPS displacements



**Figure 7-13.** Scripps Orbit and Permanent Array Center (SOPAC)'s California Real-Time Network GPS observations sampled at 1 Hz compared to seismic displacement at the Piñon Flat Observatory.

Courtesy of Sharon Kedar, Jet Propulsion Laboratory, Pasadena, Calif.

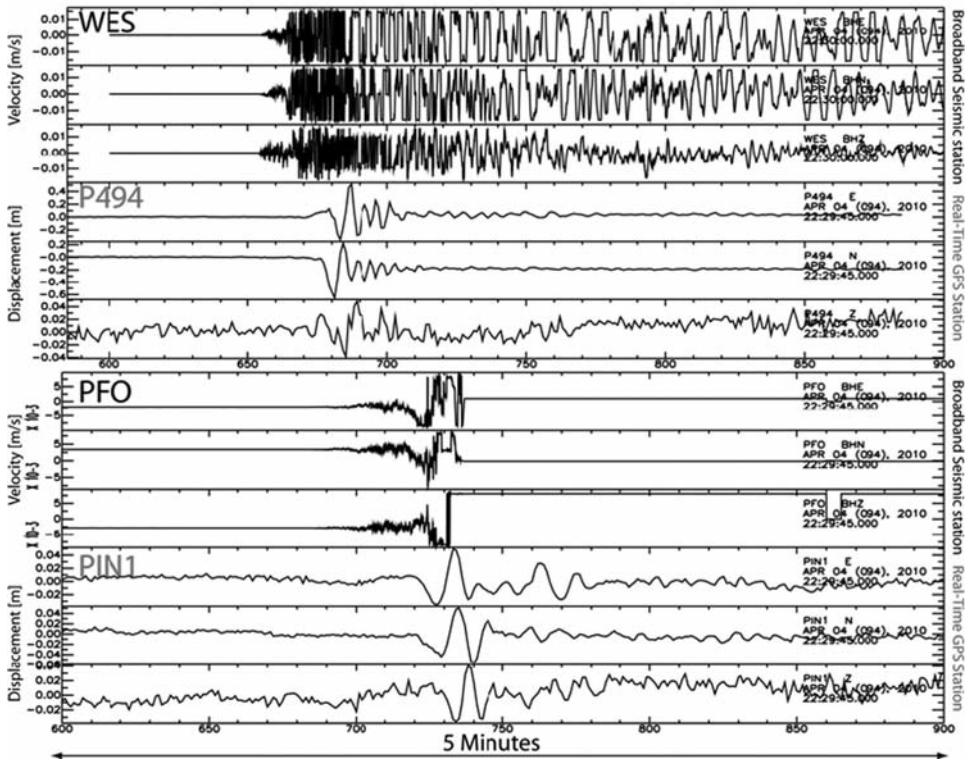
is finding its way into wristwatches, phones, tracking devices, cars, boats, planes, construction equipment, movie-making gear, farm machinery, and laptop computers. Miniaturization is seen as an inevitable trend in many industrial products and systems development. There is an increasingly strong market demand for “intelligent,” “robust,” “multifunctional,” “smaller,” and “low-cost” products, and miniaturization seem to be the only viable solution to satisfy such market demand.

### Enabling Technologies

#### Miniature Devices

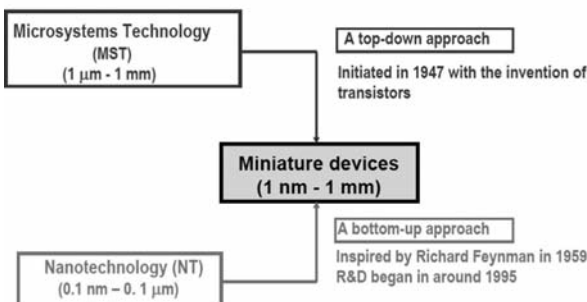
Packing many miniature functional components into a single device has led to the evolutions of many systems (Fig. 7-15). Significant technological development toward miniaturization was initiated with the invention of *transistors* by three Nobel Laureates, W. Shockley, J. Bardeen, and W. H. Brattain of Bell Laboratories in 1947 (Hsu 2008). This crucial invention led to the development of the concept of

# GPS Stations do not clip



**Figure 7-14.** Plots comparing 1-Hz GPS observations to co-located seismometers.

Courtesy of Sharon Kedar, Jet Propulsion Laboratory, Pasadena, California, and Yehuda Bock, Director, Scripps Orbit and Permanent Array Center (SOPAC), Institute of Geophysics and Planetary Physics, University of California–San Diego.



**Figure 7-15.** Enabling technologies for miniaturization.

*integrated circuits* (ICs) in 1955 and the production of the first IC 3 years later by Jack Kilby of Texas Instruments. ICs have enabled the miniaturization of many devices and engineering systems. The invention of transistors is thus regarded as the beginning of the “Third Industrial Revolution” in human civilization.

### **MEMS and Microsystems**

MEMS (*MicroElectroMechanical System*), a pioneer technology for miniaturization (Hsu 2008), is any engineering system that performs electrical and mechanical functions with components in micrometers ( $1 \mu\text{m} = 1/10$  the diameter of human hair).

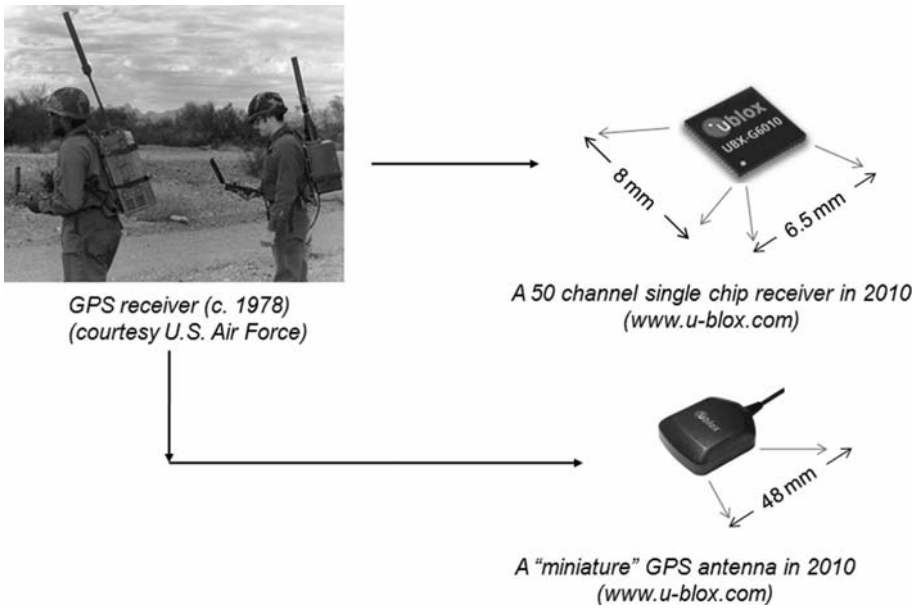
Miniaturization using MEMS and microsystems is a necessity in engineering applications. Smaller size of the systems means less of a space requirement; this allows the packaging of more functional components in a single device. Fewer material requirements mean lower cost of production and transportation, and ready mass-production in batches.

Miniaturized devices are particularly suited for integrated applications due to their smaller size and weight. They tend to move or stop more quickly due to low mechanical inertia. They are thus ideal for precision movements and for rapid actuation. Miniaturized systems encounter less thermal distortion and mechanical vibration due to low mass. They have higher dimensional stability at high temperature due to low thermal expansion.

### **Miniature GPS Devices**

So how small can a GPS receiver device get, given the available miniature technologies? It is essentially a race between different manufacturers as they compete to produce the world’s smallest GPS receiver device. However, the race is not just about producing the smallest; it is also about producing a better product (Rizos 2003). Lower power consumption, increased data rate, increased accuracy, less susceptibility to radio frequency (RF) interference, multifunctioned functionality, and higher sensitivity to weak received signals are all end goals for a better product. For the same reasons previously stated, smaller is considerably cheaper. According to Rizos (2003), “Modern digital receiver designs have achieved a high degree of miniaturization as a result of the microelectronics revolution. Current receiver designs are ‘postage-stamp’ size, consisting of two (or even one) hardware chips, making them well suited for embedding within more complex systems.” Tens of millions of GPS receiver chipsets have been embedded within cellular phones and all other kinds of tracking devices.

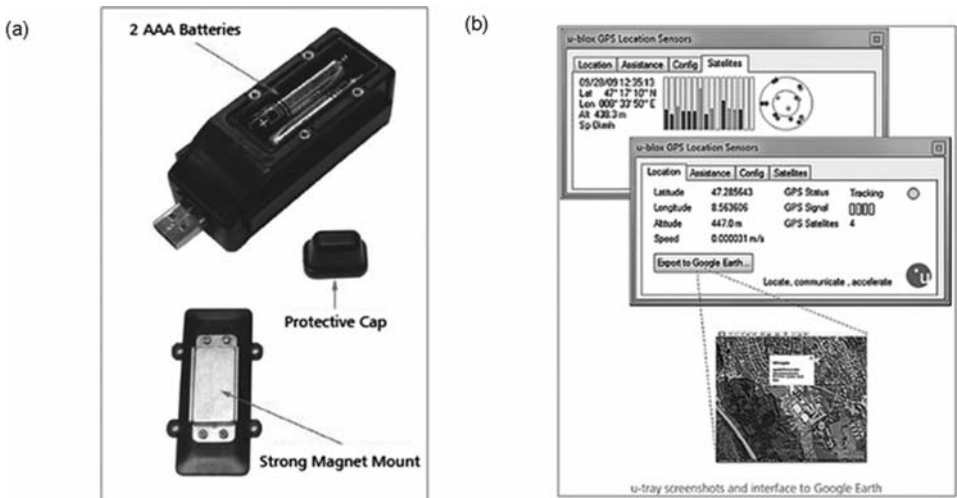
Early GPS receivers were quite bulky and had to be worn like a backpack. In contrast, today’s receivers are extremely compact and easy to integrate with other portable electronic devices. Figure 7-16 shows a remarkable case of miniaturization that took place in a period of just 30 years! But how accurate can these micro-miniature GPS systems be? They can be very efficient for some applications. For instance, they can record up to 100 hours of location and speed data accurate to within 2.5 m, using low-power sources such as two AAA batteries (Fig. 7-17). With



**Figure 7-16.** GPS receiver evolution.

such data, users can accurately determine where a person traveled, how fast they drove, where they stopped, and for how long. The recorded data can be displayed over a street map, satellite images, or in a text report.

Most manufacturers nowadays strive to accommodate both the low-end and high-end requirements for GPS receiver applications. Low-end receiver



**Figure 7-17.** (a) A 16-channel GPS tracking device with in-built antenna and magnet mount; (b) a software solution for interface with Google Earth.

Source: [www.u-blox.com](http://www.u-blox.com), with permission.

development trends include chipsets, systems on chips, single chips, dataless channels, and multipath mitigation. High-end receiver development trends include multifrequency (L1, L2, L5), multichannel receivers and multisystem receivers (e.g., GPS + GALILEO + GLONASS). Chips and OEM modules are the ideal solution for high-performance, low-power, cost-sensitive GPS applications such as automotive navigation systems, low-power trackers and loggers, smart phones, fleet and asset management systems, mobile computers, and personal navigation devices (PNDs).

## Integrations and Wireless Communications

Integration of GPS with other technologies is important for various reasons. Due to limitations of the individual systems, it may be ideal for various application scenarios to consider GPS integration with technologies such as inertial sensors, fiberoptics, and pseudolites (a contraction of the term “pseudo-satellite”). Through such integrations the complementary benefits of the individual systems are utilized and their limitations overcome. For example, inertial sensors have a drift bias problem but they can provide autonomous navigation during a GPS outage. Fiber optic sensors have high-resolution and measurement capabilities that are immune to RF, electromagnetic, and temperature interferences. Pseudolite technology, nearly as old as GPS, has been studied for many years as a possible means to augment GPS in obstructed environments such as urban canyons or open-pit mines (Dai 2002).

Wireless communications provide opportunities for both conventional positioning technologies such as RTK and personal positioning technologies using assisted-GPS (A-GPS) and wireless networks (cellular, Wi-Fi, ultrawideband, etc.) (Pfeiffer 2003). One of the popular protocols for transmitting wireless data is Bluetooth.

### ***Inertial Navigation Systems***

GPS integrated with an inertial navigation system (INS) is ideal for use on a military platform or weapons, marine and air navigation, machine guidance and control, field robotics, and precise mobile mapping/imaging applications (Rizos 2003). GPS is now clearly the standard option for navigation but GPS-only positioning is not recommended for many navigation applications. Because it is vulnerable to interference and intentional jamming, applications such as aircraft, ship, missile, and spacecraft navigation cannot rely solely on the GPS system. While GPS is a *wave-based* technology relying on radio signals, INS is a “dead reckoning” technology for inertial and orientation systems. INS can provide autonomous navigation information during periods of GPS outage or intentional interference.

INS systems have progressed from the crude electromechanical devices that guided the World War II V-2 rockets to the current solid-state devices installed in many modern vehicles (Schmidt 2004). That progression is mainly due to the



ballistic missile programs of the 1960s which accelerated the need for high accuracy at ranges of thousands of kilometers using autonomous navigation systems. In the context used here, the word “autonomous” means that no man-made signals from outside the vehicle are required to perform navigation. If no external man-made signals are required, there can be no jamming or interference.

INS systems do not indicate position perfectly because of errors in components (gyroscopes and accelerometers) and errors in the model of the gravity field that the INS utilizes. Those errors cause the error in indicated position to grow (drift) with time. The best autonomous military aircraft INSs have errors that grow at the rate of about 500 m/hour (Schmidt 2004). For vehicles with short transit times, such errors might be acceptable. For longer-duration missions it is usually necessary to provide periodic measurements to the navigation system such that the errors caused by the INS are reset as close to zero as possible. Although limited by open-sky visibility requirements and subject to interference, GPS offers worldwide, highly accurate navigation information at very low cost, and has therefore rapidly become the primary aid to be used in updating inertial systems.

In an INS/GPS system, multiple GPS measurements are combined in a Kalman filter to update the INS. The Kalman filter provides an opportunity to calibrate some of the GPS errors, such as satellite clock and ephemeris errors, as well as several of the INS errors. When properly implemented, accuracies in the integrated navigation solution will improve significantly, such as from the 20-m level to 1-m level or better.

The major INS error sources are due to gyroscope and accelerometer inertial sensor imperfections, incorrect navigation system initialization, and imperfections in the gravity model used in the computations. The major errors for the gyroscopes are in measuring angular rates, while the major errors for the accelerometer component are in measuring acceleration. For both instruments, the largest errors are usually a bias instability [measured in deg/hour for gyroscope bias drift, or micro-g ( $\mu\text{g}$ ) for the accelerometer bias], and scale-factor stability [which is usually measured in parts per million (ppm) of the sensed inertial quantity]. The smaller the inertial sensor errors, the better the quality of the instruments, the improved accuracy of the resulting navigation solution, and the higher the cost of the system. As a rule of thumb, an INS equipped with gyroscope with a bias stability of 0.01 deg/hour will see its navigation error grow at a rate of 1 nmi/hour (nautical mile per hour) of operation (Schmidt 2004). The navigation system performance specifications lead directly to the selection of specific inertial instruments in order to meet the mission requirements.

### ***Fiberoptic Sensors***

Fiberoptic sensor (FOS) technology can augment GPS in many engineering applications (Phares et al. 2005). In contrast to GPS, these sensors can be embedded in the body of a structure to continuously monitor performance with a long-term data record. They can detect performance by sending light beams down a fiberoptic cable of a known length, at regular intervals, and by measuring changes in time

of flight. There are various types of FOS, and each type is based on a different property of the light waves traveling down the fiber.

FOS are known to exhibit high shock survivability and are capable of measuring strains at multiple (two or three) orders of magnitude better than conventional electrical resistance gages. They can detect strain along the entire length of the sensor (cable). Other advantages include their compactness and freedom from drift and electromagnetic interference. They can easily be incorporated into various types of measuring devices (e.g., accelerometers, displacement transducers), and many physical quantities can be measured simultaneously with the proper system design and calibration.

### **Wireless Trilateration Technologies**

As noted earlier, a major shortcoming of GPS is the received signal strength, which is on the order of  $-160$  dB. The weak GPS signals can penetrate transparent glass material but are easily blocked by other materials such as concrete, wood, or steel. This limits GPS to outdoor applications requiring open spaces. Obstructed outdoor environments such as urban canyons or tree canopies can also cause poor satellite geometry or lack of sufficient satellites for a trilateration fix. These circumstances are undesirable for some applications.

Efforts to improve the GPS receiver technology in order to track very low signal strengths, as would be encountered inside buildings, include wireless assisted-GPS (A-GPS) and high-sensitivity receiver designs. To complement such efforts, wireless communication networks such as cellular towers and Wi-Fi networks can be used to carry out a *cellular triangulation* to locate the user to within a few tens or hundreds of meters. The advantage of such networks over GPS is that they can work both indoors and outdoors.

The E911 mandate issued by the U.S. Federal Communication Commission (FCC) in the early 2000s has been an important driver for the development of positioning technologies capable of being embedded within cellular phones. The mandate requires that cellular carriers be able to automatically locate anyone making an emergency 911 call. The general specifications include the positioning accuracy of the device making a 911 call to be on the order of 50 to 100 m (67% of the time), depending on the technology used. Thus, by law, hundreds of millions of cell phones must have location awareness. As a result of the E911 mandate, the number of GPS receivers embedded within cellular phones far outnumbers the standard GPS receivers in the market.

Two of the most prominent means for outdoor tracking are GPS and existing cellular networks. The accuracy for a GPS navigation fix is now routinely within 5 to 20 m, but GPS requires line-of-sight to satellites and does not work well in urban canyons of large cities. To get around this shortcoming, wireless carriers employ the A-GPS technology. In this approach, the cellular networks assist GPS receivers to locate satellites, speeding up the search process and helping GPS to function in areas where it might not otherwise work.

There have also been cases of *TV-enabled GPS* wherein powerful broadcast television signals are used, as opposed to cellular signals, to triangulate position

(Pfeiffer 2003). Such broadcast signals may be preferable to cellular networks since they have wider geographical coverage and can much more easily penetrate buildings.

Some cellular carriers use their existing cellular networks alone in a *cellular triangulation* using cell towers to pinpoint a user's location, but this usually provides only a rough indication of the caller's location. The accuracy is poor and can be anywhere between 30 to 150 m, depending on conditions. However, a method called *time difference of arrival* (TDOA) can be used to improve the cellular triangulation accuracy. Similar to GPS trilateration, the TDOA approach plots location by measuring the exact time it takes for a signal from a cell phone to travel to and from three or more cellular towers. If only two cellular towers (or base stations) are present, such as may be the case in rural areas, then the angles of the arriving signals can be used instead (triangulation). Users of this approach include AT&T Wireless whereas as of this writing Sprint and Verizon employ the A-GPS approach.

Another approach for locating users both indoors and outdoors is by using a popular wireless networking technology known as Wi-Fi. In most of the large urban areas, numerous carriers have installed Wi-Fi transceivers in hotels, cafes, and other commercial buildings to deliver high-speed Internet access to mobile users. By using some sort of database of a recorded network's signal strength, a location can be matched to a specific signal strength so that when customers access the network, it knows where they are. With accuracy ranging from 1 to 20 m, Wi-Fi mapping is more precise than cellular triangulation. However, a major shortcoming with this approach is that the Wi-Fi transceiver covers a limited geographical area of only about 90 m in radius. It is particularly insecure and susceptible to signal interference, as a "stalker" might be able to determine a user's location based on their signal.

*Ultrawideband*, though not fully developed at the time of this writing, is another wireless technology that uses on/off energy bursts that are billionths of a second in duration at extremely low power (one-thousandth the power of a traditional cell phone) over a large frequency spectrum. The ultrashort pulses enable signal travel time to be determined in picoseconds, allowing indoor positioning to within centimeters. Ultrawideband stations (transmitters/receivers) can be installed at strategic locations, such as within the same building. *Position* is determined by triangulation if at least three signals are received, and *vertical mapping* is possible if four signals are received. This in turn makes it possible to figure out how high the position is off the ground, or on which floor of a building a person is located. As with GPS or Wi-Fi, ultrawideband can be incorporated into cell phones and PNDs.

## Opportunities and Challenges

The GPS receiver technology has undergone a dramatic transformation from very bulky, analog-based electronics to miniature digital devices that can be embed-

ded in cell phones and PNDs. Manufacturers continue to aim for higher precision and faster measurement for all application sectors. Complementary technologies and wireless communication networks combine with GPS to enable seamless outdoor/indoor positioning. For instance, your GPS-enabled cell phone would report your location within a certain city block, and once you walk through the front door an indoor technology such as Wi-Fi takes over.

There are many advantages and opportunities in these developments, but there are also some real challenges to be addressed. For example, the E911 mandate is in the interest of security and safety, and has provided a tremendous boost to the location awareness technology developments. Location-based services are now part of normal everyday life as wireless carriers can pinpoint our locations even if we are unaware of such possibilities. But do people want their friends, the government, or strangers knowing where they are at all times? Some carriers give consumers the ability to turn off location finding at their handsets, or the option to be “invisible,” but privacy is still a matter of concern for many. Nevertheless, the advantages of location-aware computing seem to outweigh the disadvantages.

Miniaturization provides opportunities for many applications ranging from mass-market to professional consumers interested in embedded or integrated GPS solutions. There is a wide range of competing (and complementary) products and options. For example, an awareness of existing GPS networks could help a project manager make the decision of whether or not to purchase additional GPS equipment. This could be a US\$10,000 decision.

Consumers interested in developing a GPS application ought to know the capabilities and limitations of the technology, as well as those of the complementary technologies. Understanding the limitations of GPS is one of the topics addressed in Chapter 6.

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# The Future of GPS

## GPS Modernization

### *Improving the GPS Configuration*

The GPS constellation is about numbers and geometry. Having augmentation satellites on orbit is not a new state of affairs for GPS. While GLONASS (once fully operational, in 1996 for about 6 months) struggles to return to full operational capability with 24 satellites (21+3), and GALILEO is being built, the GPS constellation size has been at 24 or more satellites since 1996. New efforts by the U.S. military include a reconfiguration of the GPS constellation to improve global coverage, as well as regional coverage in areas where coverage can be degraded (for instance, in the mountainous regions of Afghanistan or in urban canyons in the big cities). In January 2010, the official military announcement laid out a new initiative to reposition some of the GPS satellites:

The [24+3] initiative will take up to 24 months to fully implement as satellites are repositioned within the constellation based on constellation health. The beneficial impact to all GPS users, including civilian users, will be slowly realized during that time period. Over the next two years, the number of GPS satellites in view from any point on earth will increase, potentially increasing accuracy of GPS receivers. (*Defense PNT Newsletter*, January 2010)

In terms of numbers, adding more satellites would improve global coverage. The auxiliary satellites on orbit have the added advantage of improving the geometry and consequently the accuracy of GPS for U.S. and allied warfighters, especially in mountainous regions and urban canyon situations. However, improving the system geometrically needs a different approach. For instance, moving three existing GPS satellites to new orbit locations would have a profound effect on GPS capabilities worldwide (Jewell 2010). There are more than 30 GPS satellites in MEO (medium Earth orbit) that are used globally. However, many of the additional satellites have been flown in tandem, side by side, with considerably older satellites, effectively limiting the constellation geometry to that of 24 satellites. Simply moving three existing GPS satellites to new orbit locations would positively

affect the positioning capabilities of GPS for all civil, commercial, and military users worldwide.

### **Operational Control Segment (OCS) Software**

The GPS ground control must modernize in step with the new codes/signals. The current GPS ground control system, known as the Architecture Evolution Plan (AEP), has been controlling the constellation since September 2007. AEP was upgraded on January 11, 2010 to enable telemetry, tracking, and commanding for the new GPS IIF satellites and provide over-the-air (OTAR) distribution of encryption keys for military user P(Y)-code equipment, better known as SAASM-based UE (selective availability anti-spoofing module user equipment). The next-generation operational control segment software will replace the AEP system. The U.S. government's fiscal year 2011 budget included allocations for these planned developments (Box 8-1).

### **Benefits to Civilian Users**

The 24+3 configuration and the new control segment software will benefit all GPS users globally (Figs. 8-1 through 8-3). The 24+3 will be especially beneficial to the

#### **Box 8-1. President Plans \$1.23 Billion for GPS in FY 2011**

President Obama's proposed budget for fiscal year 2011 (FY11) would allocate \$1.057 billion for Department of Defense (DoD) GPS-related procurement and development activities, and nearly \$180 million to the Department of Transportation (DoT) for civil GPS programs. Those figures compare with \$830 million in FY10 DoD appropriations and slightly more than \$150 million in GPS-related DoT expenditures in the current budget cycle.

The proposed FY11 DoD items include \$34.471 million for GPS Block IIF satellites and Operational Control Segment (OCS) development, \$828.171 million for GPS Block IIIA and Next-Generation Operational Control Segment (OCX) development, and \$194.8 million for other program support.

GPS-related DoT budget items include \$58.5 million for the addition of new, civil-unique capabilities to the GPS program, \$95 million for the Federal Aviation Administration's Wide Area Augmentation System (WAAS), \$14.5 million for the FAA Ground-Based Augmentation System—widely known as the Local Area Augmentation System (LAAS), and \$7.6 million for the inland component of [the] Nationwide Differential GPS (NDGPS) system.

Source: *Inside GNSS* magazine, March/April 2010 Edition, p. 14. Used with permission.

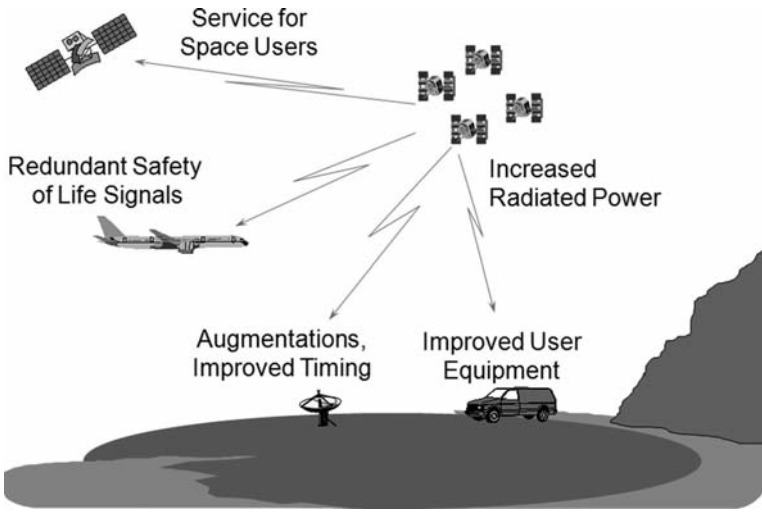


Figure 8-1. The benefits of GPS modernization.

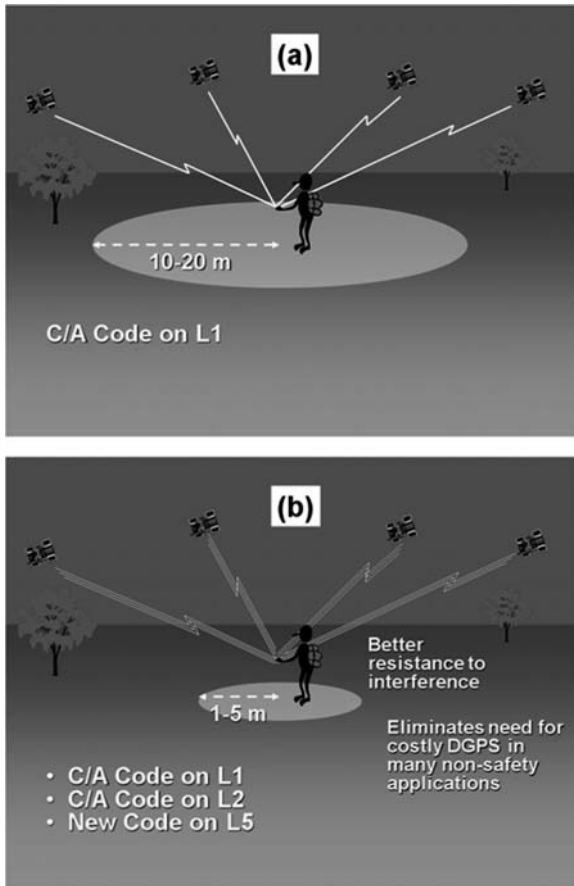
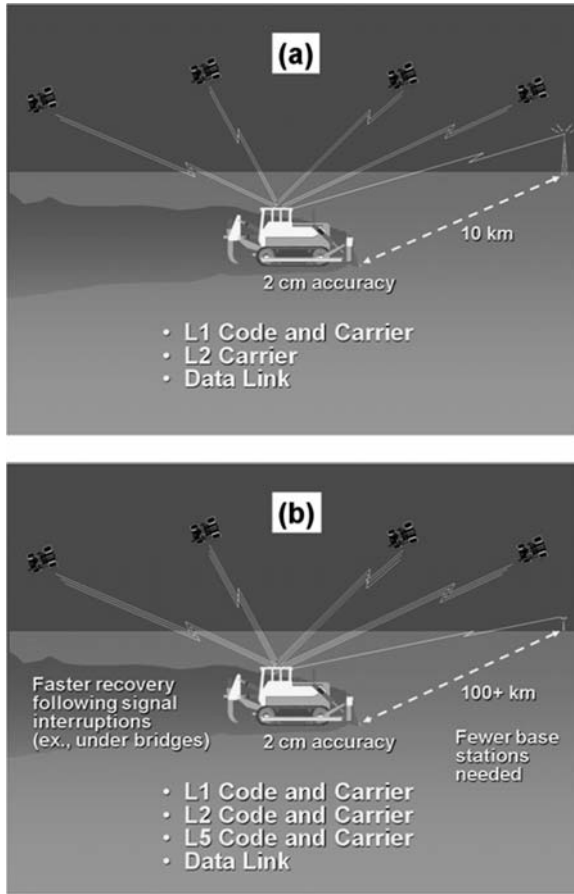


Figure 8-2. Basic positioning. (a) Today; (b) tomorrow.





**Figure 8-3.** Advanced positioning. (a) Today; (b) tomorrow.

RTK (real-time kinematic) users who currently require six satellites in view for a very precise (centimeter accuracy) position. In the past, users that require long dwell times and experience high mask angles have been forced to use GLONASS satellites as an augmentation, which works, of course, but GLONASS satellites have historically been less accurate than the GPS system. When 24+3 is fully implemented, hopefully GLONASS augmentation will no longer be necessary.

## GNSS Technologies

GPS is one component of the worldwide effort now known as the Global Navigation Satellite System (GNSS). Another component of GNSS is the Russian GLONASS, and a third is the GALILEO system administered by the European Union (EU). While GPS and GLONASS are operational systems, GALILEO is still under development and is expected to be fully operational by 2014. It is also likely that more constellations will eventually be included in the GNSS.

The current GNSS infrastructure can be classified into four layers (Table 8-1):

- *Global navigation satellite systems*: currently GPS (United States), GLONASS (Russia), future GALILEO (Europe) and COMPASS/BeiDou 2 (China).
- *Regional satellite navigation systems*: IRNSS (India), BeiDou 1 (China), and QZSS (Japan).
- *Regional satellite-based augmentation systems (SBAS)*: WAAS (United States), EGNOS (EU), MSAS (Japan), and GAGAN (India).
- *Ground-based augmentation systems (GBAS)*: differential GPS (DGPS), local area augmentation system (LAAS), and local GBAS typically based on a single GPS reference station providing RTK corrections.

**Global Navigation Satellite Systems (GNSS)**

**GLONASS**

Developed during the Cold War period as the USSR equivalent of GPS, the GLONASS constellation, consisting of 24 satellites at an altitude of 19,100 km (11,860 mi.), is deployed in three roughly circular orbital planes inclined about 64.8 deg toward the equator. In a full constellation at least five satellites are in view from any given point at any given time. The basic concepts of GLONASS are similar to those of GPS but there are technical differences, one of which is the way in which the satellite signals are transmitted. GPS, GALILEO, and COMPASS use the *code division multiple access (CDMA)* technique, whereas GLONASS uses the *frequency division multiple access (FDMA)* technique.

**Code division multiple access (CDMA)**

GPS satellites all transmit on the same frequency but with different pseudo random noise (PRN) codes. A GPS receiver gets a unique segment of the C/A and P codes

**Table 8-1.** Navigation Satellite Systems Classification

	<i>Name</i>	<i>Country</i>
Global navigation satellite systems	GPS	United States
	GLONASS	Russia
	GALILEO	European Union
	COMPASS/BeiDou	China
Regional satellite navigation systems	IRNSS	India
	BeiDou	China
	QZSS	Japan
Satellite-based augmentation systems	WAAS	United States
	EGNOS	European Union
	MSAS	Japan
	GAGAN	India
Ground-based augmentation systems	LAAS	United States
	DGPS	United States
	RTK/RTN	United States

from each satellite but all on a single carrier frequency on which they are transmitted. In other words, even though each GPS satellite broadcasts its own unique segment of the C/A code (referred to as a PRN), they all arrive at the receiver at the same frequency, L1 (1575.42 MHz). The same is true of the P code—each unique segment of the P code (a satellite's PRN) arrives at the L2 frequency, 1227.60 MHz. This approach is the CDMA technique.

#### ***Frequency division multiple access (FDMA)***

GLONASS uses an FDMA approach in which the satellites transmit using the same codes but at slightly different frequencies. Unlike GPS, each code that a GLONASS receiver collects from any of the GLONASS satellites is exactly the same. Also unlike GPS, there are a range of frequencies to assign to each GLONASS satellite from two L bands. GLONASS satellites transmit two types of signals: a standard-precision (SP) signal and a high-precision (HP) signal. The SP signal gives horizontal position accuracy within 55 m and vertical position within 70 m, based on measurements from four satellite signals. The HP service is a more accurate signal for Russian military use. The two signals are transmitted on different frequencies using a 15-channel FDMA technique.

Antenna and receiver designs for FDMA are more complex and can be harder to calibrate for the highest accuracy. Combined GPS/GLONASS receivers are available for surveying and mapping but are not likely for mass markets. There are indications that GLONASS may try CDMA in the future (the same as GPS, GALILEO, and COMPASS).

#### ***Other differences between GPS and GLONASS***

GLONASS orbits are inclined steeper than GPS to give slightly better coverage at high latitudes. The GLONASS satellites repeat every 8 days while GPS satellites repeat every day (actually 23 hours 56 min.). The GLONASS ground control is limited to tracking stations only in former USSR territory (not global like GPS); this limits the ephemeris accuracy.

#### ***GLONASS satellites***

Phase I of the GLONASS system was completed in 1991 with seven active satellites in each of two orbital planes separated by 120 deg (Hofmann-Wellenhof et al. 2008). Twelve GLONASS spacecraft were added to the network during 1993–1994. The second-generation satellites, known as Uragan-M (GLONASS-M), with a 7-year operational life, were first launched in 2001 with subsequent launches in 2004 and 2005 (Fig. 8-4). A total of 14 were in orbit at the end of 2005. The third-generation satellites, which will number 24 when the constellation is complete in 2012, are known as Uragan-K (GLONASS-K) and are designed with a lifetime of 10–12 years. They feature an additional L-band navigational signal.

### **GALILEO**

The GALILEO satellite positioning system (Fig. 8-5) is the European GNSS program. It is named after the Italian astronomer Galileo Galilei. The GALILEO positioning system is referred to as “GALILEO” instead of the abbreviation “GPS”

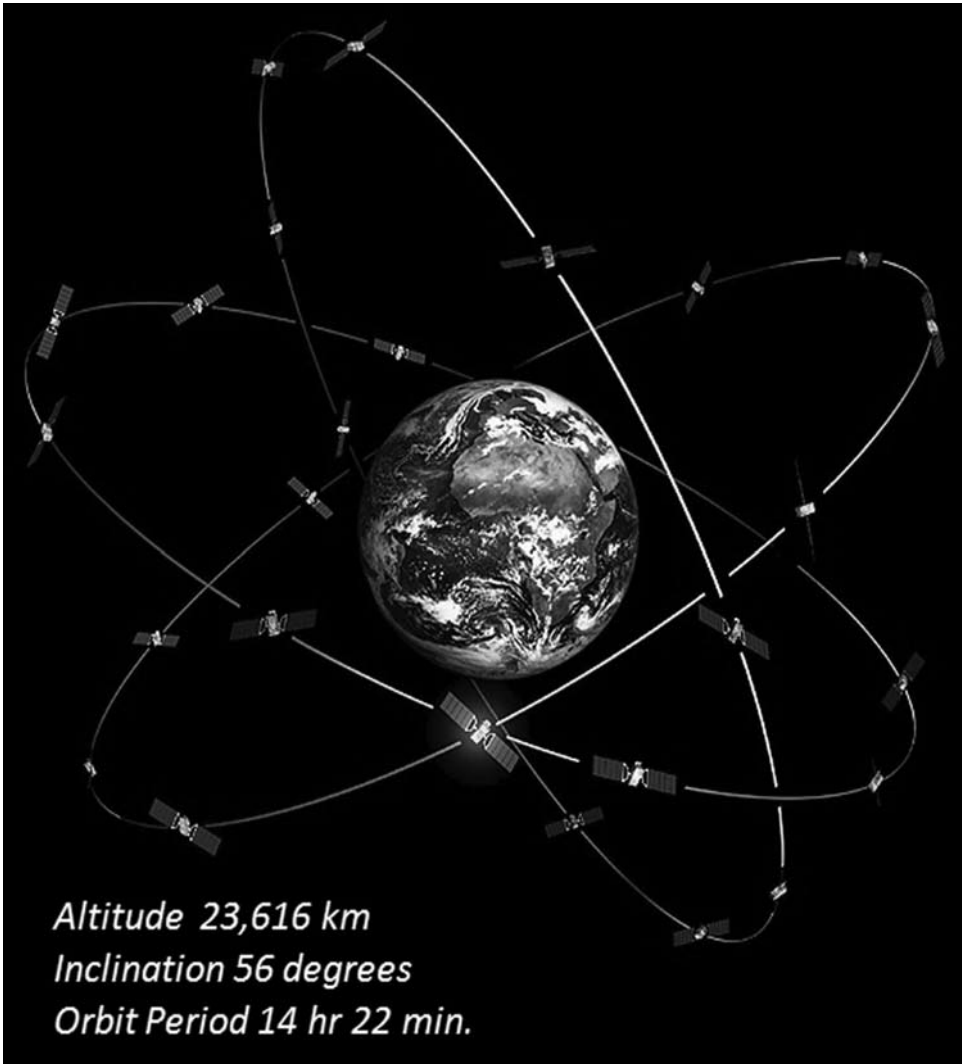


**Figure 8-4.** The Uragan-M (GLONASS-M) satellite.

to distinguish it from the existing U.S. system. It is intended to provide higher precision to all users than is currently available through GPS or GLONASS, to improve the availability of positioning services at higher latitudes, and to provide an independent positioning system upon which European nations can rely in the absence of GPS or GLONASS. The GALILEO constellation should become operational by 2014. Like the GPS system, GALILEO will utilize CDMA.

#### ***GIOVE-A and GIOVE-B***

Just over a dozen years after the idea was first proposed, the work on GALILEO culminated in the launch of a GIOVE-A (GALILEO In-Orbit Validation Experiment-A)



**Figure 8-5.** The GALILEO constellation. *Source:* European Space Agency (ESA).

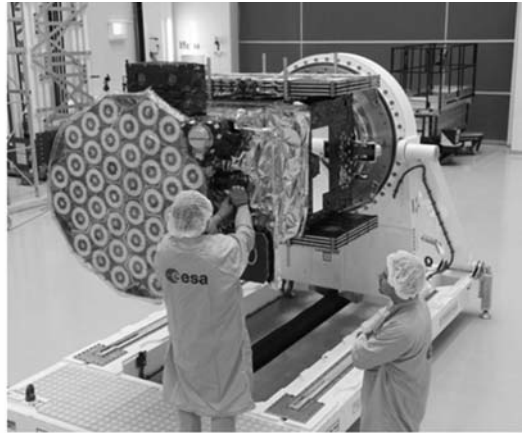
satellite (Fig. 8-6a). In addition to testing and validating the concept, the GIOVE-A satellite allowed the European government authorities to register the GALILEO frequencies with international regulators. This was necessary to buy time for the EU to build additional satellites without losing the frequency reservations. On April 27, 2008, a follow-on satellite, GIOVE-B, was launched (Fig. 8-6b). Galileo Industries, the consortium responsible for building GIOVE-B and the first batch of operational satellites, has scheduled their launches aboard Russian Soyuz rockets as an illustration of partnerships necessary for the success of GALILEO.

#### ***GALILEO signals***

Just like GPS signals, GALILEO navigation signals are right-hand circular polarized (RHCP) (Hein et al. 2003). The signals will be in the frequency ranges 1,164 to



(a) GIOVE-A . Soyuz on the launch pad ready for lift off (December 28, 2005)



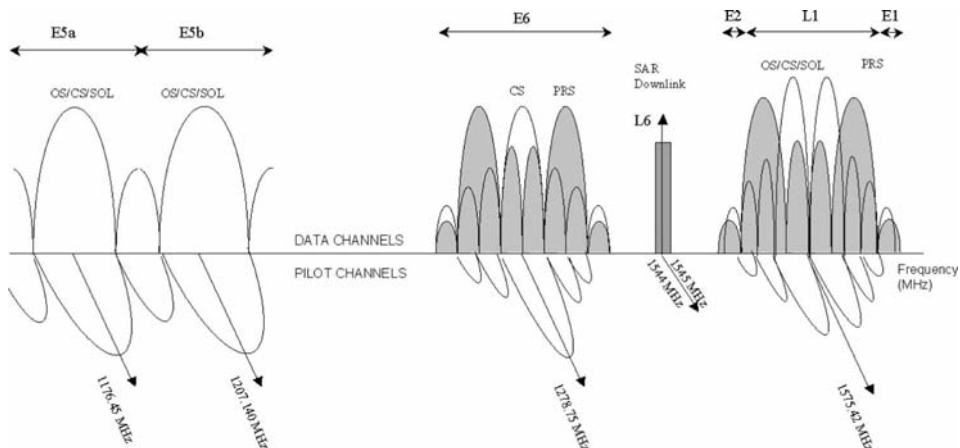
(b) GIOVE-B in the ESTEC Test Centre, the Netherlands. It was launched at the Baikonour spaceport, Kazakhstan, on April 27, 2008

**Figure 8-6.** GALILEO In-Orbit Validation Experiment (GIOVE) satellites for the GALILEO global navigation satellite system. *Source:* European Space Agency (ESA).

1,215 MHz (E5a and E5b), 1,215 to 1,300 MHz (E6), and 1,559 to 1,592 MHz (E2-L1-E1), which are part of the Radio Navigation Satellite Service (RNSS) allocation. The carrier frequencies (Fig. 8-7), as well as the frequency bands overlap with those of GPS and GLONASS. The overlapping of the signals is helpful in terms of the envisioned interoperability between GPS, GALILEO, and GLONASS. The initial interoperability agreement was signed between the EU and the United States in 2004. This agreement clarified the technical details of frequencies and code modulation (e.g., the new GPS civilian code L1C will be modulated the same way as GALILEO signals). The L3 band on GLONASS-K satellites will be within the frequency band that overlaps with GALILEO's E5b signal. GALILEO's E5a signal is centered at exactly 1,176 as is L5 of GPS, and both GALILEO's L1 and GPS's L1 are centered at 1,575.42 MHz.

### ***GALILEO levels of service***

GALILEO is designed with different levels of service. These include the open service (OS) and safety-of-life services (SoL) available to all GALILEO users on the E5a, E5b, and L1 carrier frequencies; commercial service (CS) accessible only to some dedicated users that gain access through encrypted custom solutions; and the public regulated service (PRS) with encrypted ranging codes and data is accessible to authorized users. The SoL service provides integrity monitoring, meaning that users are warned if there are signal problems. The PRS is meant to assist public security and civil authority, with protection against jamming. The CS data are transmitted on the E5b, E6, and E2-L1-E1 carriers. The PRS data are transmitted on E6 and L1 carrier frequencies.



**Figure 8-7.** GALILEO navigation signals and frequencies. *Source:* European Space Agency (ESA).

### COMPASS/BeiDou

The COMPASS Navigation Satellite System (CNSS), or BeiDou-2, its Chinese name, is a Chinese navigation satellite constellation. The BeiDou-2 system will build on the predecessor (BeiDou-1) regional positioning program. COMPASS/BeiDou-2 comprises a 35-satellite constellation, with five satellites in geostationary orbit and 30 in medium Earth orbit [12-hour, 55-deg inclination, 21,000-km (13,050-mi.-) altitude circular orbits]. While BeiDou-1 is intended for users in China and its neighboring countries, BeiDou-2 is intended to provide navigation and positioning services to global users. The initial satellite launch of the BeiDou-2 system was in April 2007, with a planned date of completion of 2015.

The CNSS positioning concept is no different from the other GNSSs. And like other GNSSs, it is driven by reasons such as sovereignty and military control. Frequencies overlap closely with those of GALILEO and GPS. Its CDMA signals are also very similar to “modernized” GPS. For users, more satellites and signals is a boon. Political and industrial competition is driving GNSS developments and the users will benefit. A hundred or more navigation satellites could be available in the next decade, with a multitude of different signals being broadcast from each satellite. Figure 8-8 illustrates the overall timeline of GNSS developments.

### Regional Satellite Navigation Systems (RNSS)

#### BeiDou-1

BeiDou-1 is China’s first space-based regional navigation and positioning network. It is a three-satellite constellation developed by the China Academy of Space Technology. Its method of operation requires two-way transmissions between the user and a central control station via a high-altitude geostationary satellite. First,

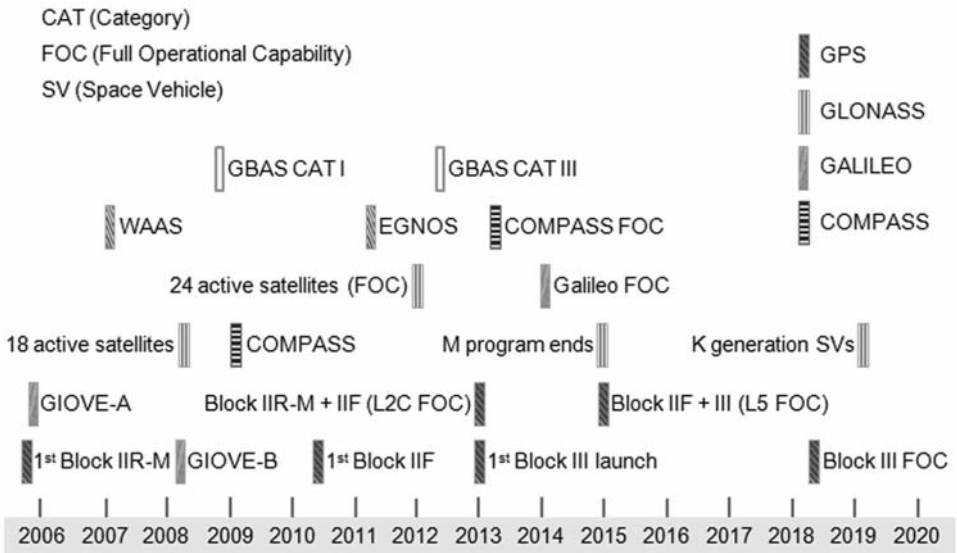


Figure 8-8. Timeline of GNSS developments.

the central control station sends inquiry signals to a user via two satellites. When the user terminal receives the signal from one satellite, it sends a response signal back to both satellites. The central station receives the responding signals sent by the user from two satellites and calculates the user’s 2-D position based on the time difference between the two signals. Because the BeiDou-1 system requires two-way transmissions between the user and the central control station via satellites at high-altitude geostationary orbit, its user segment needs extra space for a transmitter and a more powerful battery. Consequently, the BeiDou-1 user segments are much larger (20-cm antenna), heavier, and more expensive compared to GPS user receivers.

**IRNSS**

The Indian Regional Navigational Satellite System (IRNSS) is a seven-satellite constellation under development by the Indian Space Research Organization. Three of the satellites will be placed in geostationary orbit, with four in geosynchronous inclined orbit of 29 deg relative to the equatorial plane. Navigation signals will be transmitted in the S-band frequency (2–4 GHz).

IRNSS is being developed to provide a position accuracy of better than 20 m throughout India and within a region extending approximately 2,000 km (1,250 mi.) around it. The government approved the project in May 2006, intending the system to be completed and implemented by 2012.

**QZSS**

The Quasi-Zenith Satellite System (QZSS) is a proposed three-satellite regional time transfer and GPS enhancement system, receivable within Japan. The first



satellite, Michibiki, was launched on September 11, 2010, and is expected to be fully operational by 2013. The satellite is placed in a periodic highly elliptical orbit (HEO), allowing it to stay in view for more than 12 hours a day with an elevation above 70° (that is, the satellite appears almost overhead most of the time), hence the term “quasi-zenith.”

QZSS is targeted at mobile applications, to provide communications-based services (video, audio, and data) and positioning information. However, the positioning service can provide only limited accuracy on its own and is not currently designed to work in a stand-alone mode. It is viewed as a GNSS augmentation service.

### **Satellite-Based Augmentation Systems (SBAS)**

A satellite-based augmentation system (SBAS) is one that supports wide-area or regional augmentation using additional satellite-broadcast messages. Such systems commonly consist of multiple ground stations located at accurately surveyed points. The ground stations take measurements of one or more of the GNSS satellites, the satellite signals, or other environmental factors, which may affect the signal received by the users. Using these measurements, information messages are created and sent to one or more satellites for broadcast to the end users. Figure 8-9 represents various SBASs that are implemented worldwide.

The U.S. Wide Area Augmentation System (WAAS) was commissioned for use by civil aviation in July 2003. In 2007, WAAS vertical guidance was identified as being available nearly all the time, covering the full continental United States, most of Alaska, northern Mexico, and southern Canada. EGNOS (European Geo-



**Figure 8-9.** SBASs worldwide.

stationary Navigation Overlay Service) started its initial operations in July 2005 and was declared operational for safety-of-life services in March 2011. MSAS, the Multifunctional Satellite Augmentation System, became operational for safety-of-life applications in September 2007, according to the Japan Civil Aviation Bureau (Butterworth-Hayes 2009). India's GAGAN (GPS Aided Geo Augmented Navigation) is being built to provide a navigation system for all phases of flight over India and its neighbors, to be fully operational by May 2011.

### ***Ground-Based Augmentation Systems (GBAS)***

A ground-based augmentation system (GBAS) is an augmentation to GNSS that focuses its service on a localized area such as around an airport [e.g., an approximately 30-km (19-mi.) radius]. In GBAS, corrections are broadcast to users via a very high frequency (VHF) radio data link from a ground-based transmitter or via cellular towers or Internet transmission.

A local area augmentation system (LAAS) is the FAA version of the GBAS that has been defined by the International Civil Aviation Organization (ICAO). LAAS is based on a single GPS reference station facility located on the property of the airport being serviced. It allows users within 45 km (30 mi.) of the LAAS ground station to perform GPS-based position fixes with 0.5-m (95% confidence level) accuracy and to perform all civil flight operations up to non-precision approach.

The DGPS and RTN networks and services discussed in Chapters 4 and 5, respectively, are also GBAS systems. For instance, the U.S. NDGPS network is a nationwide GBAS comprised of several coastal and inland networks, operated by the United States Coast Guard, the U.S. Army Corps of Engineers, and the U.S. Department of Transportation. Several commercial RTN networks exist for real-time corrections via radio link or the Internet.

## **Market Trends and Opportunities**

### ***A Projected Growth Sector for the Next 20 or More Years***

GPS is an indispensable tool in every sector of the world economy. It is one of the global navigation satellite systems (GNSSs) that are predicted to be the major drivers of the world economies during the next few decades. Apart from GPS, which is owned by the United States, parallel similar technologies include the Russian GLONASS, the European GALILEO, and the Chinese COMPASS/BeiDou. Other nations such as India and Japan are also on track with regional satellite systems that are already boosting scientific research and mass market possibilities. By design, a single GNSS consists of more than two dozen space satellites that aid in navigation, positioning, and timing. The civilian applications have been limitless and continue to expand, currently including areas such as precision farming, car navigation systems, personal navigation and tracking devices, wireless

communications and cellular services, engineering, construction, transportation, telematics, location-based services, emergency search and rescue, tourism, maritime, aviation, mining, mapping, meteorology, and climate science.

The most recent market research suggests that, notwithstanding the impact of the 2008–2009 economic crisis, the GNSS industry is still growing at a solid pace (Pietka and Urrutia 2010). GNSS system shipments are projected to reach more than 500 million worldwide in 2010 and to continue growing to 1.1 billion in 2014. According to ABI Research forecasts, “Current projections suggest that, over the period 2009–2014, GNSS markets will grow at compound annual rate of 24 percent. . . . In today’s crisis scenario, few other industries are granted such bright prospects” (ABI Research 2010). A market study conducted by the GSA (the European GNSS Supervisory Authority) foresees that the overall worldwide GNSS-enabled market size for civil applications, combining sales of GNSS devices plus GNSS-based services, will amount to about €236 billion in 2025. Market trends suggest that GNSS-based products and services are still in the early “majority phase” of an innovation adoption cycle.

### ***Impact on Revenue and Jobs***

Although GPS (which is a GNSS) was initially primarily a military system, it has led to unexpected exponential growth in civilian applications and research interests. Hundreds of GNSS companies have been (and continue to be) created worldwide, and universities and institutions have continually expanded numerous research positions and programs in GNSS and related areas. The European GNSS alone is projected to create hundreds of thousands of jobs during the next two decades. Recently, *Inside GNSS* magazine featured an essay by economic analysts in the European Commission’s Galileo Unit describing how GALILEO, the European GNSS now under development, can contribute to Europe’s recovery from the global economic crisis. The following is an excerpt from that report:

Just in terms of market opportunities, GALILEO has the potential to generate €100 billion of accumulated revenues for European companies in the global market for navigation applications in the period 2005–2030. Such an outsource would lead to the creation of as many as 100,000 high-tech jobs across Europe.

A review of these estimates taking account of possible impacts of the economic crisis suggests that, in a worst-case scenario, the total accumulated benefits coming from GALILEO over the period 2008–2030 would be between €55 and €62 billion. . . . Even under this pessimistic scenario, the accompanying increase in employment is projected to produce around 1,400 permanent jobs created in up-stream industries—GALILEO infrastructure and operations—and between 17,000 and 21,000 incremental jobs in down-stream industries—GALILEO product manufacturers and service providers. (*Inside GNSS* 2010a)

When considering market developments and the importance that GNSS commercial services have acquired in recent years, some key conclusions become apparent:

- GNSS represents a long-term growth industry with potential revenues in the range of tens of billions of dollars, even in a context of a severe economic crisis. Political and industrial competition is driving GNSS developments and civilian users will certainly benefit. More than 100 GNSS satellites could be available in the next decade with a multitude of different signals being broadcast from each satellite.
- Today, the EU is the most important market for the GNSS products after the United States. Russia is developing their GNSS and so are China, India, and Japan. And who knows which other countries might soon follow suit? In the next 15 years, world economic dependence on GNSS is likely to increase, and so will the GNSS job opportunities. There is a steady worldwide demand for skilled professionals who can participate in GNSS-related research, product and system developments, and testing.
- GPS has been fully operational since 1993 and is currently undergoing modernization phases. The Russian GLONASS is similarly being revitalized, with many satellite launches having occurred in the recent past. There is a big push by the EU community to declare GALILEO fully operational by 2014. The system is currently being developed, tested, and validated, and many funding phases have been successful. There is a growing demand for the relevant workforce and skills, and the number of job seekers specifically interested in the GNSS industry is on the rise. All these are key indicators of the potential for growth in GNSS job opportunities as the technology matures. Potential areas of immediate and future job demand include administrators, program managers, business developers, sales engineers, software engineers, research scientists, system developers, university researchers, executives, programmers, and product developers.

### **High-Precision GNSS**

For the remainder of this chapter, *high-precision GNSS* is defined as GNSS equipment, software, or services capable of providing horizontal precision of 10 cm or less using GNSS technology. High-precision GNSS is an essential productivity tool in globally important industrial sectors such as mining, agriculture, and construction. Important milestones include the value of high-precision GNSS systems used for industrial applications such as machine control in agriculture and civil engineering, exceeding that of high-precision GNSS for traditional uses such as surveying and science applications (see earlier discussions in Chapter 7).

Annually, there are at least half a dozen or more GNSS market research reports predicting the future performance of GNSS products and services. Most of the GPS/GNSS market reports discuss the background and status of the entire

spectrum of GNSS, including GPS and GPS modernization, GLONASS and GLONASS modernization, SBAS, GALILEO, COMPASS/BeiDou, QZSS, and IRNSS systems, as well as market trends and potential challenges and opportunities. While this book discusses these topics in a conceptual and application context, the market reports include details on financial projections and competitiveness of products and services for the GNSS markets surveyed.

Some GNSS market research reports are specific to a particular GNSS consumer product, industry, or application, while others are more general in scope. *The Military GPS/GNSS Devices Market 2009–2019*, by MarketResearch.com, is one example of an industry-specific report. Another example is *World-Wide Precision Positioning Markets 2008–2012* by Lorimer and Gakstatter (2008). This second example is general in scope but specific to high-precision GNSS applications, including surveying, engineering, agriculture, mining, deformation monitoring, GIS, and marine for both machine control and nonmachine control applications. It covers details on the projected U.S. value chain in high-precision GNSS infrastructure, the market for GNSS receivers, finished GNSS goods, and GNSS augmentation and distribution services. According to this report, the global value of precision GNSS products and services would grow to between \$6 billion and \$8 billion by 2012.

## Products

As seen in Chapter 7, there is a trend toward higher precision in GNSS receiver technology. New GNSS signals and new technologies have created new market dynamics. Perhaps an important area with the most impact on high-precision applications is autosteer and machine control technology. In this particular area, there is a new breed of GNSS technology providers in agriculture, construction, engineering, and related applications.

Autosteer and other high-precision GNSS applications contribute to increased productivity in all applicable sectors. For instance, the worldwide market for high-precision GPS in agriculture is booming (Lorimer and Gakstatter 2008). For many years the leading technology for precision agriculture was GPS L1 receivers providing sub-meter precision. That precision was good enough for yield mapping, applying chemicals, field mapping, aerial spraying, and various other tasks where sub-meter precision was really useful. In the autosteer and machine control technology, the sub-meter precision was not good enough but, at 1-cm horizontal accuracy, dual-frequency RTK technology fits that application perfectly—making autosteer in agricultural equipment a practical application of high-precision GNSS. In offering high-precision GNSS solutions, many of the GPS/GNSS vendors have adjusted their product strategies to utilize the network RTK infrastructure sector (discussed in Chapter 5).

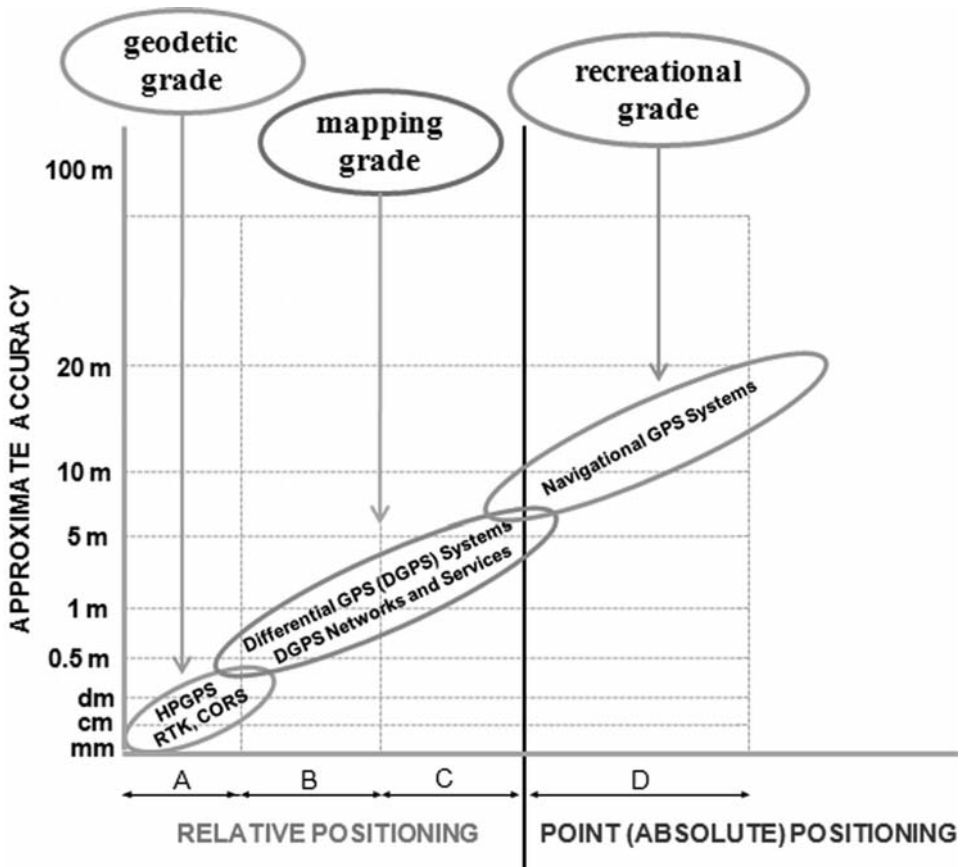
## Network Services

The growth in the number of high-precision GNSS users, estimated at more than 300,000 globally in 2008, is encouraging governments and private indus-

try to invest in high-precision GNSS infrastructure (Lorimer and Gakstatter 2008). This infrastructure uses GNSS reference stations and wireless communications to deliver a data service to multiple users, removing the need for individual users to operate their own GNSS reference stations. Such infrastructure and associated data services are forecast to be the fastest growing component of the value chain.

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## Overview of Civilian GPS Receiver Classification



- A: Carrier phase with resolved ambiguities, real-time/post-processed
- B: Carrier smoothed C/A code phase, post-processed
- C: Real-time (RTCM SC104), post-processed C/A code
- D: Real time P-code (PPS) and real time C/A code (SPS)

Figure A1-1. Overview of civilian GPS receiver classification.



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# Why GPS Carrier Signals Are in the L-Band

All GPS signals are in the L-band of the frequency spectrum (Fig. A2-1). Because L-band waves penetrate clouds, fog, rain, storms, and vegetation, GPS units can receive accurate data in all weather conditions, day or night. There are circumstances in which GPS units may not receive signals accurately, such as inside concrete buildings or under heavy forest canopies.

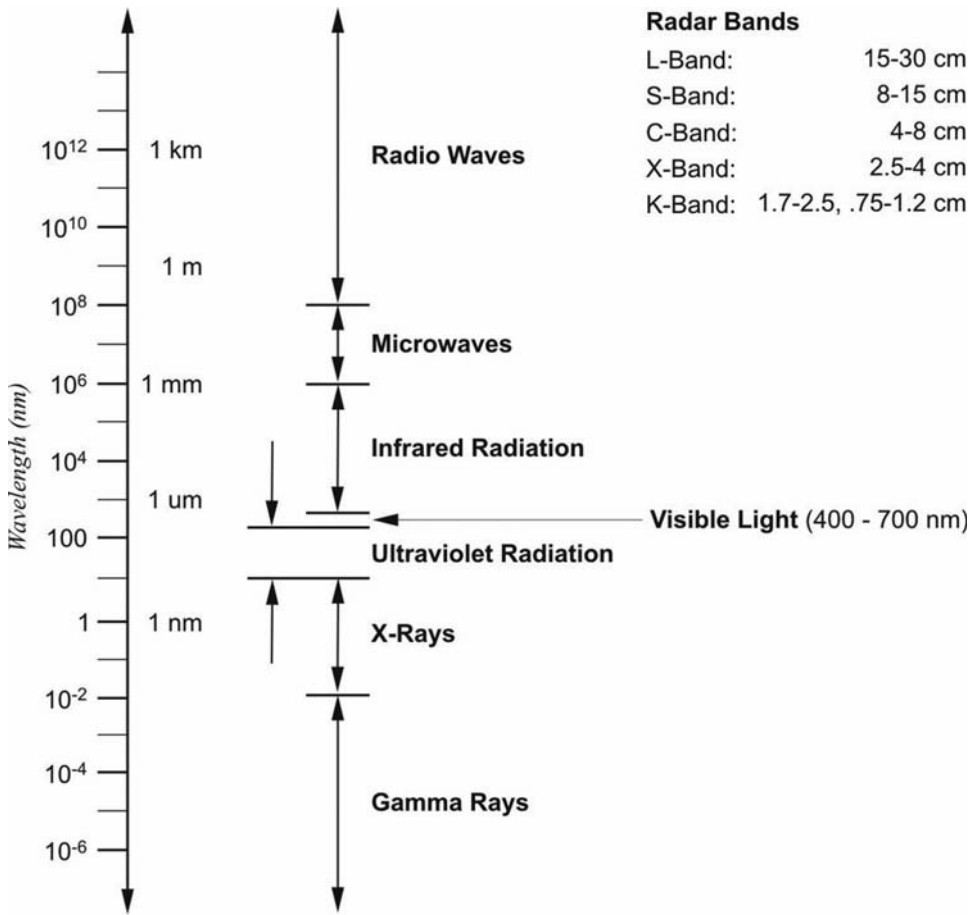
The principle of position determination by GPS and the accuracy of positions depend on the nature of the signals transmitted. A suitable signal structure was developed to fulfill a number of requirements. The choice of the GPS carrier frequency (to transport data signals) was submitted to the following requirements:

- Frequencies should be below 2 GHz, as frequencies above 2 GHz would require beam antennae for the signal reception.
- Ionospheric delays are enormous for frequency ranges below 1,000 MHz and above 10 GHz.
- The PRN codes (explained in the Glossary) require a high bandwidth for code modulation on the carrier frequency. Therefore, a range of high frequencies with the possibility of a high bandwidth had to be chosen.
- The chosen frequency should be in a range where the signal propagation is not influenced by weather phenomena like rain, snow, or clouds.

Based on these considerations, the choice of L-band frequencies proved to be advantageous. Each GPS satellite (Block IIF and beyond) transmits three carrier signals in the microwave range of the electromagnetic spectrum, designated as L1, L2, and L5 (frequencies located in the L-band between 1,000 and 2,000 MHz of the spectrum). The L1 frequency is 1,575.42 MHz (wavelength 19.05 cm), the L2 frequency is 1,227.60 MHz (wavelength 24.45 cm), and the L5 frequency is 1,176.45 MHz (wavelength 25.48 cm).

## Broadcast versus Emitted Radio Waves

The GPS (L-band carrier) signals are broadcast radio waves. *Broadcast* radio waves are created by use of transmitters. *Emitted* radio waves originate from astronomical



**Figure A2-1.** The electromagnetic spectrum.

objects such as stars and galaxies. GPS uses the former while radio astronomy uses the latter.

### **Broadcast Radio Waves**

Transmitters use electrical signals at radio frequencies (RFs) to produce an RF carrier wave. The part of a transmitter that creates the RF carrier wave is called an *oscillator*. On transmission, the RF is modulated with the information to be relayed. A receiver demodulates the modulated radio signal and removes the RF to leave the information frequency. A transmitting antenna takes waves that are generated by electrical signals inside a transmitter and converts them to waves that travel in an open space. A receiving antenna receives radio waves and guides them to a receiver, where they are reconstructed into the original message.

***Emitted Radio Waves***

The field of radio astronomy originated from the discovery that most astronomical objects in space emit radiation in the radio wavelengths as well as optical (light) wavelengths. Astronomical objects such as planets and comets, giant clouds of gas and dust, and stars and galaxies emit light at many different wavelengths. Some of the light waves they emit have very large wavelengths—sometimes as long as a mile. These long waves are in the radio region of the electromagnetic spectrum.

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# Calculation of Satellite Position from Ephemeris Data

**Table A3-1.** Representation of GPS Broadcast Ephemeris

<b>Time Parameters</b>	
$t_{0e}$	Reference time, ephemeris parameters (s)
$t_{0c}$	Reference time, clock parameters (s)
$a_0, a_1, a_2$	Polynomial coefficients for clock correction (bias (s), drift (s/s), drift rate (aging) (s/s <sup>2</sup> ))
<b>Keplerian Parameters</b>	
$\sqrt{A}$	Square root of the semi-major axis (m <sup>1/2</sup> )
$e$	Eccentricity (dimensionless)
$i_0$	Inclination angle at reference time (semicircles)
$\Omega_0$	Longitude of ascending node at reference time (semicircles)
$\omega$	Argument of perigee (semicircles)
$\bar{M}_0$	Mean anomaly at reference time (semicircles)
<b>Perturbation Parameters</b>	
$\dot{\Delta}n$	Mean motion difference from computed value (semicircles/s)
$\dot{\Omega}$	Rate of change of right ascension (semicircles/s)
$\dot{i}$	Rate of change of inclination (semicircles/s)
$C_{us}$	Amplitude of the sine harmonic correction term to the argument of latitude (rad)
$C_{uc}$	Amplitude of the cosine harmonic correction term to the argument of latitude (rad)
$C_{is}$	Amplitude of the sine harmonic correction term to the angle of inclination (rad)
$C_{ic}$	Amplitude of the cosine harmonic correction term to the angle of inclination (rad)
$C_{rs}$	Amplitude of the sine harmonic correction term to the orbit radius (m)
$C_{rc}$	Amplitude of the cosine harmonic correction term to the orbit radius (m)

Source: Seeber (2003).

The individual satellite time,  $t_{SV}$ , is corrected to GPS system time,  $t$ , using:

$$t = t_{SV} - \Delta t_{SV}$$

in which

$$\Delta t_{SV} = a_0 + a_1(t - t_{0c}) + a_2(t - t_{0c})^2 \quad (\text{A3-1})$$

Differentiating Eq. A3-1 with respect to time yields satellite clock drift.

The satellite coordinates in the WGS-84 Cartesian system are computed for a given epoch,  $t$ . The time,  $t_k$ , elapsed since the reference epoch,  $t_{0e}$ , is  $t_k = t - \Delta t_{0e}$ .

**Table A3-2.** Calculating Satellite Coordinates from GPS Broadcast Ephemeris

<i>Constants</i>	
$GM = 3.986005 \cdot 10^{14} \text{ m}^3/\text{s}^2$	WGS-84 value for the product of gravitational constant $G$ and the mass of the Earth $M$
$\omega_e = 7.292115 \cdot 10^{-5} \text{ rad/s}$	WGS-84 value of the Earth's rotation rate
$\pi = 3.1415926535898$ (exactly)	
<b>Keplerian Parameters to ECEF Coordinates</b>	
$T = 2\pi/\sqrt{GM/A^3}$	Satellite orbital period
$n_0 = \sqrt{\frac{GM}{A^3}}$	Computed mean motion
$n = n_0 + \Delta n$	Corrected mean motion
$\bar{M}_k = \bar{M}_0 + nt_k$	Mean anomaly
$E_k = \bar{M}_k + e \sin E_k$	Kepler's equation of eccentric anomaly is solved by iteration. Because of the small eccentricity of GPS orbits ( $e < 0.001$ ), two steps are usually sufficient: $E_0 = \bar{M}, E_i = \bar{M} + e \sin E_{i-1}, i = 1, 2, 3, \dots$
$\cos v_k = \frac{\cos E_k - e}{1 - e \cos E_k}$	True anomaly
$\sin v_k = \frac{\sqrt{1 - e^2} \sin E_k}{1 - e \cos E_k}$	True anomaly
$\Phi_k = v_k + \omega$	Argument of latitude
$\delta u_k = C_{uc} \cos 2\Phi_k + C_{us} \sin 2\Phi_k$	Argument of latitude correction
$\delta r_k = C_{rc} \cos 2\Phi_k + C_{rs} \sin 2\Phi_k$	Radius correction
$\delta i_k = C_{ic} \cos 2\Phi_k + C_{is} \sin 2\Phi_k$	Inclination correction
$u_k = \Phi_k + \delta u_k$	Corrected argument of latitude
$r_k = A(1 - e \cos E_k) + \delta r_k$	Corrected radius
$i_k + i_0 + \delta i_k$	Corrected inclination
$X'_k = r_k \cos u_k$	Position in the orbital plane
$Y'_k = r_k \sin u_k$	Position in the orbital plane
$\Omega_k = \Omega_0 + (\dot{\Omega} - \omega_e)t_k - \omega_e t_{0e}$	Corrected longitude of ascending node
$X_k = X'_k \cos \Omega_k - Y'_k \sin \Omega_k \cos i_k$	Earth-fixed geocentric satellite coordinate
$Y_k = X'_k \sin \Omega_k + Y'_k \cos \Omega_k \cos i_k$	Earth-fixed geocentric satellite coordinate
$Z_k = Y'_k \sin i_k$	Earth-fixed geocentric satellite coordinate

ECEF, Earth-centered, Earth-fixed.

Source: Seeber (2003).

## Calculation of Point Position from Pseudoranges

Based upon the receiver–satellite range observation (refer to Eq. 2-6 in Chapter 2), the pseudorange measurements,  $P_r^s(t)$ , can be modeled as:

$$P_r^s(t) = \rho_r^s(t) + c(dt^s(t) - dT_r(t)) + d_{ion}^s(t) + d_{trop}^s(t) + MP(t) + \varepsilon \quad (A4-1)$$

where

- $t$  = time of epoch
- $P_r^s$  = pseudorange measurement
- $\rho_r^s$  = satellite–receiver geometric distance
- $c$  = speed of light
- $dt^s$  = satellite clock bias
- $dT_r$  = receiver clock bias
- $d_{ion}^s$  = ionospheric propagation error
- $d_{trop}^s$  = tropospheric propagation error
- $MP$  = multipath
- $\varepsilon$  = receiver noise
- (ranges in meters, time in seconds)

Neglecting the propagation, multipath, and receiver errors, Eq. A4-1 becomes:

$$P_r^s(t) = \rho_r^s(t) + c(dt^s(t) - dT_r(t)) \quad (A4-2)$$

The *geometric distance* between satellite  $s$  and receiver  $r$  is given by:

$$\rho_r^s(t) = \sqrt{(x^s(t) - x_r)^2 + (y^s(t) - y_r)^2 + (z^s(t) - z_r)^2}$$

or

$$\rho_r^s(t) = f(x_r, y_r, z_r) \quad (A4-3)$$

with  $[x^s, y^s, z^s]$  = satellite position,  $[x_r, y_r, z_r]$  = receiver position in an Earth-centered Earth-fixed (ECEF) coordinate system.



In GPS point positioning (also called GPS trilateration or GPS triangulation), the goal is to solve for  $[x_r, y_r, z_r, dT_r]$ , assuming that  $[x^s, y^s, z^s, dt^s]$  are known. A major problem here is that the unknowns  $[x_r, y_r, z_r]$  are not linearly related to the observables.

Assuming that the approximate coordinates of the receiver  $[x_o, y_o, z_o]$  are known, one can write that the actual coordinates equal the approximate coordinates plus a slight *adjustment*:

$$\begin{aligned}x_r &= x_o + \Delta x_r \\y_r &= y_o + \Delta y_r \\z_r &= z_o + \Delta z_r\end{aligned}\tag{A4-4}$$

$\Delta x_r, \Delta y_r, \Delta z_r$  are the new unknowns, and we can now write:

$$f(x_r, y_r, z_r) = f(x_o + \Delta x_r, y_o + \Delta y_r, z_o + \Delta z_r)\tag{A4-5}$$

Since the approximate point  $[x_o, y_o, z_o]$  is known, Eq. A4-5 can be expanded using a Taylor's series with respect to that point:

$$\begin{aligned}f(x_r, y_r, z_r) &= f(x_o, y_o, z_o) + \frac{\partial f(x_o, y_o, z_o)}{\partial x_o} \Delta x_r + \\&\frac{\partial f(x_o, y_o, z_o)}{\partial y_o} \Delta y_r + \frac{\partial f(x_o, y_o, z_o)}{\partial z_o} \Delta z_r + \frac{1}{2!} \frac{\partial^2 f}{\partial x^2} + \dots\end{aligned}\tag{A4-6}$$

On the basis of Eq. A4-3:

$$f(x_o, y_o, z_o) = \sqrt{(x^s(t) - x_o)^2 + (y^s(t) - y_o)^2 + (z^s(t) - z_o)^2} = \rho_o^s(t)\tag{A4-7}$$

Hence, the *partial derivatives* in Eq. A4-6 are given by:

$$\begin{aligned}\frac{\partial f(x_o, y_o, z_o)}{\partial x_o} &= -\frac{x^s(t) - x_o}{\rho_o^s(t)} \\ \frac{\partial f(x_o, y_o, z_o)}{\partial y_o} &= -\frac{y^s(t) - y_o}{\rho_o^s(t)} \\ \frac{\partial f(x_o, y_o, z_o)}{\partial z_o} &= -\frac{z^s(t) - z_o}{\rho_o^s(t)}\end{aligned}\tag{A4-8}$$

Substituting Eq. A4-8 into Eq. A4-6:

$$f(x_r, y_r, z_r) = f(x_o, y_o, z_o) - \frac{x^s(t) - x_o}{\rho_o^s(t)} \Delta x_r - \frac{y^s(t) - y_o}{\rho_o^s(t)} \Delta y_r - \frac{z^s(t) - z_o}{\rho_o^s(t)} \Delta z_r \quad (\text{A4-9})$$

We now have an equation that is linear with respect to the unknowns  $\Delta x_r$ ,  $\Delta y_r$ ,  $\Delta z_r$ .

Now going back to the pseudorange measurements  $P_r^s(t)$  and rewriting Eq. A4-2:

$$P_r^s(t) = \rho_o^s(t) - \frac{x^s(t) - x_o}{\rho_o^s(t)} \Delta x_r - \frac{y^s(t) - y_o}{\rho_o^s(t)} \Delta y_r - \frac{z^s(t) - z_o}{\rho_o^s(t)} \Delta z_r + c(dt^s(t) - dT_r(t)) \quad (\text{A4-10})$$

Equation A4-10 can then be rearranged by separating the known and unknown terms on each side [the satellite clock correction  $dt^s(t)$  is provided in the navigation message]:

$$P_r^s(t) - \rho_o^s(t) - cdt^s(t) = \frac{x^s(t) - x_o}{\rho_o^s(t)} \Delta x_r - \frac{y^s(t) - y_o}{\rho_o^s(t)} \Delta y_r - \frac{z^s(t) - z_o}{\rho_o^s(t)} \Delta z_r - cdT_r(t) \quad (\text{A4-11})$$

Let:

$$\begin{aligned} a_{x_r}^s &= -\frac{x^s(t) - x_o}{\rho_o^s(t)} \\ a_{y_r}^s &= -\frac{y^s(t) - y_o}{\rho_o^s(t)} \\ a_{z_r}^s &= -\frac{z^s(t) - z_o}{\rho_o^s(t)} \\ l^s &= P_r^s(t) - \rho_o^s(t) - cdt^s(t) \end{aligned} \quad (\text{A4-12})$$

and assume that at time  $t$  we have four satellites visible simultaneously. For the four satellites, use Eq. A4-11 to generate the following simultaneous equations:

$$\begin{aligned} l^1 &= a_{x_r}^1 \Delta x_r + a_{y_r}^1 \Delta y_r + a_{z_r}^1 \Delta z_r - cdT_r \\ l^2 &= a_{x_r}^2 \Delta x_r + a_{y_r}^2 \Delta y_r + a_{z_r}^2 \Delta z_r - cdT_r \\ l^3 &= a_{x_r}^3 \Delta x_r + a_{y_r}^3 \Delta y_r + a_{z_r}^3 \Delta z_r - cdT_r \\ l^4 &= a_{x_r}^4 \Delta x_r + a_{y_r}^4 \Delta y_r + a_{z_r}^4 \Delta z_r - cdT_r \end{aligned} \quad (\text{A4-13})$$

We can then simplify the notation by assigning:

$$\begin{aligned}
 A &= \begin{bmatrix} a_{x_r}^1 & a_{y_r}^1 & a_{z_r}^1 & -c \\ a_{x_r}^2 & a_{y_r}^2 & a_{z_r}^2 & -c \\ a_{x_r}^3 & a_{y_r}^3 & a_{z_r}^3 & -c \\ a_{x_r}^4 & a_{y_r}^4 & a_{z_r}^4 & -c \end{bmatrix} \\
 \bar{X} &= \begin{bmatrix} \Delta x_r \\ \Delta y_r \\ \Delta z_r \\ dT_r \end{bmatrix} \\
 \bar{L} &= \begin{bmatrix} l^1 \\ l^2 \\ l^3 \\ l^4 \end{bmatrix}
 \end{aligned} \tag{A4-14}$$

where

$L$  = vector of  $n$  observations. Must have at least four elements (i.e., four satellites), but in reality will have from 4 to 12 elements depending on the satellite constellation geometry.

$X$  = vector of  $u$  unknowns. Four elements in this case.

$A$  = matrix of linear functions of the unknowns (= design matrix),  $n$  rows by  $u$  columns.

We can now write the problem in Eq. A4-13 in a matrix-vector form:

$$\bar{L} = A\bar{X} \tag{A4-15}$$

In general,  $n > u$ , leading to an overdetermined system. Because actual data contain observational errors and noise, this system is nonconsistent. In order to make it consistent, one must account for a noise vector,  $r$ . Equation A4-15 becomes:

$$\bar{L} - \bar{r} = A\bar{X} \tag{A4-16}$$

The noise vector,  $r$ , represents residuals, that is, observations  $\bar{L}$  minus model  $A\bar{X}$ . The *least squares solution* to Eq. A4-16 is:

$$\bar{X} = (A^T P A)^{-1} A^T P \bar{L} \tag{A4-17}$$

$P$  is the weight matrix, defined by:

$$P = \sigma_o^2 \sum_L^{-1} \tag{A4-18}$$

where

$\sigma_o^2$  = a priori variance

$\Sigma_L$  = covariance matrix of the observations.

The law of covariance propagation gives the *covariance matrix of the unknowns*,  $\Sigma_X$ :

$$\Sigma_X = (A^T \Sigma_L^{-1} A)^{-1} \tag{A4-19}$$

In the case of pseudoranges, the observations are independent and have equal variance  $\sigma_o^2$ . For uncorrelated measurements,  $\Sigma_L$  is a diagonal matrix, and therefore Eq. A4-18 becomes:

$$P = \sigma_o^2 I \tag{A4-20}$$

Assuming that the weight matrix is  $I$ , Eq. A4-17 can be simplified to:

$$\bar{X} = (A^T A)^{-1} A^T \bar{L} \tag{A4-21}$$

Having solved for  $\Delta x_r$ ,  $\Delta y_r$ ,  $\Delta z_r$ , the antenna coordinates  $[x_r, y_r, z_r]$  are obtained using Eq. A4-4.

The associated variance-covariance matrix of the unknowns  $\Sigma_X$  is:

$$\Sigma_X = (A^T A)^{-1} = \begin{bmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xz} & \sigma_{xt} \\ \sigma_{yx} & \sigma_y^2 & \sigma_{yz} & \sigma_{yt} \\ \sigma_{zx} & \sigma_{zy} & \sigma_z^2 & \sigma_{zt} \\ \sigma_{tx} & \sigma_{ty} & \sigma_{tz} & \sigma_t^2 \end{bmatrix} \tag{A4-22}$$

We can transform  $\Sigma_X$  from an ECEF frame to a local topocentric frame using the law of variance propagation (disregarding the time-correlated components of  $\Sigma_X$ ):

$$\Sigma_T = R \Sigma_X R^T = \begin{bmatrix} \sigma_n^2 & \sigma_{ne} & \sigma_{nu} \\ \sigma_{en} & \sigma_e^2 & \sigma_{eu} \\ \sigma_{un} & \sigma_{ue} & \sigma_u^2 \end{bmatrix} \tag{A4-23}$$

where  $R$  is the rotation matrix:

$$R = \begin{bmatrix} -\sin \varphi \cos \lambda & -\sin \varphi \sin \lambda & \cos \varphi \\ -\sin \lambda & \cos \lambda & 0 \\ \cos \varphi \cos \lambda & \cos \varphi \sin \lambda & \sin \varphi \end{bmatrix} \tag{A4-24}$$

where  $\varphi$  = geodetic latitude of the GPS antenna, and  $\lambda$  = geodetic longitude of the GPS antenna.

The *DOP factors* (dilution of precision) are given by:

$$\begin{aligned}VDOP &= \sigma_u \\HDOP &= \sqrt{\sigma_n^2 + \sigma_e^2} \\PDOP &= \sqrt{\sigma_n^2 + \sigma_e^2 + \sigma_u^2} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} \\TDOP &= \sigma_t \\GDOP &= \sqrt{\sigma_n^2 + \sigma_e^2 + \sigma_u^2 + \sigma_t^2}\end{aligned}\tag{A4-25}$$

## GPS Data Differencing Equations

The GPS satellite-to-receiver range measurements are characterized as:

1. Pseudorange measurements (refer to Eq. 2-6, Chapter 2)
  - i. Geometric range + clock offset + biases + noise
  - ii. Low accuracy but absolute measurements
2. Phase measurements (refer to Eq. 2-7, Chapter 2)
  - i. Geometric range + clock offset – initial ambiguity + biases + noise
  - ii. Very accurate measurements but ambiguous

These are the basic GPS observables (ranging equations). To improve accuracy, new equations are formed by differencing these basic ranging equations. Differencing is the most effective strategy for eliminating or significantly reducing the biases in GPS observations (refer to Table 3-1 in Chapter 3). It can be done for pseudorange as well as carrier phase measurements, although it is most commonly applied in carrier phase measurements. A unique mathematical operator is used for each strategy as shown in Table A5-1.

The following differenced observables are obtained using the observation equation for carrier phase measurements (Eq. 2-7):

### Between-Satellite Differences

Given two simultaneous phase observations from two satellites ( $s1$  and  $s2$ ) to one receiver ( $r$ ), the between-satellite difference is obtained as:

$$\begin{aligned} \nabla\Phi &= \Phi_r^{s1} - \Phi_r^{s2} \\ \nabla\Phi &= \nabla\rho + c\nabla dt - \nabla d_{ion} + \nabla d_{trop} - \lambda\nabla N \end{aligned} \tag{A5-1}$$

where

$$\begin{aligned} \Phi_r^{s1} &= \rho_r^{s1} + c(dt^{s1} - dT_r) - d_{ion}^{s1} + d_{trop}^{s1} - \lambda N_r^{s1} + (\text{Residual Biases} + \text{Noise}) \\ \Phi_r^{s2} &= \rho_r^{s2} + c(dt^{s2} - dT_r) - d_{ion}^{s2} + d_{trop}^{s2} - \lambda N_r^{s2} + (\text{Residual Biases} + \text{Noise}) \end{aligned} \tag{A5-2}$$

**Table A5-1.** GPS Data Differencing Methods

<i>Differencing Method</i>	<i>Strategy</i>	<i>Mathematical Operator</i>
Single differencing	Between-satellite	$\nabla$
	Between-receiver	$\Delta$
	Between-epoch	$\delta$
Double differencing	Between-satellite difference followed by between-receiver, or vice versa	$\Delta\nabla$
Triple differencing	Difference two double differences between epochs	$\delta\Delta\nabla$

### Between-Receiver Differences

Given two simultaneous phase observations from one satellite ( $s$ ) to two receivers ( $r1$  and  $r2$ ), the between-receiver difference is obtained as:

$$\begin{aligned}\Delta\Phi &= \Phi_{r1}^s - \Phi_{r2}^s \\ \Delta\Phi &= \Delta\rho - c\Delta dT - \Delta d_{ion} + \Delta d_{trop} - \lambda\Delta N\end{aligned}\quad (\text{A5-3})$$

where

$\Delta d_{ion} \approx 0$  and  $\Delta d_{trop} \approx 0$  (if baseline is short)

$$\begin{aligned}\Phi_{r1}^s &= \rho_{r1}^s + c(dt^s - dT_{r1}) - d_{ion}^s + d_{trop}^s - \lambda N_{r1}^s + \\ &\quad (\text{Residual Biases} + \text{Noise})\end{aligned}\quad (\text{A5-4})$$

$$\begin{aligned}\Phi_{r2}^s &= \rho_{r2}^s + c(dt^s - dT_{r2}) - d_{ion}^s + d_{trop}^s - \lambda N_{r2}^s + \\ &\quad (\text{Residual Biases} + \text{Noise})\end{aligned}$$

### Between-Epoch Differences

Given phase observations from one satellite ( $s$ ) to one receiver ( $r$ ) at two different epochs ( $t_1$  and  $t_2$ ), the between-epoch difference is obtained as:

$$\begin{aligned}\delta\Phi &= \Phi_r^s(t_2) - \Phi_r^s(t_1) \\ \delta\Phi &= \delta\rho + c(\delta dt^s - \delta dT_r) - \delta d_{ion} + \delta d_{trop}\end{aligned}\quad (\text{A5-5})$$

where

$\delta d_{ion} \approx 0$  and  $\delta d_{trop} \approx 0$  (if epoch separation is short)

$$\Phi_r^s(t_1) = \rho_r^s(t_1) + c(dt^s(t_1) - dT_r(t_1)) - d_{ion}^s(t_1) + d_{trop}^s(t_1) - \lambda N_r^s(t_1) + \dots \quad (\text{A5-6})$$

$$\Phi_r^s(t_2) = \rho_r^s(t_2) + c(dt^s(t_2) - dT_r(t_2)) - d_{ion}^s(t_2) + d_{trop}^s(t_2) - \lambda N_r^s(t_2) + \dots$$

## Receiver–Satellite Double Differences

Double differences are obtained by the between-satellite difference followed by the between-receiver difference, or vice versa:

$$\begin{aligned}\Delta\nabla\Phi &= (\Phi_{r1}^{s1} - \Phi_{r1}^{s2}) - (\Phi_{r2}^{s1} - \Phi_{r2}^{s2}) \\ \Delta\nabla\Phi &= \Delta\nabla\rho - \Delta\nabla d_{ion} + \Delta\nabla d_{trop} - \lambda\Delta\nabla N\end{aligned}\quad (A5-7)$$

where

$$\Delta\nabla d_{ion} \approx 0 \text{ and } \Delta\nabla d_{trop} \approx 0 \text{ (if baseline is short)}$$

## Triple Difference Observable

Triple differencing is useful for preliminary baseline computations using carrier phase data and for cycle slip detection or repair. Triple differences are obtained by differencing two double differences between epochs:

$$\delta\Delta\nabla\Phi = \delta\Delta\nabla\rho - \delta\Delta\nabla d_{ion} + \delta\Delta\nabla d_{trop}\quad (A5-8)$$

where

$$\delta\Delta\nabla d_{ion} \approx 0 \text{ and } \delta\Delta\nabla d_{trop} \approx 0 \text{ (if baseline is short)}$$



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# Datum Transformations and Map Projections

## Horizontal Datums

There are many different datums in use to express coordinates (Table A6-1). A *horizontal datum* is defined when points are positioned with reference to a particular ellipsoid the shape and size of which are known, and also its position and orientation relative to the Earth's surface. The simplest datum is an Earth-centered, Earth-fixed (ECEF) Cartesian datum, the origin of which is the center of mass of the Earth. The position and orientation of an ellipsoid are defined in the datum point, a physical point located on the Earth's surface.

Using an incorrect datum to express coordinates can result in position errors of hundreds of meters. Different countries, agencies, and applications use different datums. Great care must be taken to ensure that coordinates are associated with the correct datum.

## Datum Transformation

With the common use of GPS nowadays, there are instances when converting coordinates from one datum to another is necessary. Datum transformations vary from the straightforward three-parameter transformation to a complicated, multiple-step, seven-parameter transformation with 14-term adjustment. Seven-parameter transformations are most commonly used.

### ***Three-Parameter Transformation***

Three-parameter conversion translates latitude, longitude, and height on one datum to ECEF X-Y-Z coordinates, followed by an origin shift and reconversion into latitude, longitude, and height on the other datum. This method is crude and applies to small areas. The three shift parameters represent a shift between the centers of two ellipsoid datums.

**Table A6-1.** Some of the Datums Used Worldwide

<i>Reference Ellipsoid</i>	<i>Associated Datum</i>	<i>Semi-Major Axis (a)</i> <i>(in meters)</i>	<i>Flattening (f)</i>
Airy	OSGB36, OSGB(SN)70	6,377,563.396	1/299.3249646
International	ED50	6,378,388.000	1/297
GRS 80	WGS-84	6,378,137.000	1/298.257223563
GRS 80	NAD 83	6,378,137.000	1/298.257222101
Clarke 1866	NAD 27	6,378,206.400	1/294.978698214
Clarke 1880	LIBERIA, 1964	6,378,249.145	1/293.465

### Seven-Parameter Transformation

A seven-parameter transformation uses the same principle—an ECEF origin shift—but adds rotation along all three axes and a scale correction.

When two datums share the same origin and orientation of axes but different ellipsoid parameters, such as NAD 83 and WGS-84, the transformation of coordinates from one datum to the other may be accomplished using the form:

$$\begin{bmatrix} \phi \\ \lambda \\ h \end{bmatrix}_{D1} \leftrightarrow \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \leftrightarrow \begin{bmatrix} \phi \\ \lambda \\ h \end{bmatrix}_{D2} \quad (\text{A6-1})$$

Where the origin, orientation, and ellipsoids differ, the following general form is used:

$$\begin{bmatrix} \phi \\ \lambda \\ h \end{bmatrix}_{D1} \leftrightarrow \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{D2} \xleftarrow{\text{Seven-Parameter Transformation}} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{D2} \leftrightarrow \begin{bmatrix} \phi \\ \lambda \\ h \end{bmatrix}_{D2} \quad (\text{A6-2})$$

With the rotation angles in radians and translation in meters, the formula for the transformation becomes:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{D2} = \begin{bmatrix} dX \\ dY \\ dZ \end{bmatrix} + (1+S) \begin{bmatrix} 1 & -Rz & Ry \\ Rz & 1 & -Rx \\ -Ry & Rx & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{D1} \quad (\text{A6-3})$$

where  $S$  is the scale correction, and  $R_x$ ,  $R_y$ , and  $R_z$  are the differential rotation angles about the first, second, and third axes, respectively (if applied in reversed order, the signs of the parameters change). The typical effect of a datum shift ( $dX$ ,  $dY$ ,  $dZ$ ) is that a best fit is achieved for a limited area only.

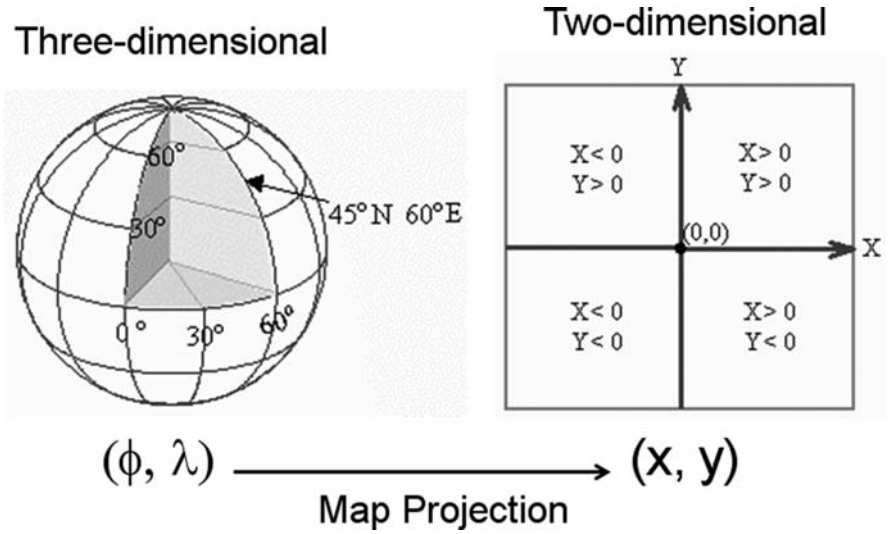
### Map Projection

Geodetic coordinates (latitude and longitude on an ellipsoidal model of the Earth) are three-dimensional, but maps and GIS software necessitate that mapped information be displayed in two dimensions. A *map projection* is used to transform mapped information from three to two dimensions, by “projecting” it from an ellipsoid to a flat surface (Fig. A6-1). Projections can be carried out in a variety of ways. Whatever the method, projecting from the ellipsoid to a flat surface cannot be done without introducing some distortion in the resultant map coordinates. Because of this effect, there is the concept of grid scale factor in map projections (Fig. A6-2). Map projections are commonly categorized into three types based upon the idea of the projection surface used: planar (or azimuthal), conical, and cylindrical.

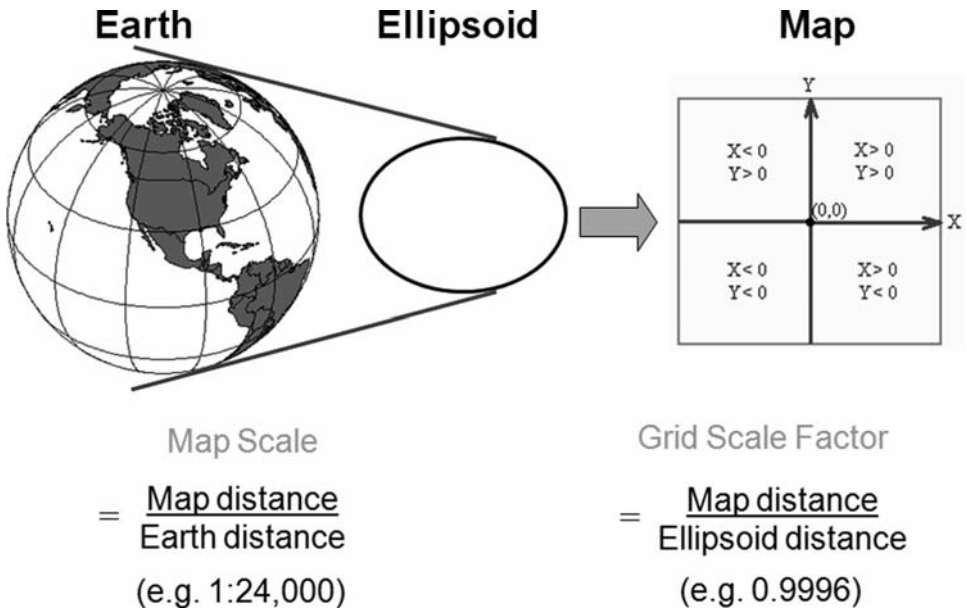
### Calculating Map Grid Coordinates

In map projections such as Universal Transverse Mercator (UTM) and State Plane Coordinate System (SPCS), distances and geodetic azimuths between points on the ground surface are reduced to the ellipsoid surface and then to the map projection surface. The projection grid coordinates of a new point relative to another point with known projection grid coordinates can be computed as follows:

$$\begin{aligned}
 N_{2(grid)} &= N_{1(grid)} + D_{grid} \cos \alpha_{grid} \\
 E_{2(grid)} &= E_{1(grid)} + D_{grid} \sin \alpha_{grid}
 \end{aligned}
 \tag{A6-4}$$



**Figure A6-1.** Map projections make it possible to map the three-dimensional world in two dimensions.



**Figure A6-2.** Terminology in the map projection process.

where  $D_{\text{grid}}$  and  $\alpha_{\text{grid}}$  are the grid distance and grid azimuth, respectively. If the following information is also available,

- $D$  = measured horizontal distance at ground level
- $h$  = ellipsoidal height (mean of values at the two points)
- $R$  = mean Earth radius
- $k$  = grid scale factor (mean of values at the two points)
- $\alpha$  = geodetic azimuth
- $\gamma$  = mapping angle,

then  $D_{\text{grid}}$  and  $\alpha_{\text{grid}}$  in Eq. A6-4 can be computed as follows:

$$S = D[R/(R + h)] = \text{geodetic distance (i.e., distance on the ellipsoid)}$$

$$D_{\text{grid}} = S (\text{geodetic distance}) \times k (\text{grid scale factor})$$

$$\alpha_{\text{grid}} = \alpha (\text{geodetic azimuth}) - \gamma (\text{mapping angle})$$

The convention of the sign of the mapping angle is from grid to geodetic.

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## Glossary

**Almanac**—A data file that contains orbit information on all satellites, clock corrections, and atmospheric delay parameters. Each GPS transmits almanac data in order to facilitate rapid satellite acquisition (tracking) by GPS receivers.

**Ambiguity**—The unknown number of whole carrier wavelengths (cycles) between a GPS satellite and the receiver.

**Ambiguity Resolution (AR)**—The mathematical process for determining the integer value for the cycle ambiguity of the carrier phase data. It is the key to fast and high-precision relative GPS positioning. If the initial integer ambiguity value for each satellite-receiver pair could be determined, then the ambiguous carrier phase measurement can be corrected to create an unambiguous and precise (millimeter accuracy) receiver-satellite distance measurement. A solution for the receiver position using the corrected carrier phase observations is known as an “ambiguity-fixed” or “bias-fixed” solution. In practice, the AR process and the ambiguity-fixed solutions are carried out on the double differenced carrier phase observables, not on the one-way satellite-receiver measurements. The process is called “On-the-Fly” AR if it occurs while the receiver is in motion.

**Anti-Spoofing (AS)**—A method implemented in GPS technology, by the U.S. Department of Defense, to deny non-U.S. military users P-code (precise code) signal, which is modulated on L1 and L2 frequencies. The AS was implemented on January 31, 1994, by the encryption of the P-code to form the Y-code. By keeping the P-code encrypted, an enemy of the U.S. could not jam the satellite signal through ground-based transmitters, nor “spooF” military GPS receivers by transmitting a false P-code signal from a satellite. The encrypted code needs a special AS-module for each receiving channel and is only accessible for authorized personnel in possession of a special key.

**Assisted-GPS (A-GPS)**—A system that uses network resources such as cellular phone networks to aid GPS positioning especially under poor signal conditions. It is used extensively with GPS-capable cellular phones.

**Baseline**—A baseline consists of a pair of stations for which simultaneous GPS data have been collected. It is mathematically expressed as a vector of coordinate differences between the two stations, or an expression of the coordinates

of one station with respect to the other (whose coordinates are assumed known, and is typically referred to as a “base” or “reference” station).

**Base Station**—A base station (or reference station) is a GPS receiver set up on a location with a known position specifically to collect data for differentially correcting data files of another receiver (which may be referred to as the “rover” receiver).

**Bluetooth**—A proprietary open wireless technology standard for exchanging data over short distances (using short-wavelength radio transmissions) from fixed and mobile devices. It was created as a wireless alternative to RS-232 data cables.

**C/A-Code**—The standard (Coarse Acquisition) GPS pseudo random noise (PRN) code, modulated on the L1 carrier signal. Used by the GPS receiver to acquire and decode the L1 satellite signal, and from which the L1 pseudorange measurement is made.

**Carrier**—A radio wave having at least one characteristic, such as frequency, amplitude, or phase, that may be varied from a known reference value by modulation.

**Carrier Phase**—GPS measurements based on the L1, L2, or L5 carrier signal.

**Carrier Phase Observable**—The fractional part of the carrier wavelength (approximately 19 cm for L1, 24 cm for L2), expressed in units of meters, cycles, or fractions of a wavelength or angle. In carrier phase-based positioning, such as is employed in GPS surveying techniques, carrier phase observable may also refer to the accumulated or integrated measurement that consists of the fractional part plus the whole number of wavelengths (or cycles) since signal lock-on.

**Channel**—A channel of a GPS receiver consists of the circuitry necessary to receive a single frequency from a single GPS satellite.

**Chip Rate**—Number of chips per second. For example, C/A code = 1.023 MHz.

**Clock Bias**—The difference between the clock’s indicated time and the true universal time.

**Code Division Multiple Access (CDMA)**—A method of frequency reuse whereby many radios use the same frequency channel but each one has a unique code. GPS uses CDMA techniques with PRN codes for cross-correlation.

**Code Phase**—GPS measurements based on the pseudo random code as opposed to the carrier of that code.

**Continuously Operating Reference Stations (CORS)**—A system of GPS base stations that originated from stations built to support air and marine navigation with real-time differential GPS correction signals. Networks of permanently constructed base stations with telemetry link to allow for data access and download for immediate or future use (analysis and/or archiving) have proliferated worldwide. They are built, operated, and maintained at various levels (regional, national, or global) by different organizations and government agencies such as NOAA.

**CORS Control**—A network of Continuously Operating Reference Stations (CORS) that provide Global Navigation Satellite System (GNSS) data consisting of carrier phase and code range measurements in support of three-dimensional positioning. Surveyors, engineers, scientists, and the public at large collecting GPS data can use CORS data to improve the precision of their positions.

**Coordinate System**—One of a number of mapping systems used to represent positions, such as geocentric Cartesian coordinates ( $X, Y, Z$ ), geodetic coordinates (geodetic latitude  $\phi$ , geodetic longitude  $\delta$ , and height above or below the ellipsoid surface,  $h$ ), and local geodetic horizon coordinates (east,  $e$ , north,  $n$ , and/or up,  $u$ ).

**Datum**—A datum is a horizontal or vertical reference system for making survey measurements and computations. A horizontal datum is defined using a mathematical figure such as an ellipsoid. A vertical datum is defined relative to the mean sea level.

**Differencing**—A mathematical technique of differencing between two GPS observables.

**Differential GPS**—A method that improves GPS positioning or navigation accuracy using pseudorange corrections (also referred to as differential corrections). Differential corrections measured at a base station with known position are incorporated (by real time transmission of corrections or by post processing) into the position calculations of other receivers operating in the same area and simultaneously tracking the same satellites. The term *differential GPS* is sometimes used to describe relative positioning (i.e., a measurement to determine the relative position of two receivers tracking the same satellites, irrespective of whether it is by code or carrier phase).

**Distance Root Mean Square (DRMS)**—The root mean square value of the distances from the true location point of the position fixes in a collection of measurements. As typically used in GPS positioning, 2DRMS is the radius of a circle that contains at least 95% of all possible fixes that can be obtained with a system.

**Dual-Frequency**—Term used for GPS receivers that can receive and process two carrier signals (e.g., both the L1 and L2 frequency signals).

**Elevation**—The orthometric height above a point of reference. For example, height above mean sea level or the vertical distance above or below the geoid.

**Ellipsoid**—A mathematical figure formed by revolving an ellipse about its minor axis. Two quantities define an ellipsoid, the length of the semi-major axis,  $a$ , and the flattening,  $f$ .

**Ephemeris**—The predictions of current satellite positions transmitted to the user in the data message; a list of locations of a celestial object as a function of time. Ephemeris errors are caused when GPS message does not transmit the correct satellite location (that is, the predicted satellite position is different from the actual position).

**Epoch**—Measurement interval or data frequency (for example, making one observation per second).

**Equipotential Surface**—A surface having constant gravity potential. Equipotential surfaces are also known as *level surfaces* or *geopotential surfaces*. A still lake surface is an equipotential surface. The geoid is also an equipotential surface.

**Frequency Division Multiple Access (FDMA)**—A channel access method that gives users an individual allocation of one or several frequency bands, or channels. GLONASS uses FDMA techniques in which the satellites transmit using the same codes, but at slightly different frequencies.



- Gain**—The *gain*, or *gain pattern*, of a GPS antenna refers to its ability to convert GPS radio waves into electrical energy. During signal reception, the GPS antenna gain describes how well the antenna converts radio waves arriving from a specified direction into electrical power. A plot of the gain as a function of direction describes the *gain pattern*. When no direction is specified, gain refers to the peak value of the gain.
- Geoid**—The equipotential surface of the earth's gravity field that best fits, in a least squares sense, the mean sea level. The geoid surface is everywhere perpendicular to the force of gravity.
- Georeferenced Control**—A project control point or network whose coordinates are defined in an absolute coordinate system such as World Geodetic System 1984 (WGS-84).
- Global Navigation Satellite Systems (GNSS)**—A system of satellites that provide autonomous positioning with global coverage. The term encompasses all the major worldwide satellite navigation systems including GPS, the Russian GLONASS, the European Galileo, and China's Compass/BeiDou.
- Inertial Navigation System (INS)**—A navigation aid that uses a computer, motion sensors (accelerometers) and rotation sensors (gyroscopes) to continuously calculate via dead reckoning the position, orientation, and velocity (direction and speed of movement) of a moving object without the need for external references. It is used on vehicles such as ships, aircraft, submarines, guided missiles, and spacecraft.
- International Terrestrial Reference Frame (ITRF)**—The ITRF is derived from the combined analysis of GPS, SLR, VLBI, and DORIS data. The ITRF is, by agreement between the United States and the European Union, the international reference standard for both GPS and the future GALILEO satellite system.
- L1 Frequency**—The 1,575.42 MHz GPS carrier frequency that contains the C/A-Code, the encrypted P-Code (or Y-Code), and the navigation message.
- L2 Frequency**—The 1,227.60 MHz GPS carrier frequency that contains the encrypted P-Code (or Y-Code) and the navigation message. Military Y-Code-capable receivers can, in addition to making L1 measurements, make pseudo-range measurements on the L2 carrier.
- L5 Frequency**—The 1,176.45 MHz GPS carrier frequency that contains the safety-of-life civilian signal, to be implemented with the GPS IIF satellites.
- L-Band**—The group of radio frequencies extending from 390 MHz to 1,550 MHz.
- Least-Squares Adjustment**—A statistical approach to finding the most probable result from a number of values. This is the principle underlying the fact that a receiver needs to observe at least four satellites (i.e., four unknowns) to be able to estimate its position coordinates and clock bias.
- Mean Radial Spherical Error (MRSE)**—This is a 3-D statistical measure that corresponds to DRMS in 2-D. It is the radius of a sphere centered at the true position, containing at least 61% of possible position fixes that can be obtained in 3-D.
- Nanosecond**—One billionth of a second.

**NMEA 0183 Protocol**—A standard for transmitting navigational messages, developed by the Nautical and Marine Electronics Association (NMEA).

**Observables**—GPS measurements based on the C/A-code and carrier signals. In code phase-based positioning, it refers to the measured (“observed”) receiver-satellite range expressed in terms of the true geometric range and modeled errors (such as satellite and receiver clock errors, satellite orbit errors, atmospheric errors, multipath, and receiver noise). In carrier phase, it refers to the fractional part of the carrier wavelength expressed in units of meters, cycles, or fractions of a wavelength or angle; it is also expressed in terms of the true geometric range, ambiguity, and modeled errors.

**On-the-Fly (OTF)**—Method of solving for the carrier phase ambiguity very quickly, making the technique applicable to moving objects such as vessels and aircraft.

**Orthometric Height**—Height from a point to the geoid as determined with, for example, level instruments.

**Outlier**—Data considered to be more than a predetermined number of the standard deviations from the most probable value or mean.

**Phase Center/Phase Center Offset**—Antenna *phase center* is the electrical center of the antenna as opposed to the geometrical or physical center. *Phase center offset* is the difference between the antenna physical reference point and its phase center. The location of an antenna phase center changes slightly with the satellite’s signal. For example, it is different for L2 than L1. In addition, as the azimuth, intensity, and elevation of the received signal changes, so does the phase center offset.

**Position Dilution of Precision (PDOP)**—In satellite positioning, dilution of precision (DOP) is an indication of the geometric strength of the configuration of satellites in a particular constellation at a particular instant, and can be used to predict the quality of results that can be expected. A high DOP value such as 11 means low quality results expected and a low DOP value such as 3 means good position results expected. The various categories of DOPs include PDOP (for three coordinates), GDOP (for three coordinates and clock offset), HDOP (for two horizontal coordinates), VDOP (for vertical coordinate, or height), and TDOP (for time only, or clock offset).

**Point Positioning**—A positioning method using only a single receiver. It is also commonly referred to as *absolute positioning* since the receiver position coordinates are defined by an absolute coordinate system such as WGS-84. This method is common in handheld receivers and navigators for real-time navigation. There is also precise point positioning which is realized by post-processing. In the post-processed mode, corrections are applied using precise clocks and precise orbits.

**Pseudolite**—Contraction of the term “pseudo-satellite”; a ground-based transmitter that mimics a GPS satellite.

**Pseudo Random Noise (PRN)**—A sequence of digital zeros and ones that appear to be randomly distributed like noise but that can be reproduced exactly. Their most important property is a low autocorrelation value for all delays or

lags except when they coincide exactly. Each GPS satellite has a unique C/A- and P-PRN code.

**Pseudorange**—A distance measurement based on the correlation of a satellite-transmitted code and the local receiver's reference code.

**P(Y)-Code**—The precise or protected code. A very long sequence of PRN binary biphasic modulations on the GPS L1 and L2 carrier at a chip rate of 10.23 MHz, which repeats about every 267 days. Each 1-week segment of this code is unique to a GPS satellite and is reset each week. Under the policy of "anti-spoofing," the U.S. Department of Defense has encrypted the P-Code (replacing it with a so-called Y-Code). Only U.S. military and authorized users can overcome anti-spoofing using special receivers.

**Radio Technical Committee for Maritime Services (RTCM)**—RTCM Special Committee 104 has developed standard message types for use by differential GPS (DGPS) transmitting stations. The message content has been defined and, hence, when the RTCM-104 standard is implemented within a user receiver, it is able to decode and apply the DGPS corrections to its raw data in order to generate a DGPS-corrected coordinate.

**Ranging Principle**—A procedure or methodology for determination of the distance or "range" between a satellite and a receiver. This involves the estimation of signal travel time from the time of transmission to the time of reception. The timing process requires two clocks, one at the satellite and another at the receiver, since the signal travels only one way. In pseudorange, it is commonly accomplished by correlation of PRN codes.

**Receiver Independent Exchange (RINEX)**—A set of standard definitions and formats that permits interchangeable use of GPS data from dissimilar receiver models or post processing software. The format includes definitions for time, phase, and range among other parameters.

**Real-Time Network (RTN)**—Also known as Network RTK, RTN deploys a network of reference stations and, using both carrier phase and pseudorange observables, models the distance-dependent errors and transmits corrections for them to the rover, enabling it to compute precise single- and multiple-baseline solutions. It comprises a regional network of CORS, some kind of central processing facility, and communications media to transfer data from the network to the user. The data can be transmitted via cellular phones, dedicated ground radio transmitters, communication satellites, or the Internet. The method provides cm-accuracy in real-time at baseline lengths of up to 300 km (thus extending the range beyond that of typical RTK positioning).

**Relative Positioning**—The process of determining the relative difference in position between two locations by placing a receiver over each site and making simultaneous measurements observing the same set of satellites at the same time. This method allows for cancellation of errors that are common to both receivers, such as satellite clock and ephemeris errors, atmospheric delays, and so forth.

**Root-Mean-Square (RMS)**—A measure used to quantify precision. It is the square root of the mean of the squared errors.

- RS-232**—A standard type of connection to a computer. It is a serial port that allows communication between a computer and a receiver.
- Selective Availability (SA)**—A U.S. Department of Defense program that was used to control the accuracy of pseudorange measurements, degrading the signal available to nonqualified receivers by dithering the time and ephemeris data provided in the navigation message. The highest-quality signal was reserved for military use and the signal available for civilian use was intentionally degraded by SA. SA was activated on March 25, 1990 and was removed on May 1, 2000.
- Single-Frequency**—Term used for GPS receivers that can receive and process only one carrier signal (e.g., the L1 or L2 frequency signal).
- Total Station**—An electronic theodolite (transit) integrated with an electronic distance meter (EDM) to read slope distances from the instrument to a particular point.
- Universal Transverse Mercator (UTM)**—A global map projection coordinate system developed by the U.S. military. It uses transverse mercator projection and divides the entire Earth into 60 zones. Each UTM zone is 60 deg wide and goes from pole to pole.
- Virtual Reference Station (VRS)**—A type of RTN method for extending the use of RTK positioning by using a two-way communication link.
- VRS Network Solution**—In order to provide a differential positioning service for a larger area, several reference stations have to be set up. In a VRS, the observations of a network of stations are pre-processed in order to generate models of the distance-dependent biases. Based on these modeled biases and the user's approximate position, individual corrections of a VRS can be predicted to enable differential positioning. VRS users send data and their approximate positions to the control and processing center. The control center returns corrections for an individual VRS, via the RTCM format, and then the baseline processing software inside the rover calculates its position using the VRS. The VRS acts as a single nearby reference station.
- Wide area RTK (WARTK)**—An RTK positioning method using a distributed network of reference stations communicating with a control center to calculate GPS error corrections over a wide area. Real-time correction data are transmitted by radio or cellular modem to the users within the network area.
- World Geodetic System 1984 (WGS-84)**—The mathematical ellipsoid used by GPS since January 1987. It is realized by the geodetic coordinates of a network of the U.S. Air Force and the National Geospatial-Intelligence Agency (NGA) tracking stations. These coordinates are derived solely from GPS signals. Utilizing GPS data from a large number of independent, globally distributed International GNSS Service (IGS) tracking stations whose International Terrestrial Reference Frame (ITRF) coordinates are known and constrained, the NGA solves for the GPS station coordinates. This, along with the adoption of common standards for physical constants and models, forces the alignment of WGS-84 with the ITRF. The NGA periodically recomputes the station coordinates to maintain centimeter-level alignment of the WGS-84 reference frame with the ITRF.

The absolute positions obtained directly from GPS pseudorange measurements are based on the 3-D WGS-84 ellipsoid. Cartesian coordinate outputs are on a rectangular coordinate system having the same origin as the WGS-84 ellipsoid, that is, geocentric. This geocentric X-Y-Z coordinate should not be confused with the X-Y (Easting-Northing) plane coordinates established on local grids (refer to Appendix 6). WGS-84 geocentric Cartesian coordinates can be easily converted into WGS-84 ellipsoidal coordinates (latitude, longitude, and ellipsoidal height). It is critical to note that the WGS-84 ellipsoidal height ( $h$ ) is not the orthometric elevation used in most civil works and engineering projects.

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## Acronyms and Abbreviations

$\mu\text{s}$	Microsecond
1-D	One-dimensional
2-D	Two-dimensional
3-D	Three-dimensional
ABET	Accreditation Board for Engineering and Technology
A-GPS	Assisted-GPS
AMG	Automated machine guidance
APPS	Automatic Precise Positioning Service
AR	Ambiguity resolution
ARP	Antenna reference point
ASCE	American Society of Civil Engineers
AUSPOS	Australian Online GPS Processing Service
C/A	Coarse acquisition
CEP	Circular error probability
CIO	Celestial International Origin
CORS	Continuously operating reference stations
CSRS	Canadian Spatial Reference System
CTS	Conventional Terrestrial System
CWAAS	Canadian Wide Area Augmentation System
dBW	Decibel-Watt
DGPS	Differential GPS
DOD	U.S. Department of Defense
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
ECEF	Earth-centered, Earth-fixed
EDM	Electronic distance measurement
EGNOS	European Geostationary Navigation Overlay Service
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FOS	Fiberoptic sensor
GAGAN	GPS Aided Geo Augmented Navigation
GBAS	Ground-based augmentation system
GDA	Geocentric Datum of Australia

GDGPS	Global Differential GPS
GEONET	GPS Earth Observation Network
GHz	Gigahertz
GIS	Geographic information system
GNSS	Global Navigation Satellite Systems
GPS	Global positioning system
GSM	Global System for Mobile Communications
HPGPS	High-precision GPS
IGS	International GNSS Service
IMU	Inertial measurement unit
INS	Inertial navigation system
ITRF	International Terrestrial Reference Frame
ITRS	International Terrestrial Reference System
km	Kilometer
LAAS	Local area augmentation system
LADGPS	Local area differential GPS
LEO	Low Earth orbit
LLH	Latitude longitude height
LOS	Line-of-sight
LVDT	Linear variable differential transformer
MCS	Master Control Station
MEMS	Microelectromechanical system
MEO	Medium Earth orbit
MHz	Megahertz
mi.	Mile
MSAS	Japanese MTSAT Satellite-Based Augmentation System
NAD	North American Datum
NDGPS	Nationwide Differential GPS
NGA	National Geospatial-Intelligence Agency
NGS	National Geodetic Survey
NMEA	National Marine Electronics Association
nmi/h	Nautical mile per hour
OEM	Original equipment manufacturer
OPUS	Online Positioning User Service
OTF	On-the-fly
PCO	Phase center offset
PCV	Phase center variation
PDOP	Position dilution of precision
PND	Personal navigation device
ppm	Part per million
PPP	Precise point positioning
PRN	Pseudo random noise
RF	Radio frequency
RHCP	Right-hand circular polarized
RINEX	Receiver INdependent EXchange

RMS	Root mean square
RS-232	Recommended Standard-232
RTCM	Radio Technical Commission for Maritime Services
RTK	Real-time kinematic
RTN	Real-time network
SBAS	Satellite-based augmentation system
SCIGN	Southern California Integrated GPS Network
SCOUT	Scripps Coordinate Update Tool
SEP	Spherical error probability
SLR	Satellite laser ranging
SPCS	State Plane Coordinate System
TDOA	Time difference of arrival
TOA	Time of arrival
TOD	Time of departure
UHF	Ultra high frequency
USCG	United States Coast Guard
UTM	Universal Transverse Mercator
VHF	Very high frequency
VLBI	Very long baseline interferometry
VRS	Virtual reference station
WAAS	Wide area augmentation system
WADGPS	Wide area differential GPS
WARTK	Wide area RTK
WGS	World Geodetic System



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## About the Author

Clement A. Ogaja, Ph.D., L.S., is an Assistant Professor in the Department of Civil and Geomatics Engineering, California State University–Fresno, where he teaches GPS theory and project design. His research focuses on the civilian applications of GPS/GNSS and satellite geodesy. A native of Kenya, he did his undergraduate work in surveying at the University of Nairobi, earning his Bachelor of Science with First Class Honors in 1997. He worked as a land surveyor at Aerophoto Systems Engineering Company from 1997 to 1998. In 1999, he joined the Satellite Navigation and Positioning Group at the University of New South Wales (UNSW) in Sydney, Australia, where he subsequently earned his Ph.D. in Geomatics Engineering, with a research focus on GPS applications. After graduating from UNSW in 2002, he joined the Geoscience Australia Space Geodesy Group, where he worked for four years. In 2007 he joined the faculty at California State University–Fresno as Assistant Professor.