GPS

GLONASS

An Introduction to GNSS

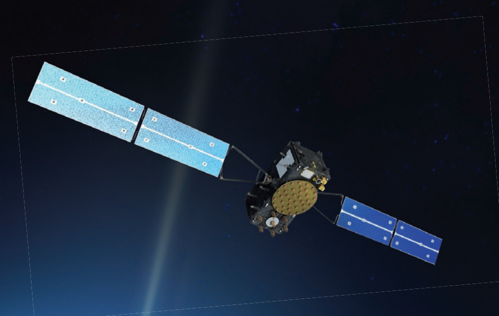
GPS, GLONASS, BeiDou, Galileo and other Global Navigation Satellite Systems

NovAtel Inc.

SECOND EDITION

BEIDOU

GALILEO



An Introduction to GNSS

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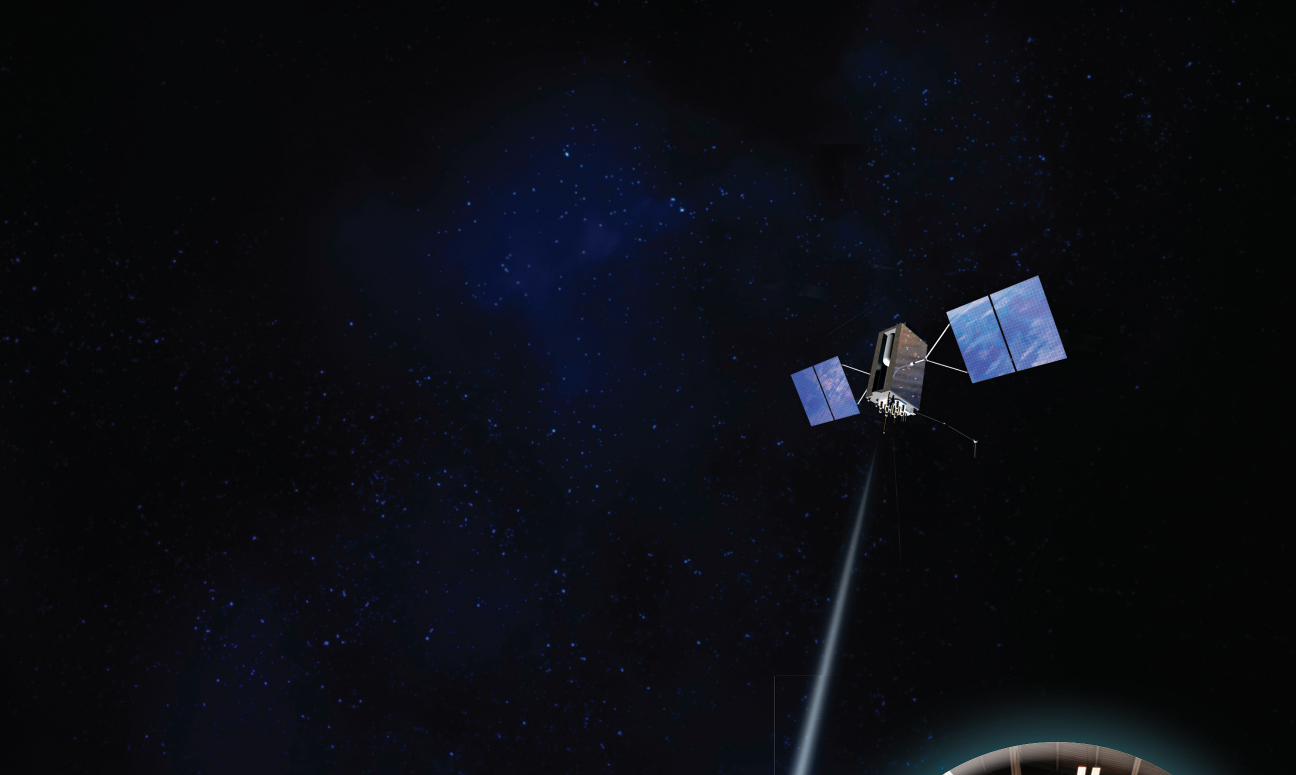
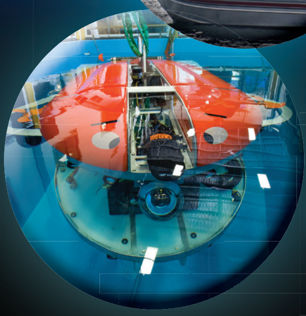
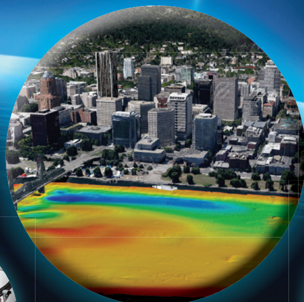
Table of Contents

List of Tables



> “Scientists dream about doing great things. Engineers do them.”
>
> **–James A. Michener**





foreword

They all laughed at Christopher Columbus When he said the world was round.[1]

Christopher Columbus wasn't the first person to propose the world was round. Far from it. By the fifth century BCE, many Greek scholars had accepted a spherical earth as fact. Around 240 BCE, Eratosthenes, a Greek mathematician, poet, athlete, geographer and astronomer—a Renaissance man—ingeniously calculated the radius of the earth with surprising accuracy.

Although Columbus knew the earth was round, he had obviously not read or agreed with Eratosthenes, for he significantly underestimated its size. He projected that heading west, the distance from the Canary Islands to Japan was 3,700 km, not 19,600 km as we now know it to be. Had Columbus known the true distance, he may have lost heart. He would certainly have had trouble convincing others to fund his first voyage or to sail with him.

Columbus navigated to the New World using dead reckoning, the technique of estimating one's current position based on a previously determined one. For example if I head west from a known location at 10 km/hr then, in two hours, I will be 20 km west of my starting point. The challenge in dead reckoning was the accurate and regular estimation of speed and heading.

A great deal of exploration was carried out at a time when positioning was not a very exact science, sometimes with dire consequences. In 1707, several ships of the Royal Navy struck the rocks near the Isles of Scilly, southwest of Cornwall, with a loss of four ships and 1,400 men. Navigational error was blamed. Although it is not certain whether the error was in the determination of longitude or latitude, the tragedy led to the Longitude Act of 1714. Through this act, the British government offered prizes for people Who

1 From "They All Laughed" by George and Ira Gershwin, a song popularized by, among others, Frank Sinatra and Ella Fitzgerald, in the 1950s.

could solve or advance the problem of accurately determining longitude, including one of £10,000 for a method that could determine longitude to within 60 nautical miles, about 111 kilometres.

Although none of the larger prizes offered by the Longitude Act were ever awarded, the initiative led to the development of many navigation techniques and equipment, including significant improvements in shipborne chronometers (clocks), then critical to the accurate determination of longitude. With the advent of radio in the early 1900s, time signals were sent to ships, which could use the signal to regularly adjust their chronometers. In the 1940s, LORAN (LOng-RANge navigation system) was introduced. This allowed ships to triangulate their position using radio signals from LORAN stations at known shore-based locations. The first satellite, Sputnik, was launched in 1957 and it was not long before scientists contemplated working back from a known satellite orbit to determine a position on earth. Many of the problems faced by earlier navigators were quickly becoming historical footnotes.

What has most significantly changed navigation techniques is the advent of Global Navigation Satellite Systems (GNSS), which started with the launch of the U.S. Department of Defense Global Positioning System (GPS) in the late 1970s. Early applications of GNSS were developed for the military and soon expanded to the survey and mapping industries—driven largely by the tremendous advances in accuracy, efficiency as well as cost reductions. Now, vehicles, whether on land, in the air or at sea—routinely rely on the precise positioning information provided by GNSS technology. In fact, the ready adoption of the technology, from mining to unmanned, and the increasingly complex requirements for positioning, anywhere, anytime, is driving innovation in the industry that includes the integration of GNSS technology with a variety of other sensors and methodologies. This multi-fusion approach is sure to drive innovation in the industry for many years to come.

The goal of this book is to present complex GNSS concepts and applications in a manner that informs without overwhelming. By the end of the book, you will understand the basics of GNSS and will have a solid foundation for further study or application.

We hope you enjoy the read.

> “The massive bulk of the earth does indeed shrink to insignificance in comparison with the size of the heavens.”
>
> –Nicolaus Copernicus

1

Chapter One

GNSS OVERVIEW

> “New ideas pass through three periods: 1) It can’t be done. 2) It probably can be done, but it’s not worth doing. 3) I knew it was a good idea all along!”
>
> –**Arthur C. Clarke,** British author, inventor and futurist.

Most of us now know that GNSS “was a good idea all along” and that we are now well into the third phase.

The basic concepts of satellite positioning are very easy to understand. They are so straightforward, in fact, that one of our employees was asked by his daughter to explain it to her grade 4 class.

Before the class started, he set up the following demonstration, his version of “string theory.” He tacked cardboard figures of three satellites to the walls and ceiling of the classroom, as shown in **Figure 1.** Each “satellite” had a length of string stapled to it. He marked a location on the floor with a movable dot, then drew the strings down and marked where they all reached the dot. The strings now represented the distances from the dot to the individual satellites. He recorded the location of the dot and removed it from the floor.

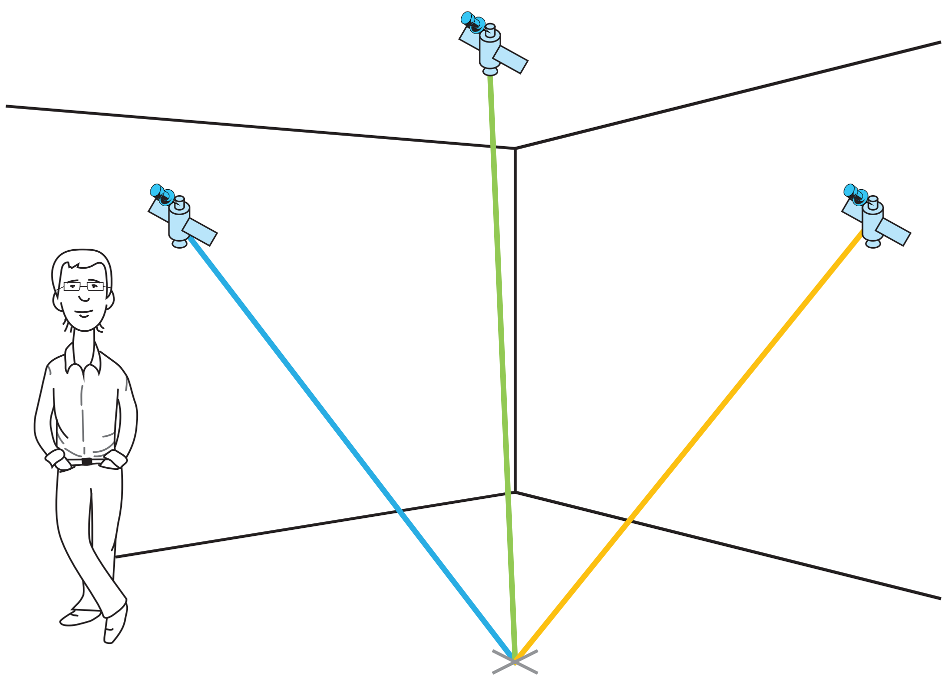


Figure 1 Classroom Demonstration of GNSS Positioning

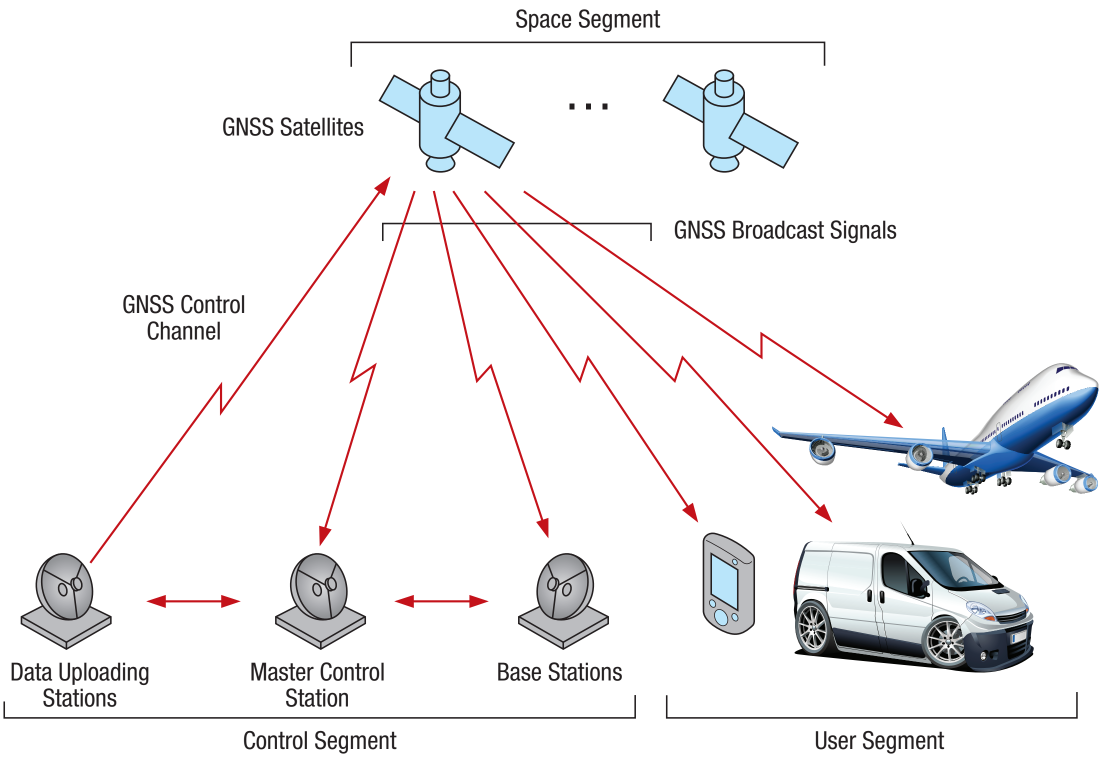


Figure 2 GNSS Segments

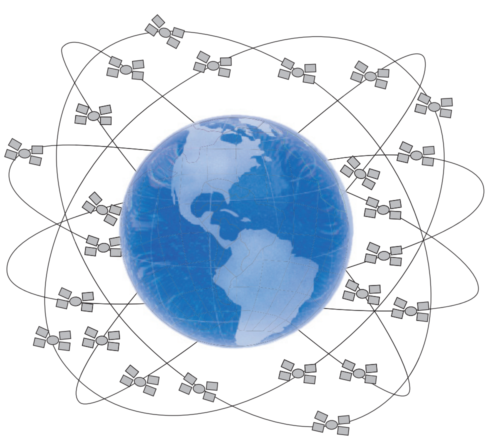


Figure 3 GNSS Satellite Orbits

> "The more you explain it, the more I don't understand it."
>
> –**Mark Twain,** American author and humorist.

When the students came into the classroom, our employee had them use the strings to determine the location. To do this, the students drew the strings down until the ends of the strings came together at one point on the floor. They marked this point with a movable dot and compared it with the previously marked position. They were very close. This simple demonstration showed that, if you know the location of three satellites and your distance from them, you can determine your position.

The determination of position is made quite a bit more complicated by several factors—the satellites are moving, the signals from the satellites are very weak by the time they reach the earth, the atmosphere interferes with the transmission of radio signals and, for cost reasons, the user equipment is not as sophisticated as the equipment in the satellites.

We agree. We will provide a more detailed explanation of position determination in Chapter 2.

GNSS SYSTEMS

Although you may already be familiar with the term "GPS" (Global Positioning System), you may not have heard the term "GNSS" (Global Navigation Satellite System), which is used to describe the collection of satellite positioning systems that are now operating or planned.

GPS (United States)

GPS was the first GNSS system. GPS was launched in the late 1970s by the United States Department of Defense. It uses a constellation of 27 satellites, and provides global coverage.

GLONASS (Russia)

GLONASS is operated by the Russian government. The GLONASS constellation consists of 24 satellites and provides global coverage.

Galileo (European Union)

Galileo is a civil GNSS system operated by the European Global Navigation Satellite Systems Agency (GSA). Galileo will use 27 satellites with the first Full Operational Capability (FOC) satellites being launched in 2014. The full constellation is planned to be deployed by 2020.

BeiDou (China)

BeiDou is the Chinese navigation satellite system. The system will consist of 35 satellites. A regional service became operational in December of 2012. BeiDou will be extended to provide global coverage by end of 2020.

IRNSS (India)

The Indian Regional Navigation Satellite System (IRNSS) provides service to India and the surrounding area. The full constellation of seven satellites is planned to be deployed by 2015.

QZSS (Japan)

QZSS is a regional navigation satellite system that provides service to Japan and the Asia-Oceania region. The QZSS system is planned to be deployed by 2018.

In Chapter 3, we will provide additional information about these systems. As GNSS constellations and satellites are added, we will be able to calculate position more accurately and in more and more places.

GNSS ARCHITECTURE

> "The future ain't what it used to be."
>
> –**Yogi Berra,** former Major League Baseball player and manager.

Mr. Berra is correct. The implementation of GNSS satellite systems has really changed things.

GNSS satellite systems consist of three major components or "segments": space segment, control segment and user segment. These are illustrated in **Figure 2.**

Space Segment

The space segment consists of GNSS satellites, orbiting about 20,000 km above the earth . Each GNSS has its own "constellation" of satellites, arranged in orbits to provide the desired coverage, as illustrated in **Figure 3.**

Each satellite in a GNSS constellation broadcasts a signal that identifies it and provides its time, orbit and status. To illustrate, consider the following. You are downtown. You call a friend. Your friend is not at home, so you leave a message:

> *This is Lori **[identity]**. The time is 1:35 p.m. **[time]**. I am at the northwest corner of 1st Avenue and 2nd Street and I am heading towards your place **[orbit]**. I am OK, but I am a bit thirsty **[status]**.*

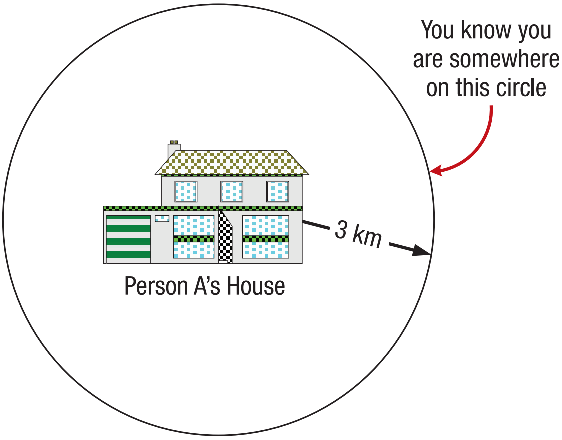


Figure 4 Illustration of Trilateration—Knowing One Distance

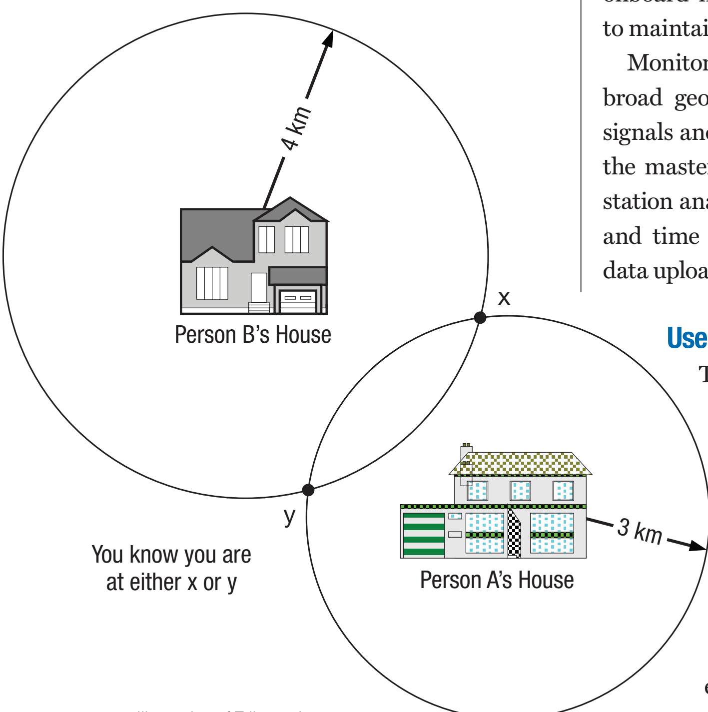


Figure 5 Illustration of Trilateration –Knowing Two Distances

Your friend returns a couple of minutes later, listens to your message and "processes" it, then calls you back and suggests you come up a slightly different way; effectively, your friend has given you an "orbit correction."

Control Segment

The control segment comprises a ground-based network of master control stations, data uploading stations and monitor stations; in the case of GPS, two master control stations (one primary and one backup), four data uploading stations and 16 monitor stations, located throughout the world.

In each GNSS system, the master control station adjusts the satellites' orbit parameters and onboard high-precision clocks when necessary to maintain accuracy.

Monitor stations, usually installed over a broad geographic area, monitor the satellites' signals and status, and relay this information to the master control station. The master control station analyses the signals then transmits orbit and time corrections to the satellites through data uploading stations.

User Segment

The user segment consists of equipment that processes the received signals from the GNSS satellites and uses them to derive and apply location and time information. The equipment ranges from smartphones and handheld receivers used by hikers, to sophisticated, specialized receivers used for high-end survey and mapping applications.

GNSS SIGNALS

GNSS radio signals are quite complex. Their frequencies are around 1.5 GHz (gigahertz)—1.5 billion cycles per second. GNSS operates at frequencies that are higher than FM radio, but lower than a microwave oven. By the time GNSS signals reach the ground, they are very, very weak. We will provide more information about how the user segment deals with this in Chapter 2.

GNSS POSITIONING

"I have never been lost, but I will admit to being confused for several weeks."

–**Daniel Boone,** American pioneer and hunter.

If you have a GNSS receiver, it is unlikely that you will ever be lost again. GNSS positioning is based on a process called "trilateration." Simply put, if you don't know your position, but do know your distance from three known points, you can trilaterate your location.

Let's say you are 3 km from Person A's house. All you know is that you are on a circle 3 km from Person A's house, as shown in **Figure 4.**

But if you also know that you are 4 km from Person B's house, you will have a much better idea of where you are, since only two places (x and y) exist on both circles, as shown in **Figure 5.**

With a third distance, you can only be in one physical location. If you are 6 km from Person C's house, you have to be at position x since this is the only location where all three circles (distances) meet.

In Chapter 2, we will show you how the technique of trilateration is extended to GNSS. Con-

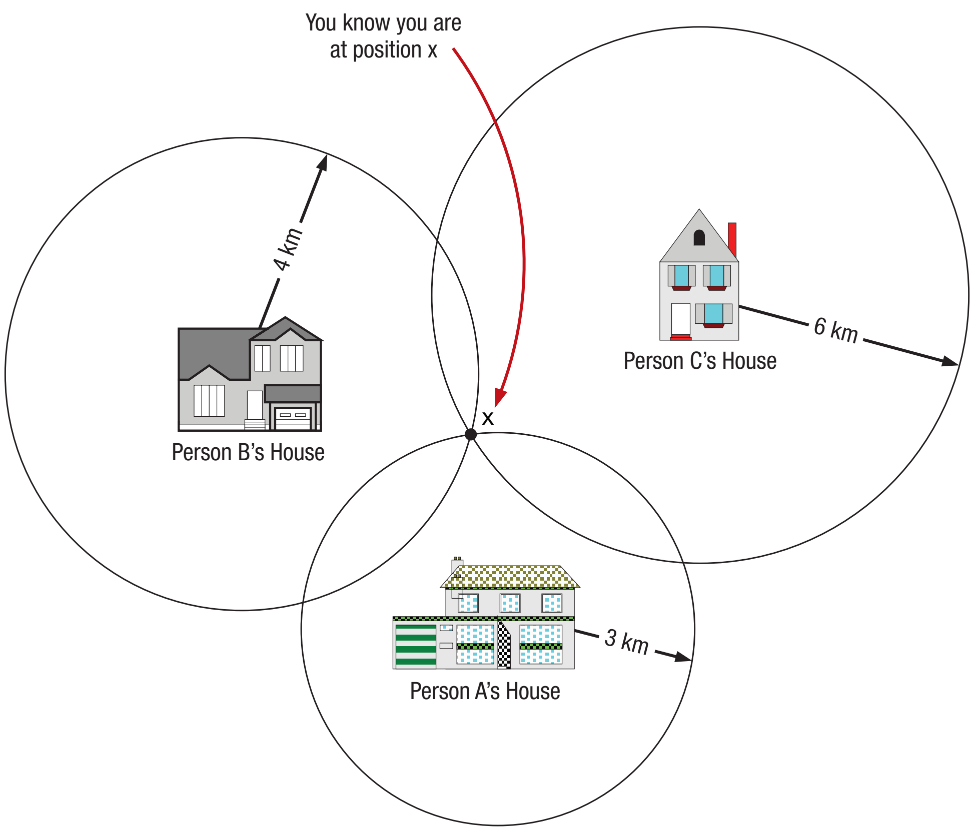


Figure 6 Illustration of Trilateration—Knowing Three Distances

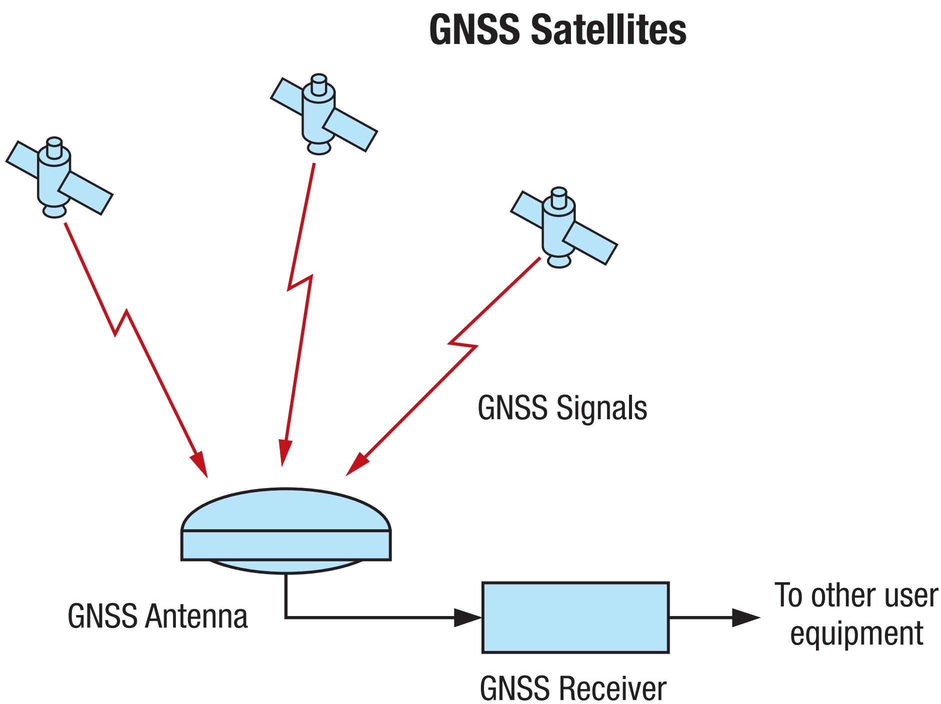


Figure 7 GNSS User Equipment

ceptually, we are just going to extend the above example by replacing the houses with satellites. And for reasons that we will outline, we will replace the three houses with four satellites.

GNSS APPLICATIONS

The first non-military applications of GNSS technology were in surveying and mapping. Today, GNSS is being used for commercial applications in agriculture, transportation, unmanned vehicles, machine control, marine navigation, and other industries where efficiencies can be gained from the application of precise, continually available position and time information. GNSS is also used in a broad range of consumer applications, including vehicle navigation, mobile communications, entertainment and athletics. As GNSS technology improves and becomes less expensive, more and more applications will be conceived and developed.

In addition to position, GNSS receivers can provide users with very accurate time, by "synchronizing" their local clock with the high-precision clocks onboard the satellites. This has enabled technologies and applications such as the synchronization of power grids, cellular systems, the Internet and financial networks.

We'll talk more about GNSS applications in Chapter 8.

GNSS USER EQUIPMENT

The primary components of the GNSS user segment are antennas and receivers, as shown in **Figure 7.** Depending on the application, antennas and receivers may be physically separate or they may be integrated into one assembly.

GNSS Antennas

GNSS antennas receive the radio signals that are transmitted by the GNSS satellites and send these signals to the receivers. GNSS antennas are available in a range of shapes, sizes and performances. The antenna is selected based on the application. While a large antenna may be appropriate for a base station, a light weight, low-profile aerodynamic antenna may be more suitable for aircraft or Unmanned Aerial Vehicles (UAV) installations. **Figure 8** presents a sampling of GNSS antennas.

GNSS Receivers

Receivers process the satellite signals recovered by the antenna to calculate position and time. Receivers may be designed to use signals from one GNSS constellation or from more than one GNSS constellation. As illustrated in **Figure 9,** receivers are available in many form factors and configurations to meet the requirements of the varied applications of GNSS.

We will talk more about GNSS equipment in Chapter 8.

GNSS AUGMENTATION

Positioning based on standalone GNSS service is accurate to within a few metres. The accuracy of standalone GNSS, and the number of available satellites, may not be adequate for the needs of some users.

Techniques and equipment have been developed to improve the accuracy and availability of GNSS position and time information. We will discuss some of these techniques in Chapter 4.

CLOSING REMARKS

Chapter 1 provided an overview of the main concepts and components of GNSS. This high-level summary will help your understanding as we present GNSS in greater detail, starting with a more thorough look at basic GNSS concepts in Chapter 2.

Figure 8 GNSS Antennas

Figure 9 GNSS Receivers


"To me there has never been a higher source of earthly honor or distinction than that connected with advances in science."
–Isaac Newton
NovAtel

Chapter Two

2 BASIC GNSS CONCEPTS

"Any sufficiently advanced technology is indistinguishable from magic."

–**Arthur C. Clarke,** British author, inventor and futurist.

In this chapter, we will introduce basic GNSS concepts. We'll discuss more advanced concepts in the subsequent chapters.

GNSS may at first seem like magic, but the more you study and learn about it, the simpler and more elegant it becomes. The basic GNSS concept shown in **Figure 10,** illustrates the steps involved in using GNSS to determine time and position through to the end user application.

STEP 1-SATELLITES: GNSS satellites orbit the earth. The satellites know their orbit ephemerides (the parameters that define their orbit) and the time very, very accurately. Ground-based control stations adjust the satellites' ephemerides and time, when necessary.

STEP 2-PROPAGATION: GNSS satellites regularly broadcast their ephemerides and time, as well as their status. GNSS radio signals pass through layers of the atmosphere to the user equipment.

STEP 3-RECEPTION: GNSS user equipment receives the signals from multiple GNSS satellites then, for each satellite, recovers

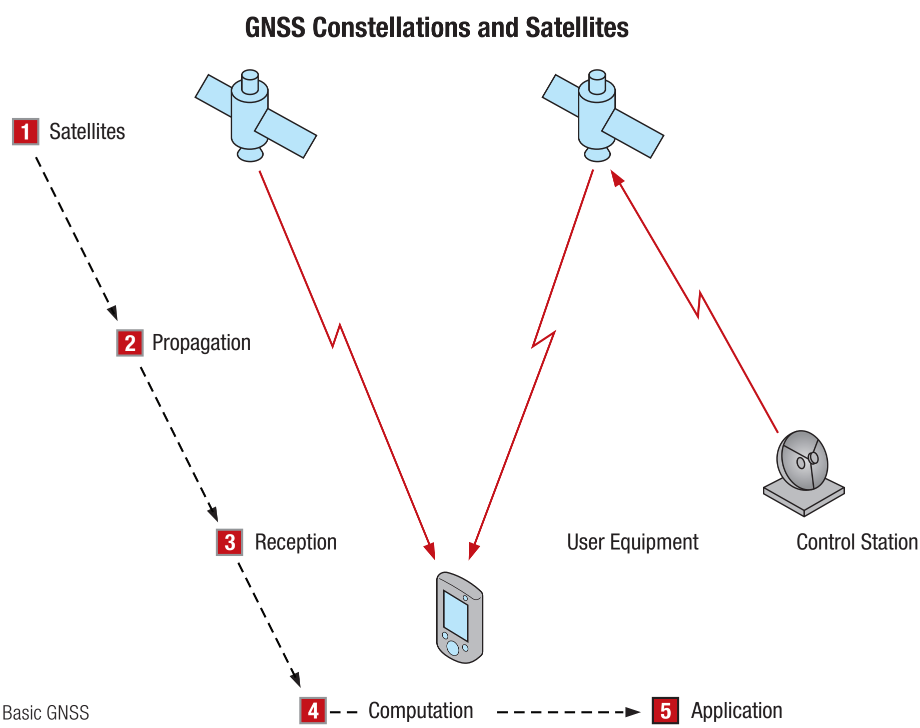


Figure 10 Basic GNSS

Lockheed Martin

Figure 11 Block IIR GPS Satellite

the information that was transmitted and determines the time of propagation, the time it takes the signals to travel from the satellite to the receiver.

STEP 4-COMPUTATION: GNSS user equipment uses the recovered information to compute time and position.

STEP 5-APPLICATION: GNSS user equipment provides the computed position and time to the end user application, for example, navigation, surveying or mapping.

In the following sections, we will discuss each of the above steps in more detail.

STEP 1–SATELLITES

There are multiple constellations of GNSS satellites orbiting the earth. A constellation is simply an orderly grouping of satellites, typically 20-30, in orbits that have been designed to provide a desired coverage, for example, regional or global. We will provide more details about GNSS constellations in Chapter 3.

GNSS satellites orbit well above the atmosphere, about 20,000 km above the earth's surface. They are moving very fast, several kilometres per second.

GNSS satellites are not as small as you might think. The latest generation of GPS satellites (Block IIF) weigh over 1,400 kg, a bit more than the weight of a Volkswagen Beetle. The body of these satellites are 2.5 m x 2.0 m x 2.2 m. **Figure 11** shows a picture of the body of a Block IIR GPS satellite, to give a sense of how large they are.

In the relative vacuum of space, satellite trajectories are very stable and predictable. As mentioned, GNSS satellites know their time and orbit ephemerides very, very accurately. If you ask a GPS satellite for the time, it won't tell you eight thirty. It will tell you 8:31.39875921.

The latest generation of GPS satellites uses rubidium clocks that are accurate to within ±5 parts in 10^{11}. These clocks are synchronized by more-accurate ground-based cesium clocks. You would need to watch one of these cesium clocks for over 100,000 years to see it gain or lose a second. By comparison, if you have a quartz watch, it will likely have an accuracy of ±5 parts in 10^6 and will lose about a second every two days.

By the way, if all GNSS receivers needed a rubidium standard, the viability of GNSS would quickly collapse. Later in the chapter, we will describe the elegant way GNSS systems "transfer" the accuracy of the satellite clocks to GNSS receivers.

You may be wondering why time is such a big deal in GNSS systems. It is because the time it takes a GNSS signal to travel from satellites to receivers is used to determine distances (ranges) to satellites. Accuracy is required because radio waves travel at the speed of light. In one microsecond (a millionth of a second), light travels 300 m. In a nanosecond (a billionth of a second), light travels 30 cm. Small errors in time can result in large errors in position.

GPS was the first GNSS constellation to be launched. At a cost of US$12 billion, it is the most accurate navigation system in the world. The Russian GLONASS constellation has also been launched and is operational. The benefit to end users of having access to multiple constellations is redundancy and availability. If one system fails, for any reason, GNSS receivers, if they are equipped to do so, can receive and use signals from satellites in other systems. System failure does not happen often, but it is nice to know that if it did, your receiver may still be able to operate.

Regardless, access to multiple constellations is of particular benefit where line of sight to some of the satellites is obstructed, as is often the case in urban or foliated areas.

Satellite Orbits

GNSS satellites orbit well above the Earth's atmosphere. GPS and GLONASS satellites orbit at altitudes close to 20,000 km. BeiDou and Galileo satellites orbit a bit higher, around 21,500 km for BeiDou and 23,000 km for Galileo. GNSS orbits, which are more or less circular, and highly stable and predictable, fall into the category of MEO, for medium earth orbit.

There is not much drag at 20,000 km, but gravitational effects and the pressure of solar radiation do affect GNSS orbits a bit and the orbits have to be occasionally corrected. While its orbit is being adjusted, a GNSS satellite's status is changed to "out of service" so user equipment knows not to use the affected signals.

Satellite Signals

> "Everything should be made as simple as possible, but no simpler." –**Albert Einstein.**

GNSS satellite signals are complex. Describing these signals requires equally complex words like pseudorandom, correlation, and Code Division Multiple Access (CDMA). To explain these GNSS concepts, let's first discuss GPS satellite signals.

First and foremost, GPS was designed as a positioning system for the US Department of Defense. To provide high-accuracy position information for military applications, a lot of complexity was designed into the system to make it secure and impervious to jamming and interference. Although military and civilian components of GPS are separate, some of the technologies used in the military component have been applied to the civilian component.

Since it achieved initial operational capability in December 1993, GPS has been available to civilian users, who have different requirements for service availability, positioning accuracy and cost.

The frequency plans (plans that describe the frequency, amplitude and width of signals) for each GNSS system are a little different. We will describe these plans in more detail in Chapter 3. To illustrate GNSS concepts, however, we will briefly describe the frequency and signal scheme used by GPS, which is shown in **Figure 12.** Conceptually, this is not much different than the frequency plan for cable or broadcast television channels.

As shown in **Figure 12,** GPS satellites transmit information on the L1, L2 and L5 frequencies. You may ask, "How can all GPS satellites transmit on the same frequencies?"

GPS works the way it does because of the transmission scheme it uses, which is called CDMA.

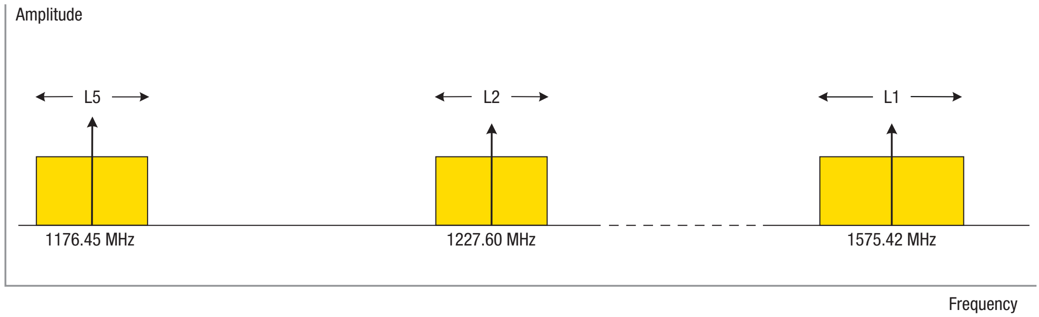


Figure 12 GPS Frequency Plan

CDMA is a form of spread spectrum. GPS satellite signals, although they are on the same frequency, are modulated by a unique pseudorandom digital sequence, or code. Each satellite uses a different pseudorandom code. Pseudorandom means that the signal only appears random; in fact, it actually repeats after a period of time. Receivers know the pseudorandom code for each satellite. This allows receivers to correlate (synchronize) with the CDMA signal for a particular satellite. CDMA signals are at a very low level, but through this code correlation, the receiver is able to recover the signals and the information they contain.

To illustrate, consider listening to a person in a noise-filled room. Many conversations are taking place, but each conversation is in a different language. You are able to understand the person because you know the language they are speaking. If you are multilingual, you will be able to understand what other people are saying too. CDMA is a lot like this.

You might be interested to learn that Hedy Lamarr, Austrian-born American scientist and actress, co-invented an early form of spread spectrum communications technology. On August 11, 1942, she and her co-worker, George Antheil, were granted U.S. Patent 2,292,387. Unbelievably, Lamarr shifted careers and went on to make 18 films from 1940 to 1949, but the concepts covered in her patent contributed to the development of today's spread spectrum communications.

GPS operates in a frequency band referred to as the L-Band, a portion of the radio spectrum between 1 and 2 GHz. L-Band was chosen for several reasons, including:

- Simplification of antenna design. If the frequency had been much higher, user antennas may have had to be a bit more complex.
- Ionospheric delay is more significant at lower frequencies. We'll talk more about ionospheric delay in *Step 2–Propagation,* later in this chapter.
- Except through a vacuum, the speed of light is lower at lower frequencies, as evident by the separation of the colors in light by a prism. You may have thought the speed of light was a constant at 299,792,458 metres per second. It is actually 299,792,458 metres per second in a vacuum, but through air or any other medium, it is less.
- The coding scheme requires a high bandwidth, which was not available in every frequency band.
- The frequency band was chosen to minimize the effect that weather has on GPS signal propagation.

L1 transmits a navigation message, the coarse acquisition C/A code (freely available to the public) and an encrypted precision (P) code, called the P(Y) code (restricted access). The navigation message is a low bit rate message that includes the following information:

- GPS date and time.
- Satellite status and health. If the satellite is having problems or its orbit is being adjusted, it will not be usable. When this happens, the satellite will transmit the out-of-service message.
- Satellite ephemeris data, which allows the receiver to calculate the satellite's position. This information is accurate to many, many decimal places. Receivers can determine exactly where the satellite was when it transmitted its time.
- Almanac, which contains information and status for all GPS satellites, so receivers know which satellites are available for tracking. On start up, a receiver will recover this "almanac." The almanac consists of coarse orbit and status information for each satellite in the constellation.

The P(Y) code is for military use. It provides better interference rejection than the C/A code, which makes military GPS more robust than civilian GPS. The L2 frequency transmits the P(Y) code and, on newer GPS satellites, it also transmits the C/A code (referred to as L2C), providing a second publicly available code to civilian users. Although the information in the P(Y) code is not accessible to everyone, clever people have figured out ways to use the L2 carrier and code, without knowing how it is coded.

While the GPS transmission scheme is complex, it was chosen for many good reasons:

- GPS receivers can recover very weak signals using very small antennas. This keeps the receiver cost low.
- Multi-frequency operation allows for ionospheric compensation, since ionospheric delays vary with frequency.

The GPS system is resistant to jamming and interference.

- Security. Signals accessed and used by military applications are not accessible by civilians.

Other GNSS systems are conceptually similar to GPS, but there are differences. We will provide more information about these differences in Chapter 3.

Satellite Errors

Satellite errors include ephemeride and clock errors. These satellite errors are very, very small,

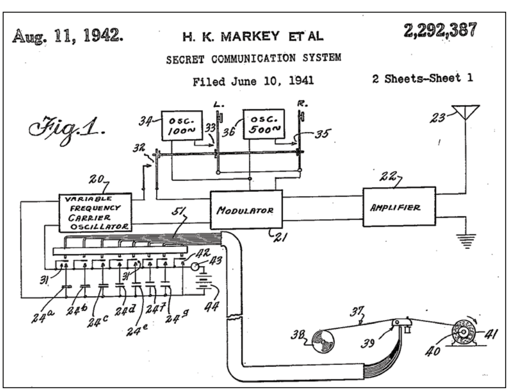
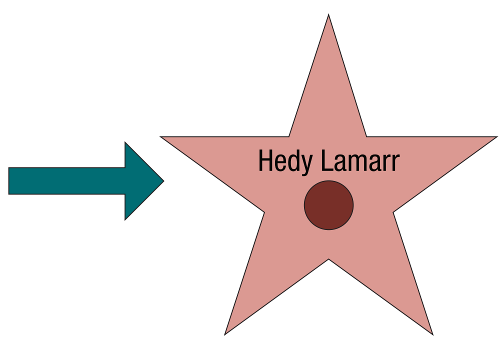


Figure 1 from US Patent 2,292,387



Hollywood Walk of Fame

Figure 13 Hedy Lamarr

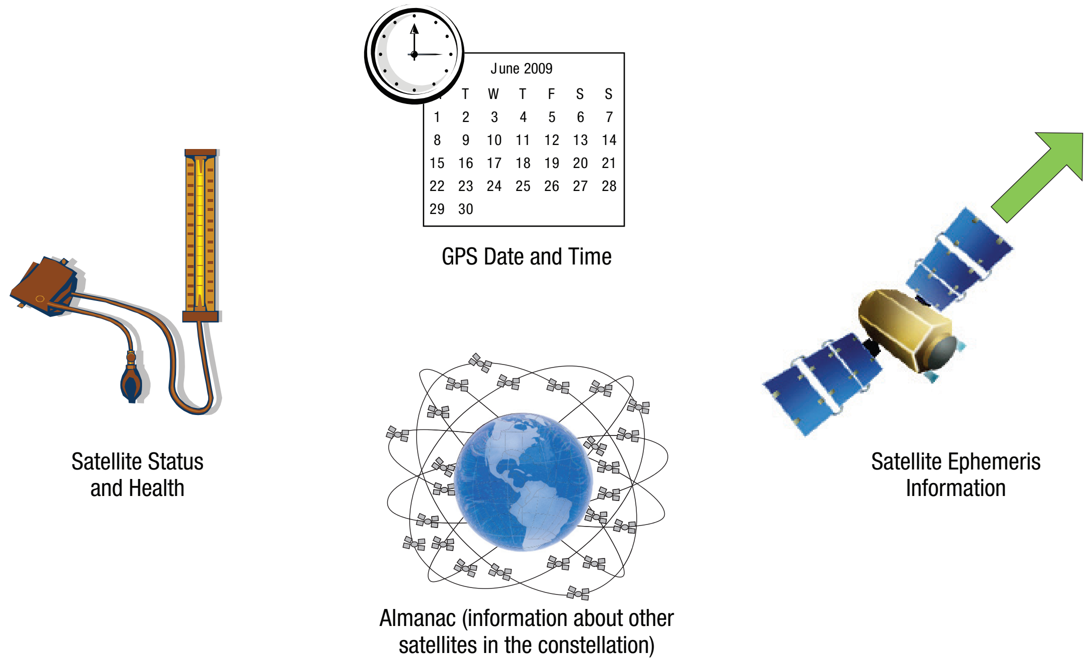


Figure 14 GPS Navigation Message

but keep in mind that in one nanosecond, light travels 30 centimetres.

Satellite Lifetimes

GNSS satellites don't last forever. Sometimes they are phased out with newer models that have new signals or improved time keeping. Sometimes GNSS satellites do fail and, if they can't be restored, are permanently removed from service.

Satellite Corrections

Earth stations continuously monitor the satellites and regularly adjust their time and orbit information to keep this broadcasted information highly accurate. If a satellite's orbit drifts outside the operating limits, it may be taken out of service and its orbit adjusted using small rocket boosters.

In our step-by-step illustration of GNSS, the radio signals have left the satellite antenna and are hurtling earthbound at the speed of light.

STEP 2–PROPAGATION

GNSS signals pass through the near-vacuum of space, then through the various layers of the atmosphere to the earth, as illustrated in **Figure 15.**

To obtain accurate position and time, we need to know the length of the direct path from the satellite to the user equipment (which we refer to as the "range" to the satellite). As shown in **Figure 15,** radio waves do not travel in a straight path. Light travels in a straight line only in a vacuum or through a perfectly homogeneous medium. Just as a straw is seemingly "bent" in a glass of water, radio signals from the satellite are bent as they pass through the earth's atmosphere. This “bending” increases the amount of time the signal takes to travel from the satellite to the receiver. As we shall explain in Step 4, the distance to the satellite is calculated by multiplying the time of propagation (which, you recall, is the time it takes the signals to travel from the satellite to the receiver) by the speed of light. Errors in the propagation time increase or decrease the computed range to the satellite. Incidentally, since the computed range contains errors and is not exactly equal to the actual range, we refer to it as a “pseudorange.”

The layer of the atmosphere that most influences the transmission of GPS (and other GNSS) signals is the ionosphere, the layer 70 to 1,000 km above the earth’s surface. Ultraviolet rays from the sun ionize gas molecules in this layer, releasing free electrons. These electrons influence electromagnetic wave propagation, including GPS satellite signal broadcasts. Ionospheric delays are frequency dependent so by calculating the range using both L1 and L2, the effect of the ionosphere can be virtually eliminated by the receiver.

The other layer of the atmosphere that influences the transmission of GPS signals is the troposphere, the lowest layer of the Earth’s atmosphere. The thickness of the troposphere varies, about 17 km in the middle latitudes, up to 20 km nearer the equator, and thinner at the poles. Tropospheric delay is a function of local temperature, pressure and relative humidity. L1 and L2 are equally delayed, so the effect of tropospheric delay cannot be eliminated the way ionospheric delay can be. It is possible, however, to model the troposphere then predict and compensate for much of the delay.

Some of the signal energy transmitted by the satellite is reflected on the way to the receiver. This phenomenon is referred to as “multipath propagation.” These reflected signals are delayed from the direct signal and, if they are strong enough, can interfere with the desired signal. Techniques have been developed whereby the receiver only considers the earliest-arriving signals and ignores multipath signals, which arrive later. In the early days of GPS, most errors came from ionospheric and tropospheric delays, but now more attention is being made to multipath effects, in the interests of continually improving GNSS performance.

STEP 3–RECEPTION

As we have indicated, receivers need at least four satellites to obtain a position. The use of more satellites, if they are available, will improve the position solution; however, the receiver’s ability to make use of additional satellites may be lim-

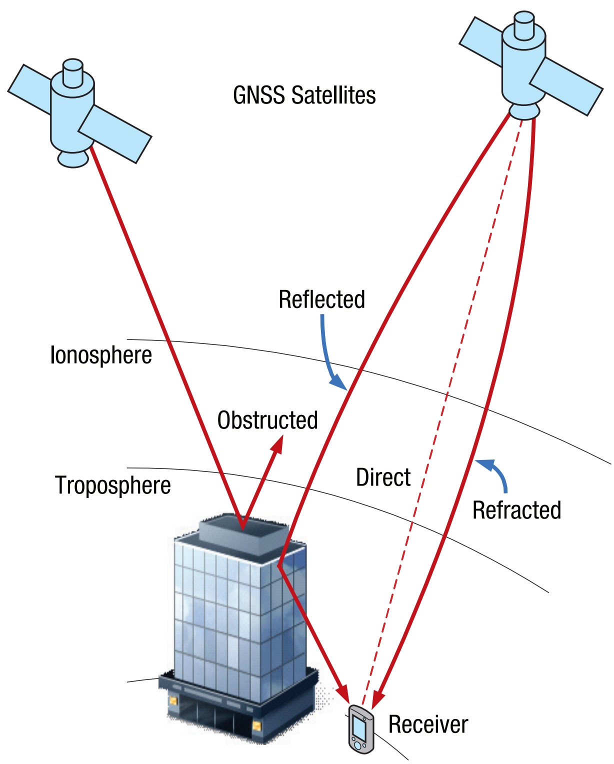


Figure 15 GNSS Signal Propogation

ited by its computational power. The manner by which the receiver uses the additional ranges will generally be the intellectual property of the manufacturer.

Depending on the implementation, user equipment can recover signals from multiple satellites in multiple GNSS constellations.

To determine a fix (position) and time, GNSS receivers need to be able to track at least four satellites. This means there needs to be a line of sight between the receiver's antenna and the four satellites.

Receivers vary in terms of which constellation or constellations they track, and how many satellites they track simultaneously.

For each satellite being tracked, the receiver determines the propagation time. It can do this because of the pseudorandom nature of the signals. To illustrate, refer to **Figure 17,** which shows the transmission of a pseudorandom code, a series of zeroes and ones. Since the receiver knows the pseudorandom code for each satellite, it can determine the time it received the code from a particular satellite. In this way, it can determine the time of propagation.

Importance of Antenna Selection

An antenna behaves both as a spatial and frequency filter, therefore, selecting the right GNSS antenna is critical for optimizing performance. An antenna must match the receiver's capabilities and specifications, as well as meet size, weight, environmental and mechanical specifications for the intended application.

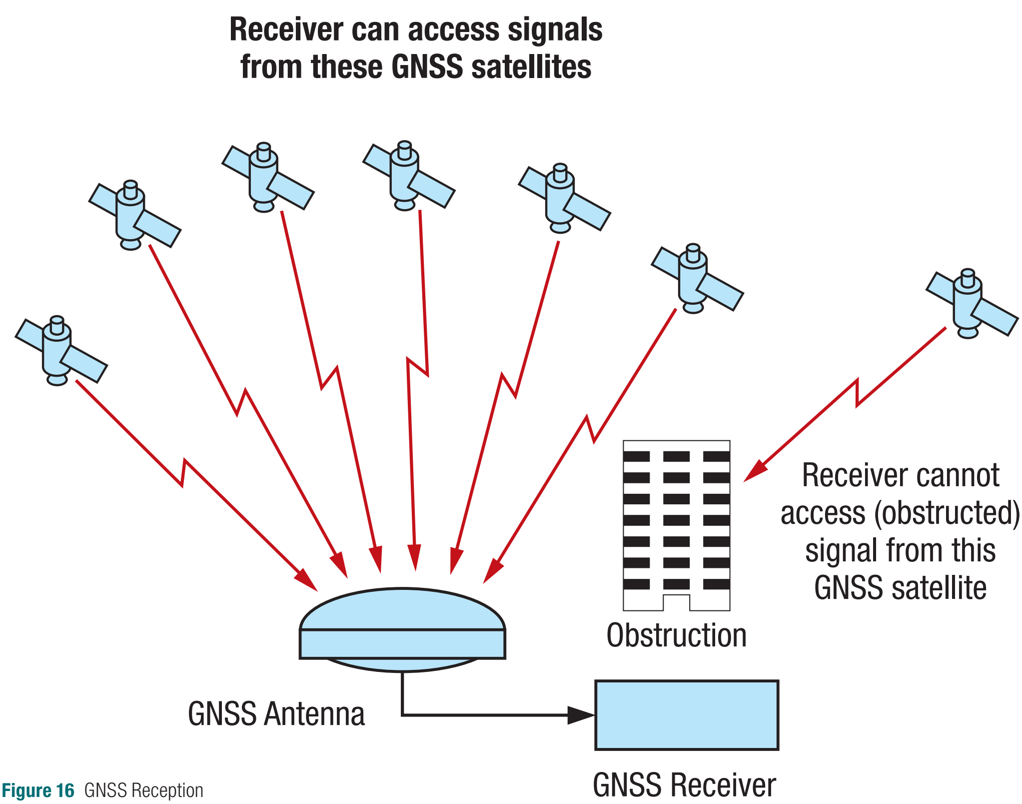


Figure 16 GNSS Reception

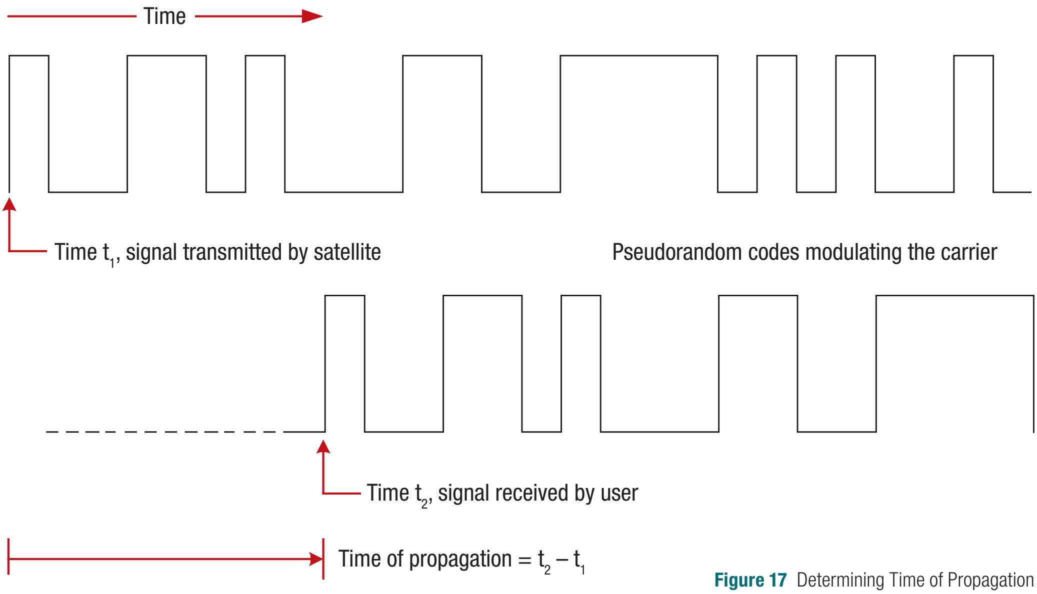


Figure 17 Determining Time of Propagation

Factors to consider when choosing a GNSS antenna include:

1. CONSTELLATION AND SIGNALS

Each GNSS constellation has its own signal frequencies and bandwidths. An antenna must cover the signal frequencies transmitted by the constellation and bandwidth supported by the GNSS receiver.

2. ANTENNA GAIN

Gain is a key performance indicator of a GNSS antenna. Gain can be defined as the relative measure of an antenna's ability to direct or concentrate radio frequency energy in a particular direction or pattern. A minimum gain is required to achieve a minimum carrier-to-power-noise ratio (C/No) to track GNSS satellites. The antenna gain is directly related to the overall C/No of the navigation GNSS receivers. Hence, antenna gain helps define the tracking ability of the system.

3. ELEMENT GAIN

The element gain defines how efficient the antenna element is at receiving the signals. In any signal chain, you are only as good as the weakest link, so an antenna element with low element gain might be compensated by an increased low noise amplifier gain. The signal-to-noise ratio or C/No, however, is degraded.

4. ANTENNA BEAMWIDTH AND GAIN ROLL-OFF

Gain roll-off is a factor of beamwidth, and specifies how much the gain changes over the elevation angle of the antenna. From the antenna's point of view, the satellites rise from the horizon towards zenith and fall back to the horizon. The variation in gain between zenith (directly overhead) and the horizon is known as the gain roll-off. Different antenna technologies have different gain roll-off characteristics.

5. PHASE CENTER STABILITY

The phase center of the antenna is the point where the signals transmitted from satellites are collected. When a receiver reports a location fix, that location is essentially the phase center of the antenna.

Desirable Features	Application											
	Survey	GIS	Reference Station	Aviation/Aerial Survey	Marine	Construction/Mining	Precision Agriculture	Vehicle Tracking	Dock Operation	Unmanned Aircraft	Unmanned Vehicle	Timing
Low Profile				•		•		•		•		
Ultra-Low PCO/PCV	•		•									
Low PCO/PCV		•		•		•	•			•	•	
High Vibration				•		•	•		•	•	•	
Rugged	•	•	•			•			•			
Single Frequency												•
Multi-Constellation	•	•	•	•	•	•	•		•	•	•	
Multi-Frequency (RTK)	•	•	•		•	•	•		•	•	•	
L-Band Frequency (Correction Services)					•		•					
Narrow Bandwidth												•
Weatherproof	•	•	•	•	•	•	•	•	•	•	•	•
Corrosion Resistance			•		•	•			•			•
High Multipath Suppression	•		•		•	•	•		•		•	
Pole Mount	•	•	•		•	•			•			•
Magnetic/Surface Mount						•	•	•	•		•	
TSO/FAA Certification				•						•		
Extended Temperature Range			•	•						•		
Small Form Factor / Low Weight		•								•		
High Altitude Operation			•	•						•		

Table 1 Features for Antenna Applications

The electrical phase center of any antenna will vary with the position of the transmitting signal it is receiving by as much as a few millimetres. As GNSS satellites move across the sky, the electrical phase center of the signal received will typically move with the satellite position unless the antenna has been carefully designed to minimize Phase Center Offset (PCO) and Phase Center Variation (PCV).

The PCO, with respect to the Antenna Reference Point (ARP), is the difference between the mechanical center of antenna rotation

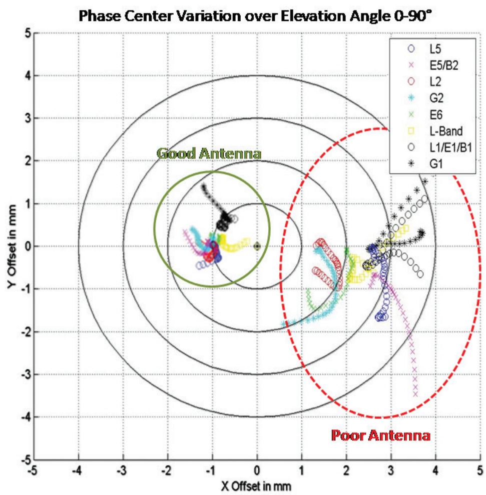


Figure 18 Plot of Good and Poor Antenna Phase Center Variation over Elevation Angle

and electrical phase center location. The PCO is also frequency dependent which means that there can be a different offset for each signal frequency. The PCV identifies how much the phase center moves with respect to the satellite elevation angles.

Many users can accept accuracies of less than a metre so these small phase center variations cause a negligible amount of position error. But if you require high precision, such as Real Time Kinematic (RTK) receivers that can achieve position accuracies of 2-4 cm, a few millimetres of phase center error can translate to a 10-15% error in reported position. For RTK survey applications, geodetic grade antennas offer superior PCO/PCV performance.

6. APPLICATION

An antenna has to meet the performance, environmental, mechanical and operational requirements of the intended application. For example, GNSS antennas used for aviation applications should ideally be TSO/FAA certified and be rugged enough to handle extreme temperatures and vibration profiles. Survey rover antennas should be able to survive rough handling by surveyors including a pole drop.

Table 1 highlights some of the important desirable features needed for a GNSS antenna based upon the user's application.

STEP 4–COMPUTATION

If we knew the exact position of three satellites and the exact range to each of them, we would geometrically be able to determine our location. We have suggested that we need ranges to four satellites to determine position. In this section, we will explain why this is so, and how GNSS positioning actually works.

For each satellite being tracked, the receiver calculates how long the satellite signal took to reach it, as follows:

Propagation Time = Time Signal Reached Receiver – Time Signal Left Satellite

Multiplying this propagation time by the speed of light gives the distance to the satellite.

For each satellite being tracked, the receiver now knows where the satellite was at the time of transmission (because the satellite broadcasts its orbit ephemerides) and it has determined the distance to the satellite when it was there. Using trilateration, a method of geometrically determining the position of an object, in a manner similar to triangulation, the receiver calculates its position.

To help us understand trilateration, we'll present the technique in two dimensions. The receiver calculates its range to Satellite A. As we mentioned, it does this by determining the amount of time it took for the signal from Satellite A to arrive at the receiver, and multiplying this time by the speed of light. Satellite A communicated its location (determined from the satellite orbit ephemerides and time) to the receiver, so the receiver knows it is somewhere on a circle with radius equal to the range and centered at the location of Satellite A, as illustrated in **Figure 19.** In three dimensions, we would show ranges as spheres, not circles.

The receiver also determines its range to a second satellite, Satellite B. Now the receiver knows it is at the intersection of two circles, at either Position 1 or 2, as shown in **Figure 20.**

You may be tempted to conclude that ranging to a third satellite would be required to resolve your location to Position 1 or Position 2. But one of the positions can most often be eliminated as not feasible because, for example, it is in space or in the middle of the Earth. You might also be tempted to extend our illustration to three dimensions and suggest that only three ranges are needed for positioning.

But as we discussed earlier, four ranges are necessary. Why is this?

It turns out that receiver clocks are not nearly as accurate as the clocks on board the satellites. Most are based on quartz crystals. Remember, we said these clocks were accurate to only about 5 parts per million. If we multiply this by the speed

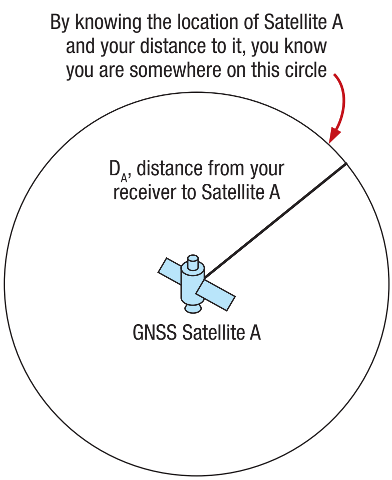


Figure 19 Ranging to First Satellite

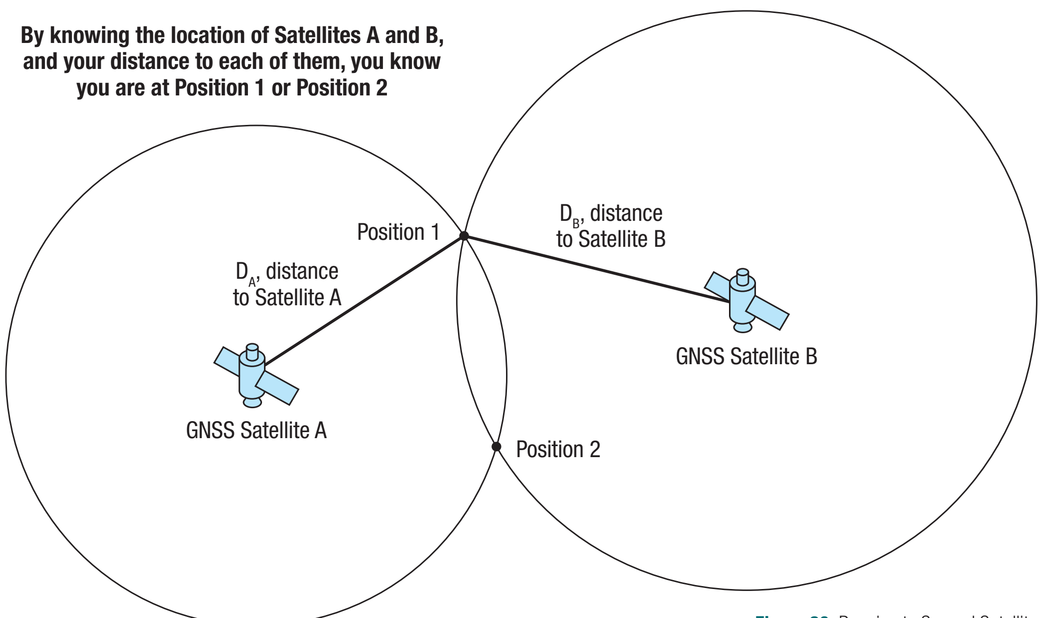


Figure 20 Ranging to Second Satellite

of light, it will result in an accuracy of ±1500 metres. When we determine the range to two satellites, our computed position will be out by an amount proportional to the inaccuracy in our receiver clock, as illustrated in **Figure 21.**

We want to determine our actual position but, as shown in **Figure 21,** the receiver time inaccuracy causes range errors that result in position errors. The receiver knows there is an error, it just does not know the size of the error. If we now compute the range to a third satellite, it will not intersect the computed position, as shown in **Figure 22.**

Now for one of the ingenious techniques used in GNSS positioning.

The receiver knows that the reason the pseudoranges to the three satellites are not intersecting is because its clock is not very good. The receiver is programmed to advance or delay its clock until the pseudoranges to the three satellites converge at a single point, as shown in **Figure 23.**

The incredible accuracy of the satellite clock has now been "transferred" to the receiver clock, eliminating the receiver clock error in the position determination. The receiver now has both an accurate position and a very, very accurate time. This presents opportunities for a broad range of applications, as we shall discuss.

The above technique shows how, in a two-dimensional representation, receiver time inaccuracy can be eliminated and position determined using ranges to three satellites. When we extend this technique to three dimensions, we need to add a range to a fourth satellite. This is the reason why line-of-sight to a minimum of four GNSS satellites is needed to determine position.

GNSS Error Sources

A GNSS receiver calculates position based on data received from satellites. However, there

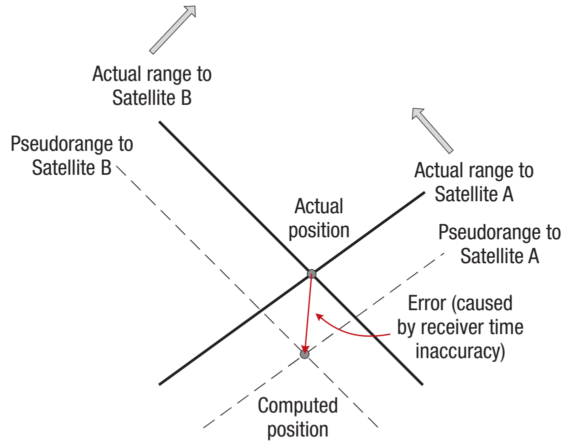


Figure 21 Position Error

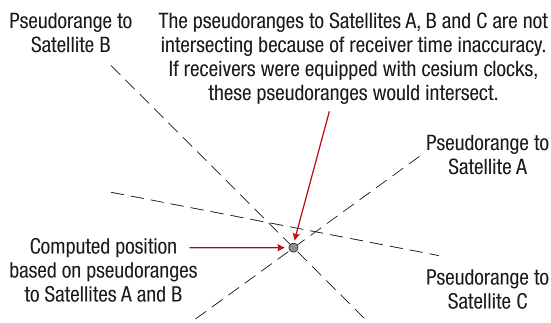


Figure 22 Detecting Position Error

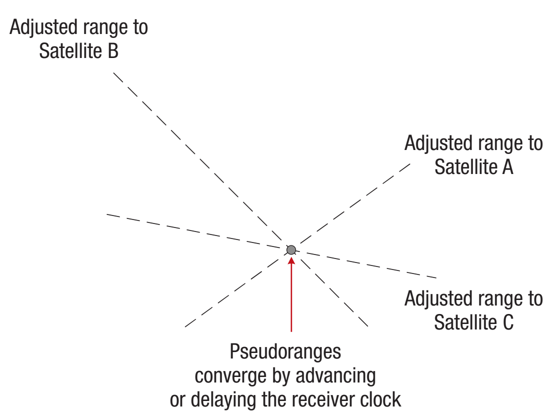


Figure 23 Convergence

are many sources of errors that, if left uncorrected, cause the position calculation to be inaccurate. Some of these errors, such as those caused by the refraction of the satellite signal as it passes through the ionosphere and troposphere, are due to natural causes, and some, such as a government's Selective Availability (SA) methods, are introduced on purpose.

The type of error and how it is mitigated is essential to calculating precise position, as the level of precision is only useful to the extent that the measurement can be trusted. This book dedicates three chapters to this important topic. Chapter 4 presents key sources of GNSS error while Chapter 5 discusses methods of error resolution and impact on accuracy and other performance factors. Chapter 8 presents the equipment and network infrastructure necessary to generate and receive correction data.

Dilution of Precision (DOP)

The geometric arrangement of satellites, as they are presented to the receiver, affects the accuracy of position and time calculations. Receivers will ideally be designed to use signals from available satellites in a manner that minimizes this so called "dilution of precision."

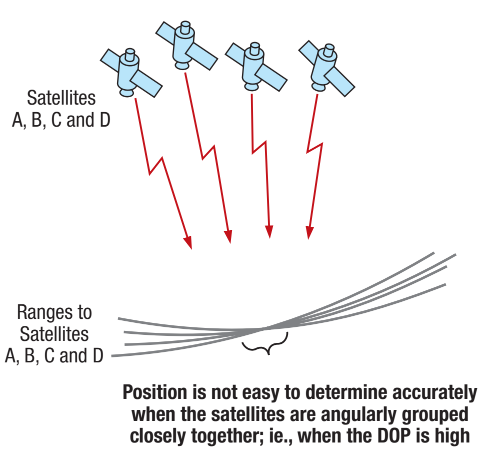


Figure 24 Dilution of Precision (poor satellite geometry)

To illustrate DOP, consider the example shown in **Figure 24,** where the satellites being tracked are clustered in a small region of the sky. As you can see, it is difficult to determine where the ranges intersect. Position is "spread" over the area of range intersections, an area which is enlarged by range inaccuracies (which can be viewed as a "thickening" of the range lines).

As shown in **Figure 25,** the addition of a range measurement to a satellite that is angularly separated from the cluster allows us to determine a fix more precisely.

Although it is calculated using complex statistical methods, we can say the following about **DOP:** ***DOP is a numerical representation of satellite geometry, and it is dependent on the locations of satellites that are visible to the receiver.***

The smaller the value of DOP, the more precise the result of the time or position calculation. The relationship is shown in the following formula:

Inaccuracy of Position Measurement =
DOP x Inaccuracy of Range Measurement

So, if DOP is very high, the inaccuracy of the position measurement will be much larger than the inaccuracy of the range measurement.

- DOP can be used as the basis for selecting the satellites on which the position solution will be based; specifically, selecting satellites to minimize DOP for a particular application.
- A DOP above 6 results in generally unacceptable accuracies for DGNSS and RTK operations.
- DOP varies with time of day and geographic location but, for a fixed position, the geometric presentation of the satellites repeats every day, for GNSS.
- DOP can be calculated without determining the range. All that is needed is the satellite positions and the approximate receiver location.

DOP can be expressed as a number of separate elements that define the DOP for a particular type of measurement, for example, HDOP (Horizontal Dilution of Precision), VDOP (Vertical Dilution of Precision), and PDOP (Position Dilution of Precision). These factors are mathematically related. In some cases, for example when satellites are low in the sky, HDOP is low and it will therefore be possible to get a good to excellent determination of horizontal position (latitude and longitude), but VDOP may only be adequate for a moderate altitude determination. Similarly, when satellites are clustered high in the sky, VDOP is better than HDOP.

In Canada, and in other countries at high latitude, GNSS satellites are lower in the sky and achieving optimal DOP for some applications, particularly where good VDOP is required, is sometimes a challenge.

Applications where the available satellites are low on the horizon or angularly clustered, such as those in urban environments or in deep open-pit mining, may expose users to the pitfalls of DOP. If you know your application will have obstructed conditions, you may want to use a mission planning tool to determine the ideal time—the time with the ideal DOP.

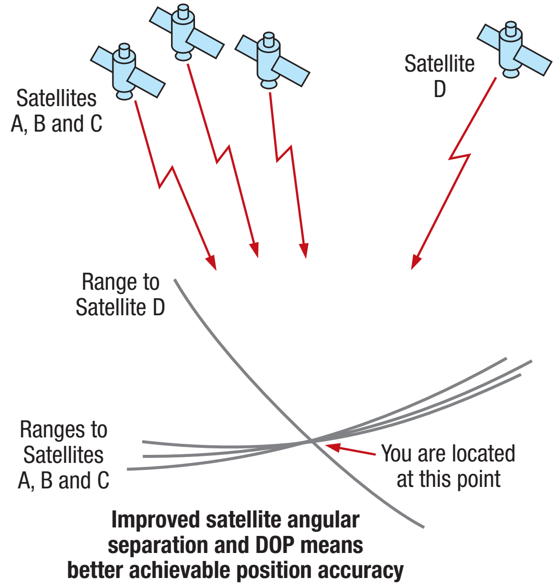


Figure 25 Dilution of Precision (improved geometry)

STEP 5–APPLICATION

Once the errors have been accounted for in the GNSS equation, the receiver can determine its position and time, and pass this information on to the end user application. The GNSS technology market is a ubiquitous, multi-billion dollar industry. Applications range from simple hand-held metre-level navigation aids, to robust, centimetre-level positioning solutions for survey, unmanned and military. With users demanding GNSS positioning functionality in increasingly challenging environments, GNSS technology is being integrated with other sensors such as inertial technology to enhance positioning capabilities and dependability. We look at a variety of sensors in Chapter 6.

As applications become more complex and ubiquitous, the opportunity for GNSS denied scenarios, whether intentional or unintentional, increase. Chapter 7 discusses causes and mitigation techniques of GNSS denial such as jamming and spoofing. Our final chapter, Chapter 8 promises to inspire with some of our most exciting customer applications.

CLOSING REMARKS

This has been a tough chapter and we're pleased you persevered through the basics of GNSS positioning. Chapter 3 provides additional information about the GNSS constellations that have been implemented or are planned. Chapters 4, 5, 6 and 7 discuss advanced GNSS concepts, and Chapter 8 discusses equipment and applications—how the simple outputs of this incredible technology are being used.


"Look deep into nature, and then you will understand everything better."
–Albert Einstein

3 *Chapter Three*
GNSS SATELLITE SYSTEMS

"The dinosaurs became extinct because they didn't have a space program."

—**Larry Niven,** American science fiction author.

European Space Agency

Figure 26 Launch of Galileo Satellite

Larry Niven is suggesting that if the dinosaurs had had a space program, they could have intercepted and deflected the asteroid that some think may have hit the earth and led to the extinction of the dinosaurs.

Unlike the dinosaurs, several countries now have existing or planned space programs that include the implementation of national or regional Global Navigation Satellite Systems. In this chapter, we will provide an overview of these systems.


Lockheed Martin

Figure 27 GPS IIRM Satellite (artist's rendition)

Satellites	27 plus 4 spares
Orbital Planes	6
Orbit Inclination	55 degrees
Orbit Radius	20,200 km

Table 2 GPS Satellite Constellation

The following GNSS systems are operational:

- GPS (United States)
- GLONASS (Russia)
- BeiDou (China)

At the time of writing, the following navigation satellite systems are progressing toward operational capability:

- Galileo GNSS system (European Union)
- IRNSS regional navigation satellite system (India)
- QZSS regional navigation satellite system (Japan)

GPS

(GLOBAL POSITIONING SYSTEM), UNITED STATES

GPS was the first GNSS system. GPS (or NAVSTAR, as it is officially called) satellites were first launched in the late 1970s and early 1980s for the US Department of Defense. Since that time, several generations (referred to as "Blocks") of GPS satellites have been launched. Initially, GPS was available only for military use but in 1983, a decision was made to extend GPS to civilian use. A GPS satellite is depicted in **Figure 27.**

Space Segment

The GPS space segment is summarized in **Table 2.** The orbit period of each satellite is approximately 12 hours, so this provides a GPS receiver with at least six satellites in view from any point on Earth, under open-sky conditions.

A GPS satellite orbit is illustrated in **Figure 28.**

GPS satellites continually broadcast their identification, ranging signals, satellite status and corrected ephemerides (orbit parameters). The satellites are identified either by their Space Vehicle Number (SVN) or their Pseudorandom Noise (PRN) code.

DESIGNATION	FREQUENCY	DESCRIPTION
L1	1575.42 MHz	L1 is modulated by the C/A code (Coarse/Acquisition) which is available to all users and the P-code (Precision) which is encrypted for military and other authorized users.
L2	1227.60 MHz	L2 is modulated by the P-code and, beginning with the Block IIR-M satellites, the L2C (civilian) code. L2C has begun broadcasting civil navigation (CNAV) messages and is discussed later in this chapter under "GPS Modernization".
L5	1176.45 MHz	L5, available beginning with Block IIF satellites, has begun broadcasting CNAV messages. The L5 signal is discussed later in chapter under "GPS Modernization".

Table 3 GPS Signal Characteristics

Signals

Table 3 provides further information on GPS signals. GPS signals are based on CDMA (Code Division Multiple Access) technology, which we discussed in Chapter 2.

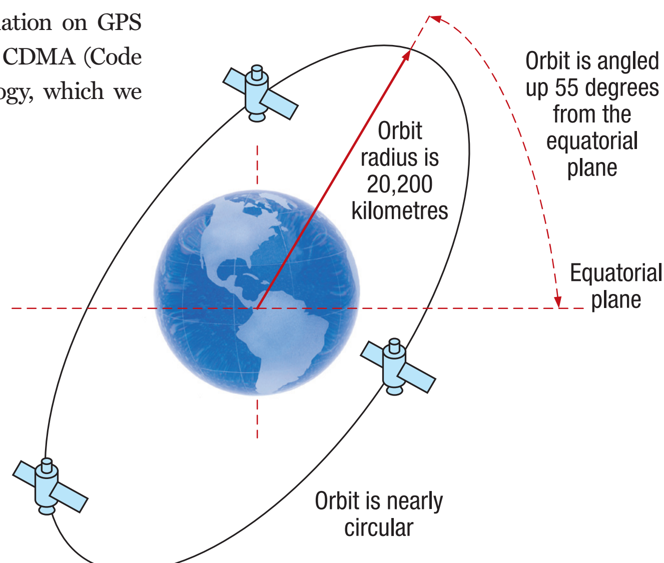


Figure 28 GPS Satellite Orbit

Figure 29 GPS Control Segment

Master Control Station	Schriever AFB
Alternate Master Control Station	Vandenberg AFB
Air Force Monitor Stations	Schriever AFB, Cape Canaveral, Hawaii, Ascension Island, Diego Garcia, Kwajalein
AFSCN Remote Tracking Stations	Schriever AFB, Vandenberg AFB, Hawaii, New Hampshire, Greenland, United Kingdom, Diego Garcia, Guam
NGA Monitor Stations	USNO Washington, Alaska, United Kingdom, Ecuador, Argentina, South Africa, Bahrain, South Korea, Australia, New Zealand
Ground Antennas	Cape Canaveral, Ascension Island, Diego Garcia, Kwajalein

Control Segment

The GPS control segment consists of a master control station (and a backup master control station), monitor stations, ground antennas and remote tracking stations, as shown in **Figure 29.**

There are 16 monitor stations located throughout the world; six from the US Air Force and ten from the NGA (National Geospatial Intelligence Agency, also part of the United States Department of Defense). The monitor stations track the satellites via their broadcast signals, which contain satellite ephemeris data, ranging signals, clock data and almanac data. These signals are passed to the master control station where the ephemerides are recalculated. The resulting ephemerides and timing corrections are transmitted back up to the satellites through data up-loading stations.

The ground antennas are co-located with monitor stations and used by the Master Control Station to communicate with and control the GPS satellites.

The Air Force Satellite Control Network (AFSCN) remote tracking stations provide the Master Control Station with additional satellite information to improve telemetry, tracking and control.

GPS Modernization

GPS reached Fully Operational Capability (FOC) in 1995. In 2000, a project was initiated to modernize the GPS space and ground segments, to take advantage of new technologies and user requirements.

Space segment modernization includes new signals, as well as improvements in atomic clock accuracy, satellite signal strength and reliability. Control segment modernization includes improved ionospheric and tropospheric modelling and in-orbit accuracy, and additional monitoring stations. User equipment has also evolved, to take advantage of space and control segment improvements.

L2C

The modernized GPS satellites (Block IIR-M and later) are transmitting a new civilian signal, designated L2C, ensuring the accessibility of two civilian codes. L2C is easier for the user segment to track and it delivers improved navigation accuracy. It also provides the ability to directly measure and remove the ionospheric delay error for a particular satellite, using the civilian signals on both L1 and L2. The L2C signal is expected to be available from 24 satellites by 2018.

L5

The United States has implemented a third civil GPS frequency (L5) at 1176.45 MHz. The modernized GPS satellites (Block II-F and later) are transmitting L5.

The benefits of the L5 signal include meeting the requirements for critical safety-of-life applications such as that needed for civil aviation and providing:

- Improved ionospheric correction.
- Signal redundancy.
- Improved signal accuracy.
- Improved interference rejection.

The L5 signal is expected to be available from 24 satellites by 2021.

L1C

A fourth civilian GPS signal, L1C, is planned for the next generation of GPS satellites, Block III. L1C will be backward compatible with L1 and will provide greater civilian interoperability with Galileo. The Japanese QZSS, Indian IRNSS and Chinese BeiDou also plan to broadcast L1C, making it a future standard for international interoperability.

L1C features a new modulation scheme that will improve GPS reception in cities and other challenging environments. It is expected that the first Block III satellites will be launched in 2016 and that there will be 24 satellites broadcasting L1C by 2026.

Other

In addition to the new L1C, L2C and L5 signals, GPS satellite modernization includes new military signals.

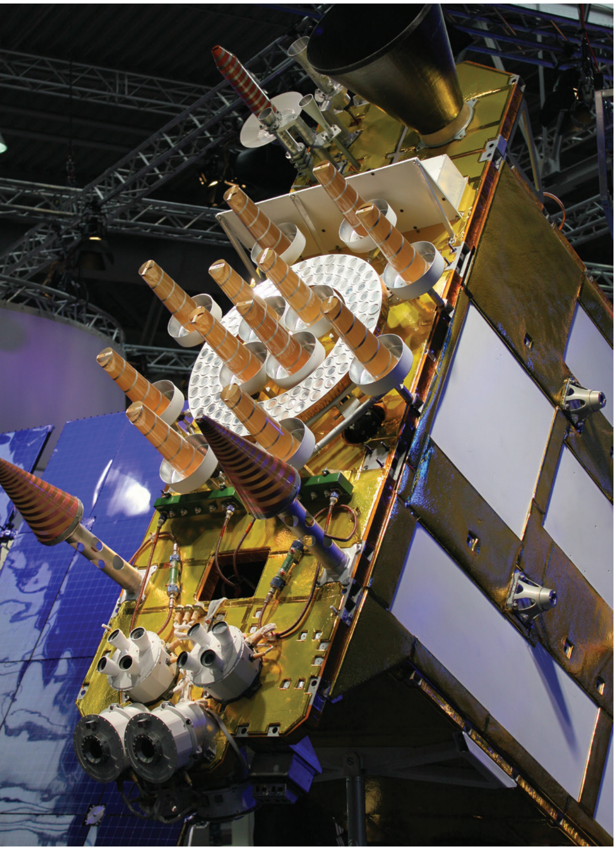


Figure 30 GLONASS-M Satellite in Final Manufacturing

Satellites	24 plus 3 spares
Orbital Planes	3
Orbital Inclination	64.8 degrees
Orbit Radius	19,140 km

Table 4 GLONASS Satellite Constellation

GLONASS

(GLOBAL NAVIGATION SATELLITE SYSTEM), RUSSIA

GLONASS was developed by the Soviet Union as an experimental military communications system during the 1970s. When the Cold War ended, the Soviet Union recognized that GLONASS had commercial applications, through the system's ability to transmit weather broadcasts, communications, navigation and reconnaissance data.

The first GLONASS satellite was launched in 1982 and the system was declared fully operational in 1993. After a period where GLONASS performance declined, Russia committed to bringing the system up to the required minimum of 18 active satellites. Currently, GLONASS has a full deployment of 24 satellites in the constellation.

GLONASS satellites have evolved since the first ones were launched. The latest generation, GLONASS-M, is shown in **Figure 30** being readied for launch.

GLONASS System Design

The GLONASS constellation provides visibility to a variable number of satellites, depending on your location. A minimum of four satellites in view allows a GLONASS receiver to compute its position in three dimensions and to synchronize with system time.

GLONASS Space Segment

The GLONASS space segment is summarized in **Table 4.**

The GLONASS space segment consists of 24 satellites, in three orbital planes, with eight satellites per plane.

The GLONASS constellation geometry repeats about once every eight days. The orbit pe-

1 A sidereal day is the time it takes for one complete rotation of the earth, relative to a particular star. A sidereal day is about four minutes shorter than a mean solar day

DESIGNATION	FREQUENCY	DESCRIPTION
L1	1598.0625–1609.3125 MHz	L1 is modulated by the HP (High Precision) and the SP (Standard Precision) signals.
L2	1242.9375–1251.6875 MHz	L2 is modulated by the HP and SP signals. The SP code is identical to that transmitted on L1.

Table 5 GLONASS Signal Characteristics

riod of each satellite is approximately 8/17 of a sidereal[1] day so that, after eight sidereal days, the GLONASS satellites have completed exactly 17 orbital revolutions.

Each orbital plane contains eight equally spaced satellites. One of the satellites will be at the same spot in the sky at the same sidereal time each day.

The satellites are placed into nominally circular orbits with target inclinations of 64.8 degrees and an orbital radius of 19,140 km, about 1,060 km lower than GPS satellites.

The GLONASS satellite signal identifies the satellite and includes:

- Positioning, velocity and acceleration information for computing satellite locations.
- Satellite health information.
- Offset of GLONASS time from UTC (SU) [Coordinated Universal Time Russia].
- Almanac of all other GLONASS satellites.

NASA

Figure 31 View of Earth (as seen by Apollo 17 crew)

“The Earth was absolutely round…I never knew what the word ‘round’ meant until I saw Earth from space.”

–**Alexei Leonov,** Soviet astronaut, talking about his historic 1985 spacewalk.

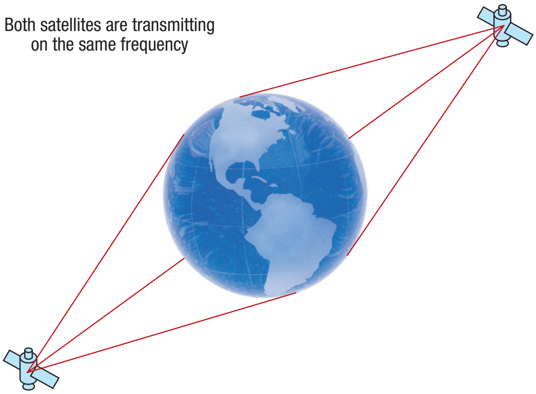


Figure 32 GLONASS Antipodal Satellites

GLONASS Control Segment

The GLONASS control segment consists of the system control center and a network of command tracking stations across Russia. The GLONASS control segment, similar to that of GPS, monitors the satellites health, determines the ephemeris corrections, as well as the satellite clock offsets with respect to GLONASS time and UTC (Coordinated Universal Time). Twice a day, it uploads corrections to the satellites.

GLONASS Signals

Table 5 summarizes the GLONASS signals.

Each GLONASS satellite transmits on a slightly different L1 and L2 frequency, with the P-code (HP code) on both L1 and L2, and the C/A code (SP code), on L1 (all satellites) and L2 (most satellites). GLONASS satellites transmit the same code at different frequencies, a technique known as FDMA, for frequency division multiple access. Note that this is a different technique from that used by GPS.

GLONASS signals have the same polarization (orientation of the electromagnetic waves) as GPS signals, and have comparable signal strength.

The GLONASS system is based on 24 satellites using 12 frequencies. The satellites can share the frequencies by having antipodal satellites transmitting on the same frequency. Antipodal satellites are in the same orbital plane but are separated by 180 degrees. The paired satellites can transmit on the same frequency because they will never appear at the same time in view of a receiver on the Earth's surface, as shown in **Figure 32.**

GLONASS Modernization

As the current GLONASS-M satellites reach the end of their service life, they will be replaced with next generation GLONASS-K satellites. The new satellites will provide the GLONASS system with new GNSS signals.

L3

The first block of GLONASS-K satellites (GLONASS-K1) will broadcast the new civil signal, designated L3, centered at 1202.025 MHz. Unlike the existing GLONASS signals, L3 is based on CDMA which will ease interoperability with GPS and Galileo.

The first GLONASS-K1 satellite was launched in February 2011.

L1 and L2 CDMA

The second block of GLONASS-K satellites (GLONASS-K2) adds two more CDMA based signals broadcast at the L1 and L2 frequencies. The exiting FDMA L1 and L2 signals will continue to be broadcast as well to support legacy receivers. GLONASS-K2 satellites are planned to be launched starting in 2015.

L5

The third block of GLONASS-K satellites (GLONASS-KM) will add an L5 signal to the GLONASS system.

BEIDOU NAVIGATION SATELLITE SYSTEM

(CHINA)

China has started the implementation of a GNSS system known as BeiDou Navigation Satellite System (BDS). The system is being implemented in two phases: the initial phase provides regional coverage, while the second phase will provide global coverage.

The initial phase of the BeiDou system officially became operational in December 2012, providing coverage for the Asia Pacific region. The regional BeiDou space segment has five Geostationary Earth Orbit (GEO) satellites, five Inclined Geosynchronous Orbit (IGSO) satellites and four Medium Earth Orbit (MEO) satellites (summarized in **Table 6**).

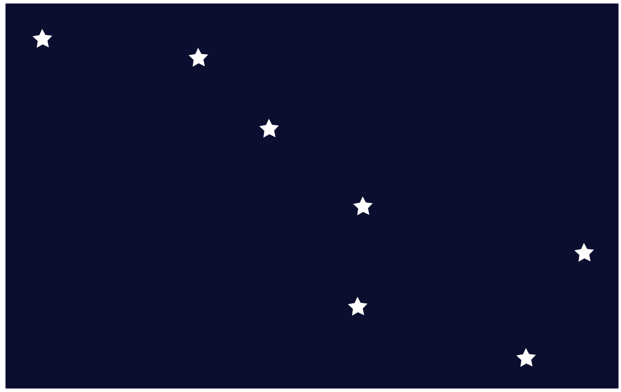


Figure 33 In Chinese, the Big Dipper Constellation is known as BeiDou

The second phase of the BeiDou system is planned to be completed by the end of 2020 and will provide global coverage with enhanced regional coverage. The space segment will consist of a constellation of 5 GEO, 3 IGSO and 27 MEO satellites, as shown in **Table 7.**

Satellites	5 GEO	5 IGSO	4 MEO
Orbital Inclination	–	55 degrees	55 degrees
Orbit Radius	35,787 km	35,787 km	21,528 km

Table 6 Regional BeiDou Satellite Constellation

Satellites	5 GEO	3 IGSO	27 MEO
Orbital Planes	–	–	3
Orbital Inclination	–	55 degrees	55 degrees
Orbit Radius	35,787 km	35,787 km	21,528 km

Table 7 Planned Global BeiDou Satellite Constellation

DESIGNATION	FREQUENCY	DESCRIPTION
B1	1561.098 MHz	B1 provides both public service signals and restricted service signals.
B2	1207.140 MHz	B2 provides both public service signals and restricted service signals.
B3	1268.520 MHz	B3 provides restricted service signals only.

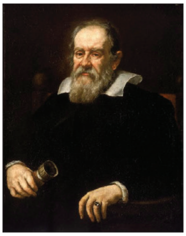
Table 8 BeiDou Signal Characteristics

BeiDou Signals

The BeiDou signals, based on CDMA technology, are summarized in **Table 8.**

Three levels of service will be provided:

- Public service for civilian use and free to users. The public service provides position accuracy of 10 metres, velocity accuracy within 0.2 metres per second and timing accuracy of 10 nanoseconds.
- Licensed service is available only to users who have obtained a subscription. The licensed service improves position accuracy to 2 metres. This service also provides bi-directional short messaging (120 Chinese characters) and provides information about the system status.
- Restricted military service, more accurate than the public service, also provides system status information and military communications capability.



portrait by Justus Sustermans

Figure 34 Galilei Galileo

> "Measure what is measurable, and make measurable what is not so."
>
> **–Galilei Galileo,** Italian physicist, mathematician, astronomer, and philosopher.

GALILEO

(EUROPEAN UNION)

In May 1999, a mountaineering expedition carried a GPS receiver to the summit of Mount Everest, allowing them to accurately measure its elevation at 8,850 m (29,035 ft). We think Galileo would have been happy.

Galileo, Europe's planned global navigation satellite system, will provide a highly accurate and guaranteed global positioning service under civilian control. The United States and European Union have been cooperating since 2004 to ensure that GPS and Galileo are compatible and interoperable at the user level.

By offering dual-frequencies as standard, Galileo will deliver real-time positioning accuracy down to the metre range, previously not achievable by a publicly available system.

Galileo will guarantee availability of service under all but the most extreme circumstances and it will inform users, within seconds, of a failure of any satellite. This makes it suitable for applications where safety is crucial, such as in air and ground transportation.

The first experimental Galileo satellite, part of the Galileo System Test Bed (GSTB) was launched in December 2005. The purpose of this experimental satellite was to characterize critical Galileo technologies, which were already in development under European Space Agency (ESA) contracts. Four operational satellites were launched, two in October 2011 and two in October 2012, to validate the basic Galileo space and ground segment. In coming years, the remaining satellites will be launched, with plans to reach FOC likely sometime after 2020.

European Space Agency

Figure 35 Galileo Satellite in Orbit

Satellites	27 operational and three active spares
Orbital planes	3
Orbital inclination	56 degrees
Orbit radius	23,222 km

Table 9 Galileo Satellite Constellation

System Design

The Galileo space segment is summarized in **Table 9**. Once the constellation is operational, Galileo navigation signals will provide coverage at all latitudes. The large number of satellites, together with the optimization of the constellation and the availability of the three active spare satellites, will ensure that the loss of one satellite has no discernible effect on the user segment.

Two Galileo Control Centres (GCC), located in Europe, control the Galileo satellites. Data recovered by a global network of thirty Galileo Sensor Stations (GSS) will be sent to the GCC through a redundant communications network. The GCCs will use the data from the sensor stations to compute integrity information and to synchronize satellite time with ground station clocks. Control centres will communicate with the satellites through uplink stations, which will be installed around the world.

Galileo will provide a global Search and Rescue (SAR) function, based on the operational search and rescue satellite-aided Cospas-Sarsat[2] system. To do this, each Galileo satellite will be equipped with a transponder that will transfer

DESIGNATION	FREQUENCY	DESCRIPTION
E1 A	1575.42 MHz	Public regulated service signal.
E1 B		Safety-of-Life and open service signal (data).
E1 C		Safety-of-Life and open service signal (dataless).
E5a I	1176.45 MHz	Open service signal (data).
E5a Q		Open service signal (dataless).
E5b I	1207.14 MHz	Safety-of-Life and open service signal (data).
E5b Q		Safety-of-Life and open service signal (dataless).
AltBOC	1191.795 MHz	Combined E5a/E5b signal.
E6 A	1278.75 MHz	Public regulated service signal.
E6 B		Commercial service signal (data).
E6 C		Commercial service signal (dataless).

Table 10 Galileo Signal Characteristics

SERVICE	DESCRIPTION
Free Open Service (OS)	Provides positioning, navigation and precise timing service. It will be available for use by any person with a Galileo receiver. No authorization will be required to access this service.
Highly reliable Commercial Service (CS)	Service providers can provide added-value services, for which they can charge the end customer. The CS signal will provide high data throughput and accurate authenticated data relating to these additional commercial services.
Safety-of-Life Service (SOL)	Improves on the Open Service by providing timely warnings to users when it fails to meet certain margins of accuracy. A service guarantee will be provided for this service.
Government encrypted Public Regulated Service (PRS)	Highly encrypted restricted-access service offered to government agencies that require a high availability navigation signal.

Table 11 Galileo Services

distress signals to the Rescue Coordination Centre (RCC), which will then initiate the rescue operation. At the same time, the system will provide a signal to the user, informing them that their situation has been detected and that help is underway. This latter feature is new and is considered a major upgrade over existing systems, which do not provide feedback to the user.

Galileo Signals

Table 10 provides further information about Galileo signals.

Galileo Services

Five Galileo services are proposed, as summarized in **Table 11.**

2 Cospas-Sarsat is an international satellite-based Search And Rescue (SAR) distress alert detection and information distribution system, established by Canada, France, United States and the former Soviet Union in 1979.

DESIGNATION	FREQUENCY	DESCRIPTION
L5	1176.45 MHz	L5 will be modulated with the SPS and RS signals.
S	2492.028 MHz	S will be modulated with the SPS and RS signals. Navigation signals will also be transmitted on S.

Table 12 IRNSS Signal Characteristics

IRNSS

(INDIAN REGIONAL NAVIGATION SATELLITE SYSTEM), INDIA

India is in the process of launching its own regional navigation satellite system to provide coverage for India and the surrounding regions. The IRNSS system will consist of seven satellites, three of them in geostationary orbits and four in inclined geosynchronous orbits.[3] The system will provide a position accuracy of better than 10 metres throughout India and better than 20 metres for the area surrounding India by 1500 km.

IRNSS will provide two services. A Standard Positioning Service (SPS) available to all users and a Restricted Service (RS) available to authorized users only.

Table 12 summarizes the IRNSS signals.

The first IRNSS satellite was launched in July of 2013 and the second satellite was launched in April 2014. The full constellation of seven satellites is planned to be completed by 2015.

QZSS

(QUASI-ZENITH SATELLITE SYSTEM), JAPAN

QZSS is a four satellite system that will provide regional communication services and positioning information for the mobile environment. One of the four satellites was launched in 2010. The focus of this system is for the Japan region, but it will provide service to the Asia-Oceania region.

QZSS will provide limited accuracy in standalone mode, so it is viewed as a GPS augmentation service. The QZSS satellites use the same frequencies as GPS and have clocks that are synchronized with GPS time. This allows the QZSS satellites to be used as if they were additional GPS satellites. QZSS satellites also broadcast an SBAS compatible signal and a high-precision signal at E6.

Three of the QZSS satellites will be placed in a periodic Quasi-Zenith Orbit (QSO). These orbits will allow the satellites to "dwell" over Japan for more than 12 hours a day, at an elevation above 70° (meaning they appear almost overhead most of the time).

In the future, Japan intends to expand the QZSS system to a seven satellite system.

3 A geosynchronous orbit has an orbital period matching the Earth's sidereal rotation period. This synchronization means that for an observer at a fixed location on Earth, a satellite in a geosynchronous orbit returns to exactly the same place in the sky at exactly the same time each day. The term geostationary is used to refer to the special case of a geosynchronous orbit that is circular (or nearly circular) and at zero (or nearly zero) inclination, that is, directly above the equator. Satellites in geostationary orbits appear stationary at one location at all times.

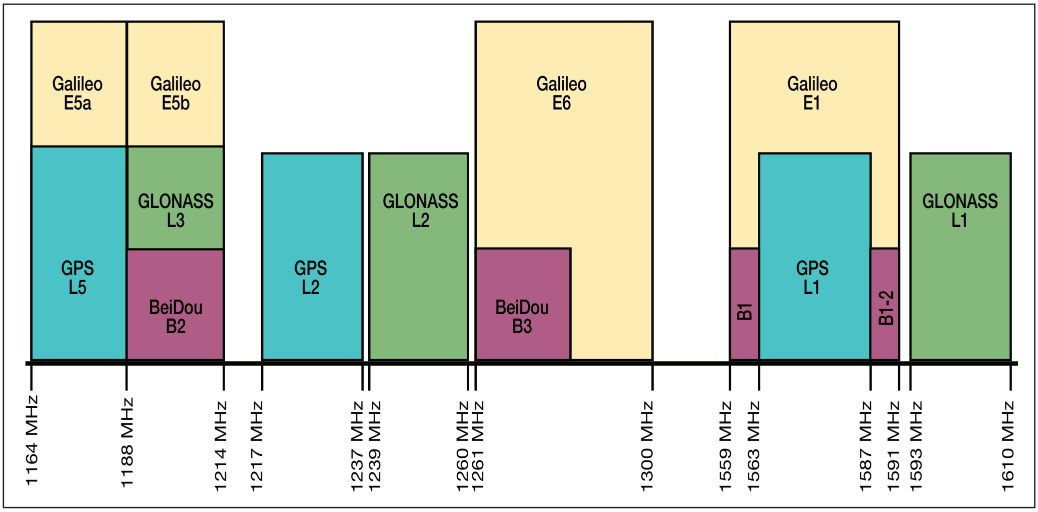


Figure 36 GNSS Signals

GNSS Signal Summary

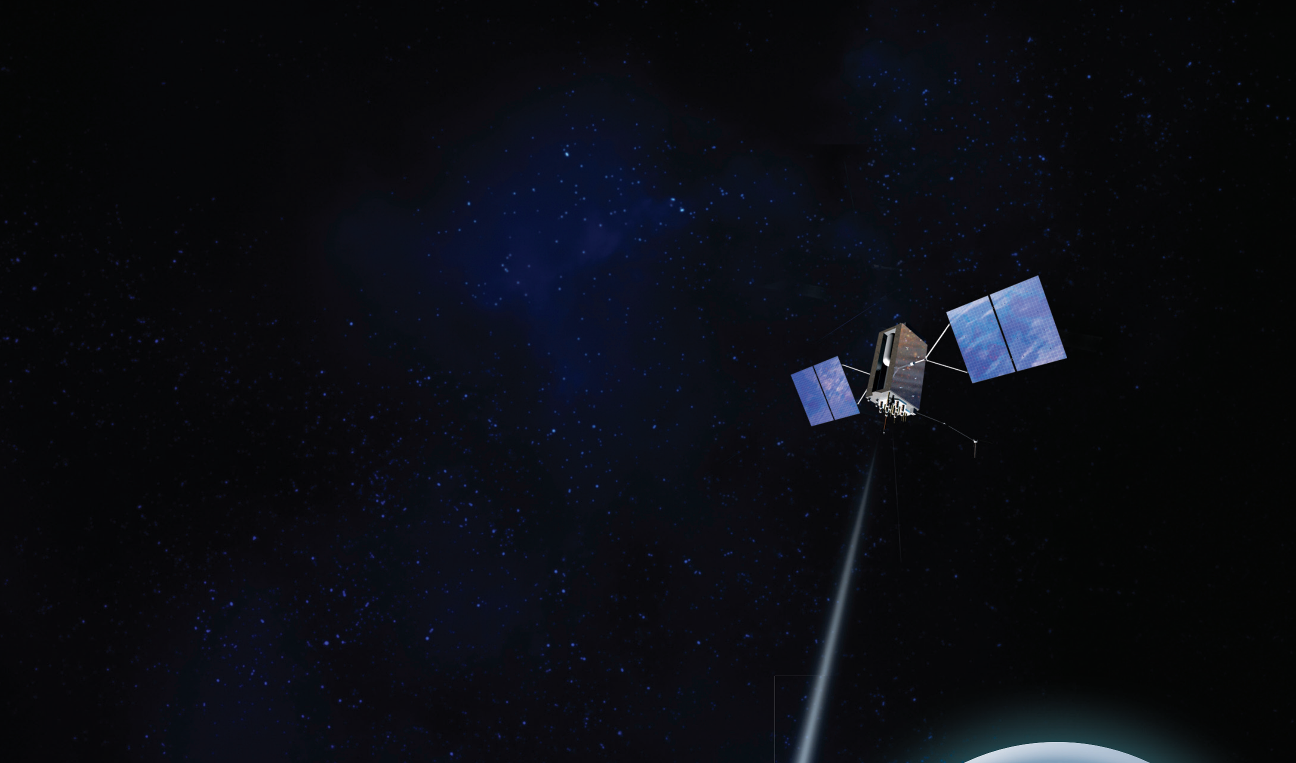
As more GNSS constellations and signals become available, the more complex the GNSS spectrum becomes. **Figure 36** shows the signals for the four global GNSS systems.

Closing Remarks

Now that you know more about global navigation satellite systems, we will discuss advanced GNSS concepts in the following chapters.

"By perseverance the snail reached the ark."

—**Charles Haddon Spurgeon,** English preacher.



"The diversity of the phenomena of nature is so great, and the treasures hidden in the heavens so rich, precisely in order that the human mind shall never be lacking in fresh nourishment."

–Johannes Kepler

Chapter Four

4 GNSS ERROR SOURCES

In Chapter 2, we introduced the concept of GNSS error sources. These are the factors that make it difficult for a GNSS receiver to calculate an exact position. In this chapter, we will look more deeply into these error sources.

Contributing Source	Error Range
Satellite clocks	±2 m
Orbit errors	±2.5 m
Ionospheric delays	±5 m
Tropospheric delays	±0.5 m
Receiver noise	±0.3 m
Multipath	±1 m

Table 13 GNSS System Errors

SATELLITE CLOCKS

The atomic clocks in the GNSS satellites are very accurate, but they do drift a small amount. Unfortunately, a small inaccuracy in the satellite clock results in a significant error in the position calculated by the receiver. For example, 10 nanoseconds of clock error results in 3 metres of position error.

The clock on the satellite is monitored by the GNSS ground control system and compared to the even more accurate clock used in the ground control system. In the downlink data, the satellite provides the user with an estimate of its clock offset. Typically, the estimate has an accuracy of about ±2 metres, although the accuracy can vary between different GNSS systems. To obtain a more accurate position, the GNSS receiver needs to compensate for the clock error.

One way of compensating for clock error is to download precise satellite clock information from an Spaced Based Augmentation System (SBAS) or Precise Point Positioning (PPP) service provider. The precise satellite clock information contains corrections for the clock errors that were calculated by the SBAS or PPP system. More information about SBAS and PPP is provided in Chapter 5.

Another way of compensating for clock error is to use a Differential GNSS or Real Time Kinematic (RTK) receiver configuration. Chapter 5 discusses Differential GNSS and RTK in depth.

ORBIT ERRORS

GNSS satellites travel in very precise, well known orbits. However, like the satellite clock, the orbits do vary a small amount. Also, like the satellite clocks, a small variation in the orbit results in a significant error in the position calculated.

The GNSS ground control system continually monitors the satellite orbit. When the satellite orbit changes, the ground control system sends a correction to the satellites and the satellite ephemeris is updated. Even with the corrections from the GNSS ground control system, there are still small errors in the orbit that can result in up to ±2.5 metres of position error.

One way of compensating for satellite orbit errors is to download precise ephemeris information from an SBAS system or PPP service provider. SBAS and PPP are discussed further in

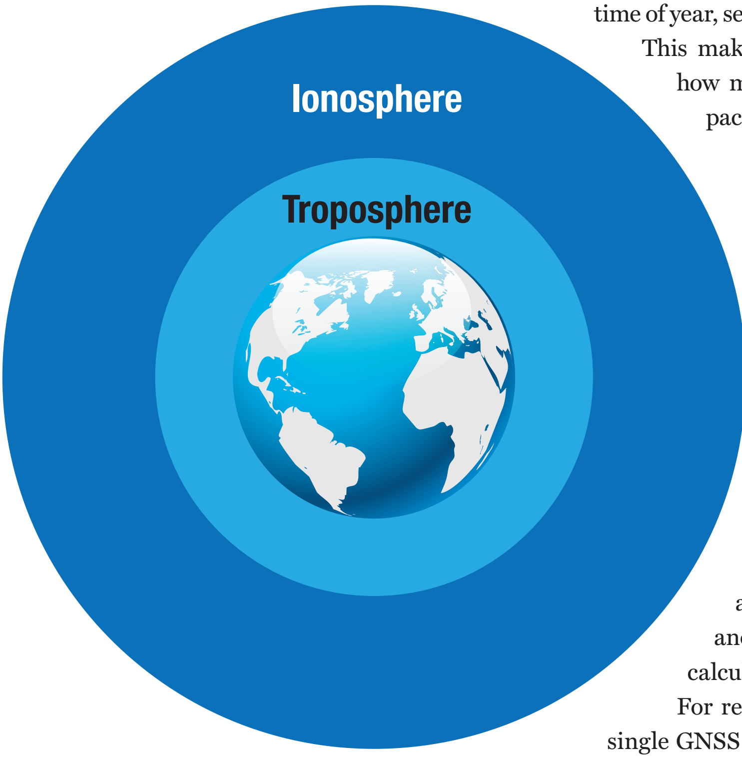


Figure 37 Ionosphere and Troposphere

Chapter 5.

Another way of compensating for satellite orbit errors is to use a Differential GNSS or RTK receiver configuration. More information about Differential GNSS and RTK is provided in Chapter 5.

IONOSPHERIC DELAY

The ionosphere is the layer of atmosphere between 80 km and 600 km above the earth. This layer contains electrically charged particles called ions. These ions delay the satellite signals and can cause a significant amount of satellite position error (Typically ±5 metres, but can be more during periods of high ionospheric activity).

Ionospheric delay varies with solar activity, time of year, season, time of day and location. This makes it very difficult to predict how much ionospheric delay is impacting the calculated position.

Ionospheric delay also varies based on the radio frequency of the signal passing through the ionosphere. GNSS receivers that can receive more than one GNSS signal, L1 and L2 for example, can use this to their advantage. By comparing the measurements for L1 to the measurements for L2, the receiver can determine the amount of ionospheric delay and remove this error from the calculated position.

For receivers that can only track a single GNSS frequency, ionospheric models are used to reduce ionospheric delay errors. Due to the varying nature of ionospheric delay, models are not as effective as using multiple frequencies at removing ionospheric delay.

Ionospheric conditions are very similar within a local area, so the base station and rover receivers experience very similar delay. This allows Differential GNSS and RTK systems to compensate for ionospheric delay.

TROPOSPHERIC DELAY

The troposphere is the layer of atmosphere closest to the surface of the Earth.

Variations in tropospheric delay are caused by the changing humidity, temperature and atmospheric pressure in the troposphere.

Since tropospheric conditions are very similar within a local area, the base station and rover receivers experience very similar tropospheric delay. This allows Differential GNSS and RTK systems to compensate for tropospheric delay.

GNSS receivers can also use tropospheric models to estimate the amount of error caused by tropospheric delay.

Receiver Noise

Receiver noise refers to the position error caused by the GNSS receiver hardware and software. High end GNSS receivers tend to have less receiver noise than lower cost GNSS receivers.

MULTIPATH

Multipath occurs when a GNSS signal is reflected off an object, such as the wall of a building, to the GNSS antenna. Because the reflected signal travels farther to reach the antenna, the reflected signal arrives at the receiver slightly delayed. This delayed signal can cause the receiver to calculate an incorrect position.

The simplest way to reduce multipath errors is to place the GNSS antenna in a location that is away from the reflective surface. When this is not possible, the GNSS receiver and antenna must deal with the multipath signals.

Long delay multipath errors are typically handled by the GNSS receiver, while short delay multipath errors are handled by the GNSS antenna. Due to the additional technology required to deal with multipath signals, high end GNSS receivers and antennas tend to be better at rejecting multipath errors.

CLOSING REMARKS

This chapter has described the errors sources that cause inaccuracies in the calculation of position. In Chapter 5, we will describe the methods that GNSS receivers use to mitigate these errors and provide a more accurate position.

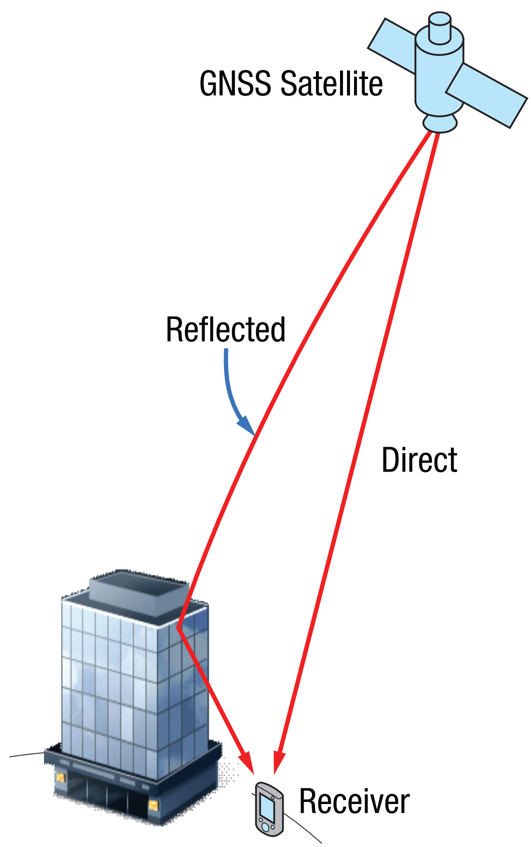


Figure 38 Multipath


“Logic will get you from A to B.
Imagination will take you everywhere.”
–Albert Einstein

Chapter Five

5 RESOLVING ERRORS

Resolving errors is fundamental to the performance of a GNSS receiver. How a manufacturer develops a receiver, including both hardware and software design elements, directly impacts the effectiveness of error resolution. The more errors a receiver can eliminate, the higher the degree of positioning accuracy and reliability it can achieve.

What is the ideal technique to correct for errors? There really is no "best way", as it all depends on the positioning performance required by the end user application. Using the GNSS receiver in your cell phone to find that new restaurant does not require the same level of performance as landing an unmanned helicopter on a moving platform, for example.

There are trade-offs between the different methods of removing errors in GNSS signals. The methods employed depend on the unique requirements of each application such as level of accuracy, system complexity, solution availability, reliability and cost.

In Chapter 2, we introduced the basic concepts of GNSS positioning, specifically as they apply to single-point positioning, where a single GNSS receiver operates individually, or "standalone," to determine its location and time. In this chapter, we introduce methods by which GNSS receivers improve performance by using more advanced techniques that mitigate or eliminate errors within the position calculation. Fundamentally GNSS positioning all starts with the simple mathematical formula of: Velocity = Distance ÷ Time. Therefore, factors that affect the distance to the satellite or the time it takes for a satellite signal to arrive at the antenna need to be addressed.

Luckily, some very smart people have developed techniques to resolve errors. In general, these techniques can be described as follows:

A. Averaging of repeated observations at the same location (the least efficient method).

B. Modeling of the phenomenon that is causing the error and predicting the correction values.

C. Differential Corrections (DGNSS).

In this chapter we will examine a number of correction techniques, how they work and some of the benefits and challenges of each method. But let's first look at the concepts of multi-constellation/multi-frequency and code versus carrier phase GNSS measurements and their impact on error resolution and positioning performance.

MULTI-CONSTELLATION, MULTI-FREQUENCY

The ability of a GNSS receiver to handle multiple frequencies from multiple constellations in the calculation of position is essential to optimal error resolution.

Multi-Frequency

Using multi-frequency receivers is the most effective way to remove ionospheric error from the position calculation. Ionospheric error varies with frequency so it impacts the various GNSS signals differently. By comparing the delays of two GNSS signals, L1 and L2, for example, the receiver can correct for the impact of ionospheric errors.

The new and modernized wideband signals in the L5/E5a band provide inherent noise and multipath mitigation capabilities. When receivers combine L5/E5a capabilities with the ability to remove ionospheric error using dual-frequency, significant improvements in both measurement and positioning accuracy can be achieved.

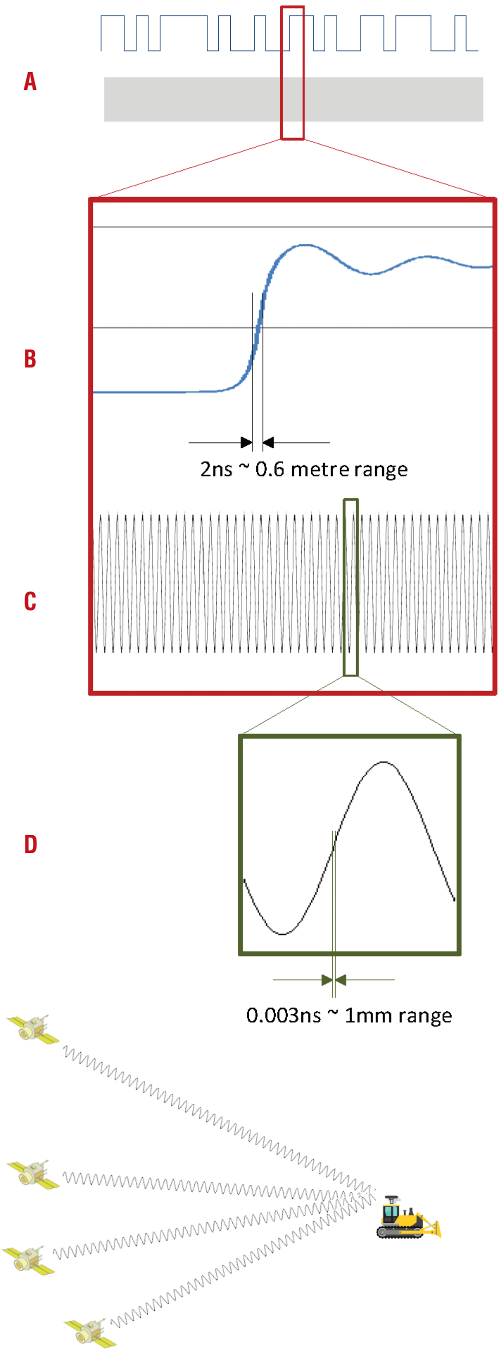


Figure 39 Code vs Carrier Phase

Multi-frequency receivers also provide more immunity to interference. If there is interference in the L2 frequency band around 1227 MHz, a multi-frequency receiver will still track L1 and L5 signals to ensure ongoing positioning.

Multi-Constellation

As described previously, a multi-constellation receiver can access signals from several constellations: GPS, GLONASS, BeiDou and Galileo for example. The use of other constellations in addition to GPS, results in there being a larger number of satellites in the field of view, which has the following benefits:

- Reduced signal acquisition time.
- Improved position and time accuracy.
- Reduction of problems caused by obstructions such as buildings and foliage.
- Improved spatial distribution of visible satellites, resulting in improved dilution of precision.

When a receiver utilizes signals from a variety of constellations, redundancy is built into the solution. If a signal is blocked due to the working environment, there is a very high likelihood that the receiver can simply pick up a signal from another constellation—ensuring solution continuity. While extremely rare, if a GNSS system fails, there are other systems available.

To determine a position in GPS-only mode, a receiver must track a minimum of four satellites. In multi-constellation mode, the receiver must track five satellites, at least one of which must be from a satellite in the other constellation, so the receiver can determine the time offset between constellations.

GNSS MEASUREMENTS—CODE AND CARRIER PHASE PRECISION

The positioning technique described in Chapter 2 is referred to as a code-based technique because the receiver correlates with and uses the Pseudorandom Noise (PRN) codes transmitted by four or more satellites to determine its position and time. This results in positioning accuracies of a few metres. For some applications, such as surveying, higher accuracies are required. Carrier-based techniques such as Real-Time Kinematic (RTK) and Precise Point Positioning (PPP) have been developed that can provide positions that are orders of magnitude more accurate than code-based GNSS.

A. Phase modulation of the carrier wave using the PRN code is used to differentiate satellite signals and to provide signal timing information for range measurements.

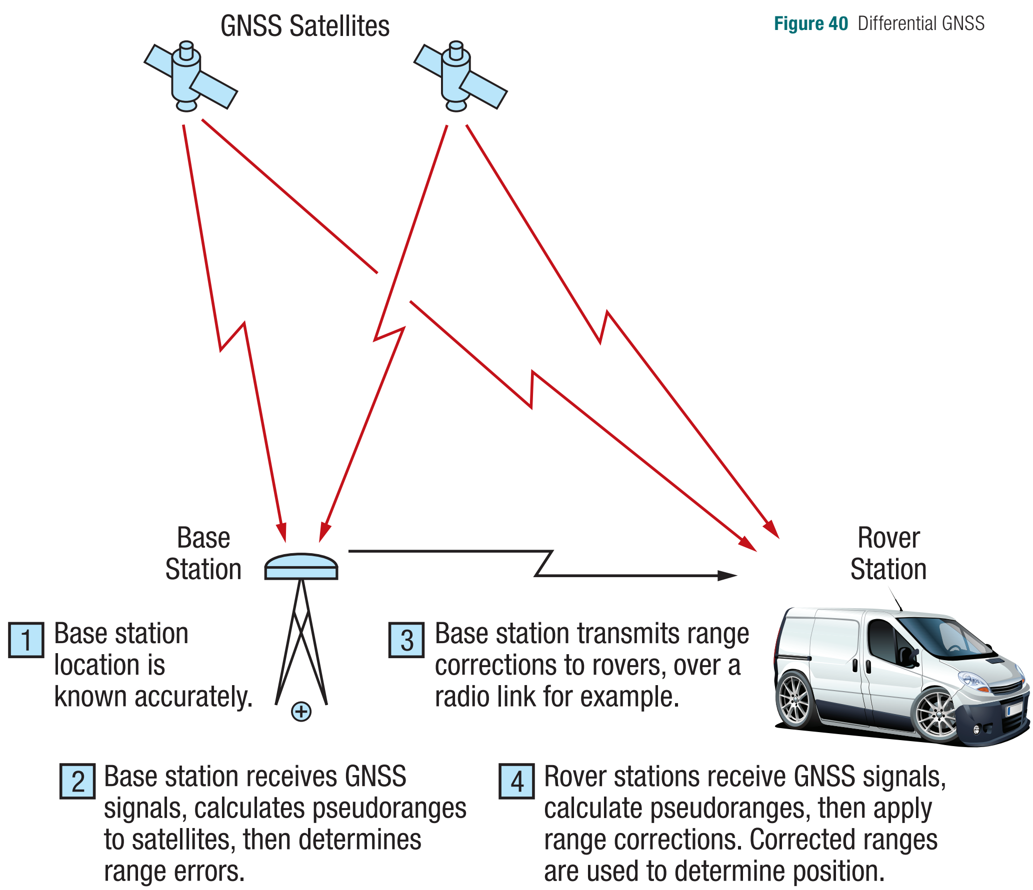
B. Measurements based on the PRN modulation are unambiguous, but precision is limited to sub-metre.

C. The carrier wave for the GNSS signal is a sine wave with a period of less than one metre (19 cm for L1), allowing for more precise measurements.

D. Measurements of the phase of the carrier wave can be made to millimetre precision, but the measurement is ambiguous because the total number of cycles between satellite and receiver is unknown.

Resolving or estimating the carrier phase ambiguities is the key to achieving precise positioning with RTK or PPP. The two methods use dif-

Figure 40 Differential GNSS



ferent techniques to achieve this but both make use of:

- Pseudorange (code-based) position estimates.
- Mitigation of positioning errors, either by using relative positioning or correction data.
- Multiple satellite signal observations to find the ambiguity terms that fit best with the measurement data.

Therefore, the method employed by the receiver, code or carrier based measurements, impacts the positioning performance.

DIFFERENTIAL GNSS

A commonly used technique for improving GNSS performance is differential GNSS, which is illustrated in **Figure 40.**

In differential GNSS, the position of a fixed GNSS receiver, referred to as a base station, is determined to a high degree of accuracy using conventional surveying techniques. Then, the base station determines ranges to the GNSS satellites in view using:

- The code-based positioning technique described in Chapter 2.
- The location of the satellites determined from the precisely known orbit ephemerides and satellite time.

The base station compares the surveyed position to the position calculated from the satellite ranges. Differences between the positions can be attributed to satellite ephemeris and clock errors, but mostly to errors associated with atmospheric delay. The base station sends these errors to other receivers (rovers), which incorporate the corrections into their position calculations.

Differential positioning requires a data link between the base station and rovers, if corrections need to be applied in real-time, and at least four GNSS satellites in view at both the base station and the rovers. The absolute accuracy of the rover's computed position will depend on the absolute accuracy of the base station's position.

Since GNSS satellites orbit high above the earth, the propagation paths from the satellites to the base stations and rovers pass through similar atmospheric conditions, as long as the base station and rovers are not too far apart. Differential GNSS works very well with base-station-to-rover separations of up to tens of kilometres.

SATELLITE BASED AUGMENTATION SYSTEMS

For applications where the cost of a differential GNSS system is not justified, or if the rover stations are spread over too large an area, a Satellite Based Augmentation System (SBAS) may be more appropriate for enhancing position accuracy.

SBAS systems are geosynchronous satellite systems that provide services for improving the accuracy, integrity and availability of basic GNSS signals.

- Accuracy is enhanced through the transmission of wide-area corrections for GNSS range errors.
- Integrity is enhanced by the SBAS network quickly detecting satellite signal errors and sending alerts to receivers that they should not track the failed satellite.
- Signal availability can be improved if the SBAS transmits ranging signals from its satellites.

SBAS systems include reference stations, master stations, uplink stations and geosynchronous satellites, as shown in **Figure 41.**

Reference stations, which are geographically distributed throughout the SBAS service area, receive GNSS signals and forward them to the master station. Since the locations of the reference stations are accurately known, the master station can accurately calculate wide-area corrections.

Corrections are uplinked to the SBAS satellite then broadcast to GNSS receivers throughout the SBAS coverage area.

User equipment receives the corrections and applies them to range calculations.

The following sections provide an overview of some of the SBAS services that have been implemented around the world or that are planned.

Wide Area Augmentation System (WAAS)

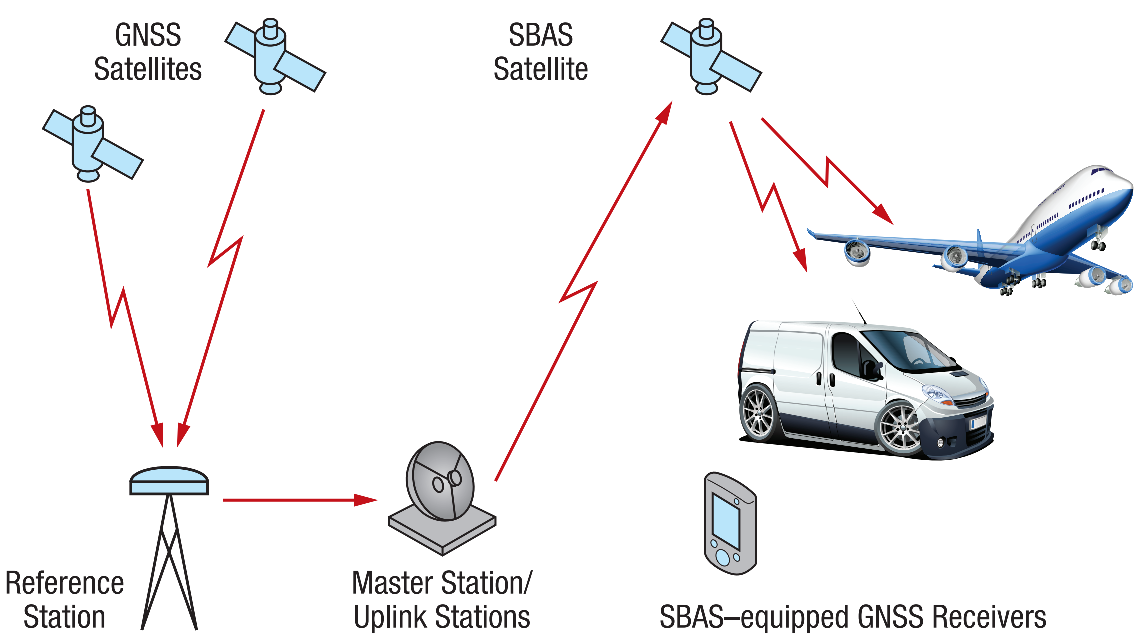
The US Federal Aviation Administration (FAA) has developed the Wide Area Augmentation System (WAAS) to provide GPS corrections and a certified level of integrity to the aviation industry, to enable aircraft to conduct precision approaches to airports. The corrections are also available free of charge to civilian users in North America.

A Wide Area Master Station (WMS) receives GPS data from Wide Area Reference Stations (WRS) located throughout the United States. The WMS calculates differential corrections then uplinks these to two WAAS geostationary satellites for broadcast across the United States.

Separate corrections are calculated for ionospheric delay, satellite timing, and satellite orbits, which allows error corrections to be processed separately, if appropriate, by the user application.

WAAS broadcasts correction data on the same frequency as GPS, which allows for the use of the same receiver and antenna equipment as that used for GPS. To receive correction data, user equipment must have line of sight to one of the WAAS satellites.

Figure 41 SBAS System Overview



European Geostationary Navigation Overlay Service (EGNOS)

The European Space Agency, in cooperation with the European Commission (EC) and EUROCONTROL (European Organization for the Safety of Air Navigation) has developed the European Geostationary Navigation Overlay Service (EGNOS), an augmentation system that improves the accuracy of positions derived from GPS signals and alerts users about the reliability of the GPS signals.

Three EGNOS satellites cover European Union member nations and several other countries in Europe. EGNOS transmits differential correction data for public use and has been certified for safety-of-life applications. EGNOS satellites have also been placed over the eastern Atlantic Ocean, the Indian Ocean, and the African mid-continent.

MTSAT Satellite Based Augmentation System (MSAS)

MSAS is an SBAS that provides augmentation services to Japan. It uses two Multi-functional Transport Satellites (MTSAT) and a network of ground stations to augment GPS signals in Japan.

GPS-Aided GEO Augmented Navigation system (GAGAN)

GAGAN is an SBAS that supports flight navigation over Indian airspace. The system is based on three geostationary satellites, 15 reference stations installed throughout India, three uplink stations and two control centers. GAGAN is compatible with other SBAS systems, such as WAAS, EGNOS and MSAS.

System for Differential Corrections and Monitoring (SDCM)

The Russian Federation is developing SDCM to provide Russia with accuracy improvements and integrity monitoring for both the GLONASS and GPS navigation systems. By 2016, the Russian Federation plans to provide L1 SBAS coverage for all Russian territory and by 2018 L1/L5 coverage. SDCM will also provide Precise Point Positioning (PPP) services for L1/L3 GLONASS by 2018.

Other SBAS Systems

China is planning SNAS (Satellite Navigation Augmentation System), to provide WAAS-like service for the China region.

Ground Based Augmentation System

A Ground Based Augmentation System (GBAS) provides differential corrections and satellite integrity monitoring to receivers using a VHF radio link. Also known as a Local Area Augmentation System (LAAS), a GBAS consists of several GNSS antennas placed at known locations, a central control system and a VHF radio transmitter.

GBAS covers a relatively small area (by GNSS standards) and is used for applications that require high levels of accuracy, availability and integrity. Airports are an example of a GBAS application.

REAL-TIME KINEMATIC (RTK)

The positioning technique we described in Chapter 2 is referred to as code-based positioning, because the receiver correlates with and uses the pseudorandom codes transmitted by four or more satellites to determine the ranges to the satellites. From these ranges and knowing where the satellites are, the receiver can establish its position to within a few metres.

For applications that require higher accuracies, RTK is a technique that uses carrier-based ranging and provides ranges (and therefore positions) that are orders of magnitude more precise than those available through code-based positioning.

RTK techniques are complicated. The basic concept is to reduce and remove errors common to a base station and rover pair, as illustrated in **Figure 42.**

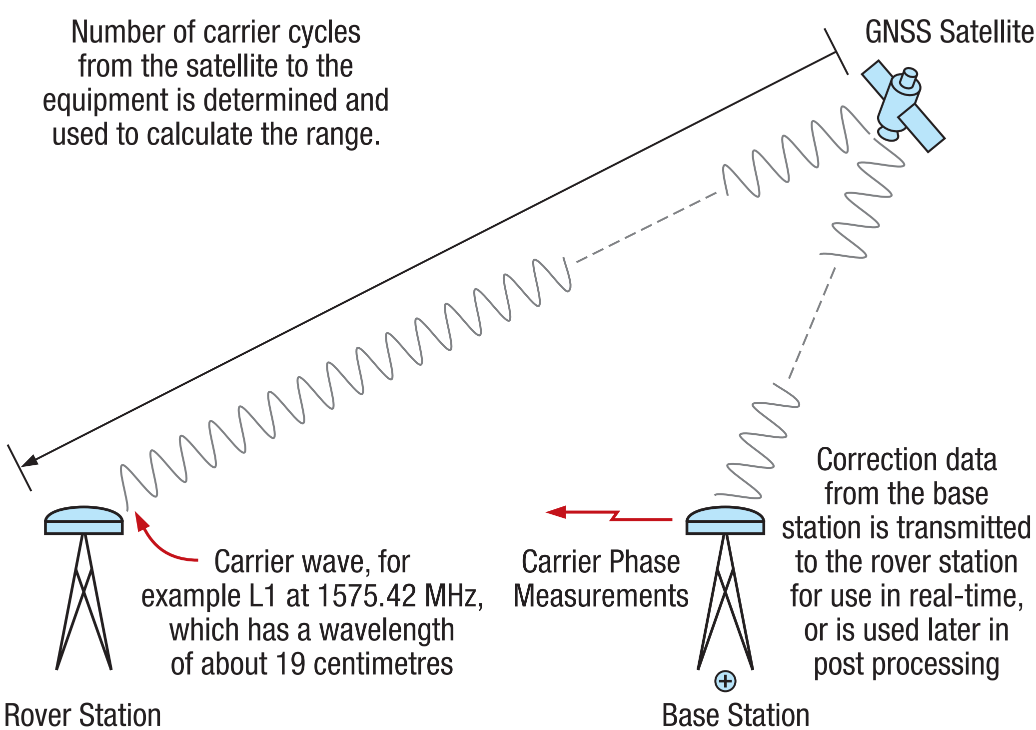
At a very basic conceptual level, the range is calculated by determining the number of carrier cycles between the satellite and the rover station, then multiplying this number by the carrier wavelength.

The calculated ranges still include errors from such sources as satellite clock and ephemerides, and ionospheric and tropospheric delays. To eliminate these errors and to take advantage of the precision of carrier-based measurements, RTK performance requires measurements to be transmitted from the base station to the rover station.

A complicated process called "ambiguity resolution" is needed to determine the number of whole cycles. Despite being a complex process, high precision GNSS receivers can resolve the ambiguities almost instantaneously. For a brief description of ambiguities, see the *GNSS Measurements–Code and Carrier Phase Precision* section earlier in this chapter. For further information about ambiguity resolution, see the references at the back of this book.

Rovers determine their position using algorithms that incorporate ambiguity resolution and differential correction. Like DGNSS, the position accuracy achievable by the rover depends on, among other things, its distance from the base station (referred to as the "baseline")

Figure 42 Real-Time Kinematic



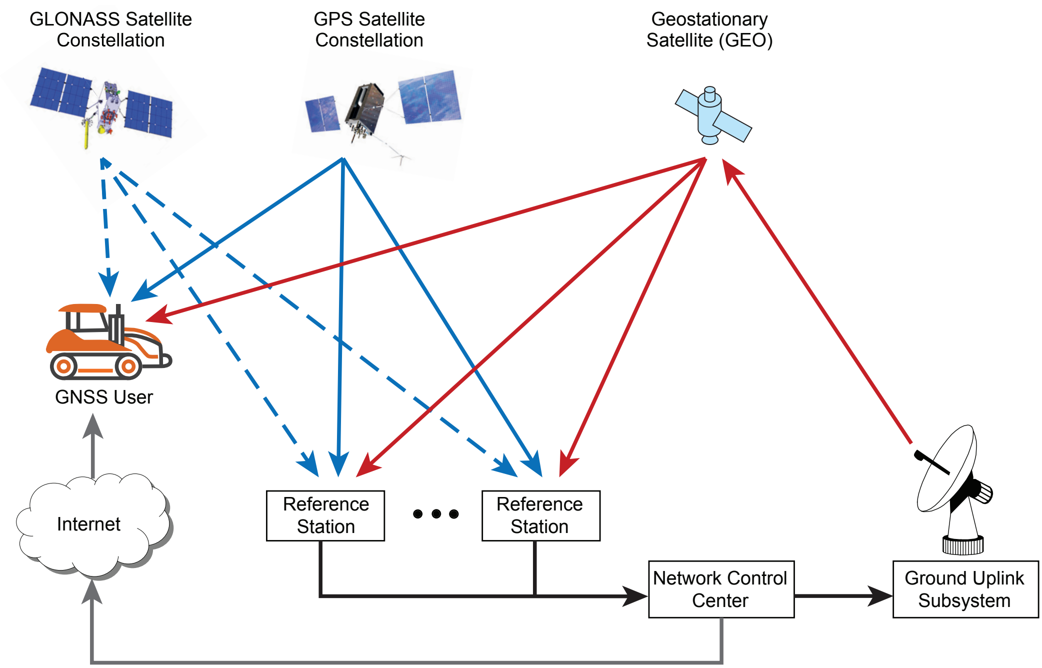


Figure 43 Precise Point Positioning (PPP) System Overview

and the accuracy of the differential corrections. Corrections are as accurate as the known location of the base station and the quality of the base station's satellite observations. Site selection is important for minimizing environmental effects such as interference and multipath, as is the quality of the base station and rover receivers and antennas.

Network RTK

Network RTK is based on the use of several widely spaced permanent stations. Depending on the implementation, positioning data from the permanent stations is regularly communicated to a central processing station. On demand from RTK user terminals, which transmit their approximate location to the central station, the central station calculates and transmits correction information or corrected position to the RTK user terminal. The benefit of this approach is an overall reduction in the number of RTK base stations required. Depending on the implementation, data may be transmitted over cellular radio links or other wireless medium.

PRECISE POINT POSITIONING (PPP)

PPP is a positioning technique that removes or models GNSS system errors to provide a high level of position accuracy from a single receiver. A PPP solution depends on GNSS satellite clock and orbit corrections, generated from a network of global reference stations. Once the corrections are calculated, they are delivered to the end user via satellite or over the Internet. These corrections are used by the receiver, resulting in decimetre-level or better positioning with no base station required.

A typical PPP solution requires a period of time to converge to decimetre accuracy in order to resolve any local biases such as the atmospheric conditions, multipath environment and satellite geometry. The actual accuracy achieved and the convergence time required is dependent on the quality of the corrections and how they are applied in the receiver. Up to 3 centimetre accuracy is possible.

Similar in structure to an SBAS system, a PPP system provides corrections to a receiver to increase position accuracy. However, PPP systems typically provide a greater level of accuracy and charge a fee to access the corrections. PPP systems also allow a single correction stream to be used worldwide, while SBAS systems are regional. A typical PPP system is shown in **Figure 43.**

The main error sources for PPP are mitigated in following ways:

DUAL-FREQUENCY OPERATION: The first-order ionospheric delay is proportional to the carrier wave frequency. Therefore, the first-order ionospheric delay can totally be eliminated by using the combinations of dual-frequency GNSS measurements.

EXTERNAL ERROR CORRECTION DATA: This includes satellite orbit and clock corrections. In the case of TerraStar service, the corrections generated are broadcast for end-users by Inmarsat telecommunication satellites.

MODELING: The tropospheric delay is corrected using the UNB model developed by the University of New Brunswick. However, the wet part of tropospheric delay is highly varying and it cannot be modeled with sufficient accuracy. Thus, residual tropospheric delay is estimated when estimating position and other unknowns. Modeling is also used in the PPP receiver to correct the solid earth tides effect.

PPP FILTER ALGORITHMS: An Extended Kalman Filter (EKF) is used for the PPP estimation. Position, receiver clock error, tropospheric delay and carrier-phase ambiguities are estimated EKF states. EKF minimizes noise in the system and enables estimating position with centimetre-level accuracy. The estimates for the EKF states are improved with successive GNSS measurements, until they converge to stable and accurate values. The typical convergence time of PPP to under 10 cm horizontal error is between 20 and 40 minutes, but it depends on the number of satellites available, satellite geometry, quality of the correction products, receiver multipath environment and atmospheric conditions.

There are several providers of PPP services, including, VERIPOS, TerraStar, OmniSTAR and StarFire. PPP service providers operate a network of ground reference stations to collect correction data for the different signals broadcast by each satellite. The corrections calculated from this data are broadcast from geostationary satellites to the receivers of subscribed users.

More information about PPP is also available in the Advanced GNSS Positioning Solution article in the 2014 Velocity magazine. This magazine is available on line at: *http://www.novatel.com/technology-in-action/velocity/*

GNSS DATA POST-PROCESSING

For many applications, such as airborne survey, corrected GNSS positions are not required in real-time. For these applications, raw GNSS satellite measurements are collected and stored for processing post-mission. Unlike RTK GNSS positioning, post-processing does not require real-time transmission of differential correction messages. This simplifies the hardware configuration greatly.

During post-processing, base station data can be used from one or more GNSS receivers. Multi-base processing helps preserve high accuracy over large project areas, which is a common occurrence for aerial applications. Depending on the project's proximity to a permanently operating GNSS network, base station data can often be freely downloaded, eliminating the need for establishing your own base station(s). Moreover, it is possible to process without any base station data through PPP, which utilizes downloaded precise clock and ephemeris data.

Post-processing applications offer a great deal of flexibility. Applications can involve stationary or moving base stations, and some support integration with customer or third-party software modules. Post-processing applications may be designed to run on personal computers, accessible through simple-to-use graphical user interfaces.

In the example shown in **Figure 44,** the route taken by the vehicle is shown in the left side of the screen, and measurements recorded during the mission, such as velocity, resolved into horizontal and vertical components, are shown in the right side.

Post-processing generally results in a more accurate, comprehensive solution than is possible in real-time.

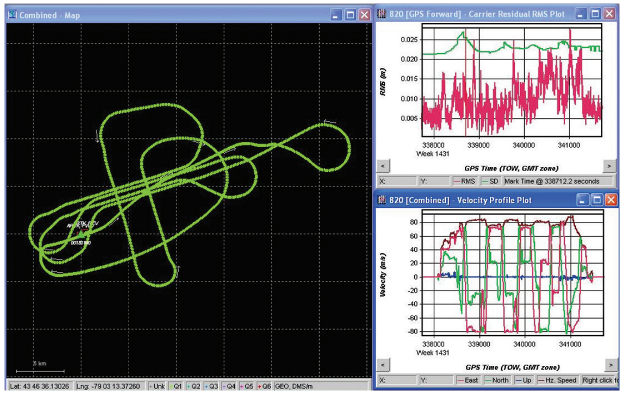


Figure 44 Post-Processing of GNSS Data

WHICH CORRECTION METHOD?

As discussed at the start of this chapter, there is no best GNSS correction method, only a method that best suites the intended application. **Figure 45** compares the accuracy and practical range of use for each of the methods discussed in this chapter.

The following sections provide comparisons between the correction methods.

DGNSS vs RTK

The configuration of Differential GNSS (DGNSS) and RTK systems are similar in that both methods require a base station receiver setup at a known location, a rover receiver that gets corrections from the base station and a communication link between the two receivers. The difference is that RTK (a carrier phase method) is significantly more accurate than DGNSS (a code-based method).

The advantage of DGNSS is that it is useful over a longer baseline (distance between base station and rover receivers) and a DGNSS system is less expensive. The technology required to achieve the higher accuracy of RTK performance makes the cost of a RTK-capable receiver higher than one that is DGNSS-capable only.

SBAS vs PPP

An SBAS system and a PPP system are similar in

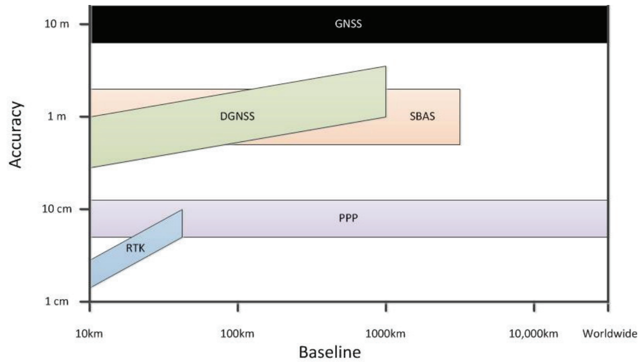


Figure 45 Comparison of GNSS Correction Method Accuracy

that both systems receive corrections from satellites. However, a PPP system is significantly more accurate than an SBAS system. Part of the accuracy advantage is the correction method. PPP systems use the carrier phase method and SBAS systems use the code method. The other part of the accuracy advantage is that the private corrections services typically used by PPP systems provide higher quality corrections and are multi-frequency, multi-constellation.

The advantage of SBAS systems is that the corrections services are free for everyone to use. While the private corrections services provide higher quality corrections and are available world wide, a paid subscription is required to access the signals.

Also, since SBAS is a code-based method, there are no ambiguities to resolve and full SBAS accuracy is available almost immediately. PPP systems require time to converge (resolve ambiguities) before full accuracy is available.

DGNSS vs SBAS

While the accuracy of DGNSS and SBAS are similar, the equipment required for the systems is different.

An SBAS system only requires an SBAS capable receiver and a GNSS antenna. A DGNSS system requires a base station receiver and antenna, a rover receiver and antenna and a communication link between the base station and rover. As well, the DGNSS system requires additional system setup as the base station must be in a known location.

RTK vs PPP

Like DGNSS and SBAS, RTK and PPP offer similar accuracies, but the equipment and setup required is different.

An RTK system offers higher accuracy and quick initialization, but is more complex to setup and more expensive.

The RTK system requires at least two RTK capable receivers (one base station and one or more rovers), a GNSS antenna for each receiver and a communication link between the receivers. Also, to achieve the high level of accuracy, the base station must be very precisely set up at a known location.

A PPP system has a simpler configuration; a single PPP compatible receiver, an antenna capable of receiving GNSS and L-Band frequencies and a subscription to a corrections service provider. However, PPP has a somewhat lower accuracy and longer initial convergence time.

Another differentiator is the baseline length. The distance between base station and rover (baseline length) on an RTK system directly impacts system accuracy. At short baseline lengths, a few kilometres, RTK is very accurate. However, as the baseline length increases, the accuracy and availability of a solution decreases. At long baseline lengths RTK can no longer be used. Because PPP does not use a base station, it is not affected by baseline length and can provide full accuracy anywhere in the world.

CLOSING REMARKS

This chapter has described, at a high level, some very complex GNSS concepts. If you want to learn more about these, we have provided a list of references at the end of the book.

“Science is a way of thinking much more than it is a body of knowledge.”

–Carl Sagan

6 Chapter Six
GNSS + INS

In Chapter 5, we described the techniques used to improve GNSS accuracy by reducing the impact of GNSS error sources. In this chapter, we introduce systems in which GNSS receivers work with other sensors to provide position and navigation when GNSS conditions are difficult.

GNSS+INS SYSTEMS

As discussed, GNSS uses signals from orbiting satellites to compute position, time and velocity. GNSS navigation has excellent accuracy provided the antenna has line of sight visibility to at least four satellites. When the line of sight to satellites is blocked by obstructions such as trees or buildings, navigation becomes unreliable or impossible.

An Inertial Navigation System (INS) uses rotation and acceleration information from an Inertial Measurement Unit (IMU) to compute a relative position over time. An IMU is made up of six complimentary sensors arrayed on three orthogonal axes. On each of the three axes is coupled an accelerometer and a gyroscope. The accelerometers measure linear acceleration and the gyroscopes measure rotational acceleration. With these sensors, an IMU can measure its precise relative movement in 3D space. The INS uses these measurements to calculate position and velocity. An additional advantage of the IMU measurements is they provide an angular solution about the three axes. The INS translates this angular solution into a local attitude (roll, pitch and azimuth) solution which it can provide in addition to the position and velocity.

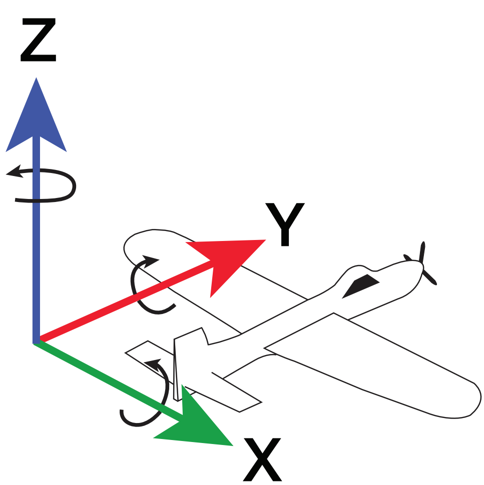


Figure 46 Example of IMU Axes

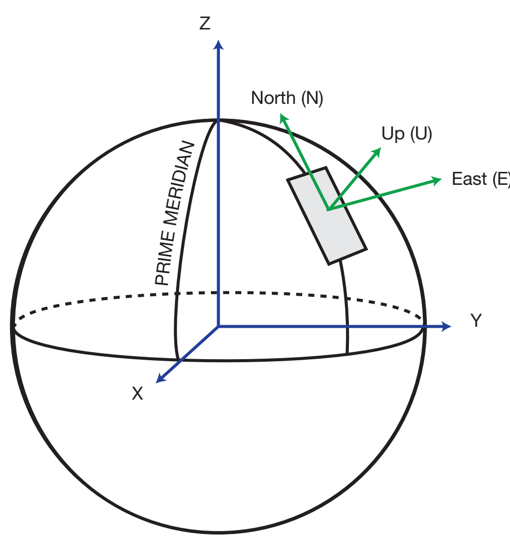


Figure 47 Axes Relative to Earth

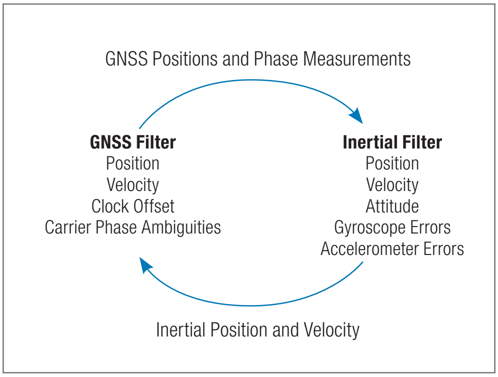


Figure 48 Tightly Coupled GNSS+INS System

The ability of the INS to provide attitude determination is an important addition for several applications, such as aerial survey and hydrography. For example, in aerial surveys it is not only important to know where the camera was when the picture was taken, but also what angle the camera was relative to the ground.

An IMU provides these accelerations and rotations to the INS system as discrete measurements at a specific frequency. Typically, INS systems run at rates between 50 and 1000 Hz, although most IMUs are capable of sampling their data at much faster rates.

Of course, all systems, including IMUs and therefore INS, have their own drawbacks. First, an INS provides only a relative solution from an initial start point. This initial start point must be provided to the INS. Second, and more critically, the high frequency measurements provided by the IMU include several error sources. Depending on the quality (i.e., cost/size) of the IMU these errors can be fairly large relative to the actual measurements being recorded. Navigating in 3D space with an IMU is effectively a summation (or integration) of hundreds/thousands of samples per second during which time the errors are also being accumulated. This means that an uncorrected INS system will drift from the true position quickly without an external reference. Providing an external reference to the INS allows it to estimate the errors in the IMU measurements using a mathematical filter and mitigate their effect.

That external reference can quite effectively be provided by GNSS. GNSS provides an absolute set of coordinates that can be used as the initial start point. As well, GNSS provides continuous positions and velocities thereafter which are used to update the INS filter estimates. When GNSS is compromised due to signal obstructions, the INS system can continue to navigate effectively for longer periods of time.

Using GNSS positions and velocities to estimate INS errors is called a 'loosely coupled' system. However GNSS+INS combined systems can get much more elaborate than that. A variety of terms such as 'tightly coupled' or 'deeply coupled' clearly indicate a much more symbiotic relationship between the two. In these systems, raw GNSS measurements are used directly to aid the INS and the INS can even be used as a constraint to help GNSS reacquire lost signals more quickly or reject bad signals. **Figure 48** shows a simplified diagram of a tightly coupled system.

Thus, when GNSS and INS are combined, the two techniques enhance each other to provide a powerful navigation solution, as illustrated in **Figure 49.** When the GNSS conditions are good (line of sight to several satellites), the GNSS receiver provides accurate position and time to the navigation system. When the GNSS conditions become poor, the INS provides the position and navigation until the GNSS conditions improve.

ODOMETERS

GNSS is not the only useful input to aid inertial navigation. For different environments, different sensors can also be added to aid the solution. A common external sensor for ground vehicles is the addition of an odometer. This provides another independent measurement of displacement and velocity that can aid the GNSS+INS navigation solution. This is mostly of use when the GNSS signal is denied, for example when traveling through a tunnel.

VISION AIDED NAVIGATION

Another potential aiding source is the use of photogrammetry, or using vision aided navigation. In a vision aided navigation system, imagery is used to provide position information to a navigation system. Images from a camera are processed by the navigation system to recognize and track objects in the environment.

There are two ways this can be used. Known surveyed camera targets can be used to generate an absolute position in a certain environment or everyday objects can be used as control points; when an object is recognized by the system, the relative change in successive images can be used to generate a relative position change of the camera in 3D space.

This means that a vision aided system can be combined with a GNSS+INS system to provide position and attitude updates to the INS when GNSS updates are not available. An example application for a vision aided navigation system is an unmanned vehicle used to carry a load from a yard into a warehouse. When the unmanned vehicle is outside, the GNSS+INS provides the navigation for the vehicle. When inside the warehouse, the vision aided system uses known features/targets within the building to provide position updates to the INS.

SENSOR FUSION

A term growing in popularity in this field is 'sensor fusion'. Increasingly it is not just GNSS, or even GNSS+INS, it is an amalgamation of any and all available information to create the most robust and accurate solution available in all conditions. All of the input technologies, GNSS, INS, cameras, odometers, digital elevation models, range sensors, etc. are taken into account.

CLOSING REMARKS

If you want to learn more about the topic in this chapter, we have provided a list of references at the end of the book.

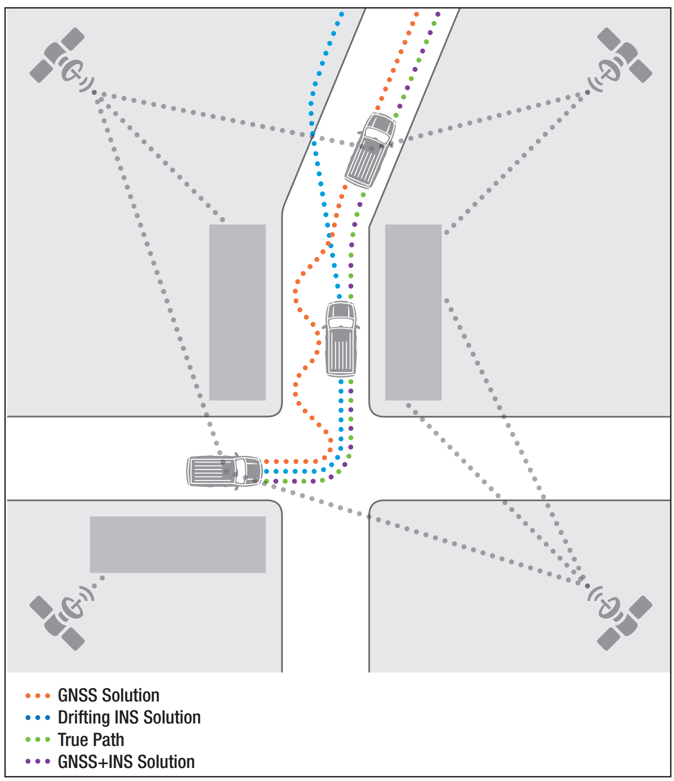
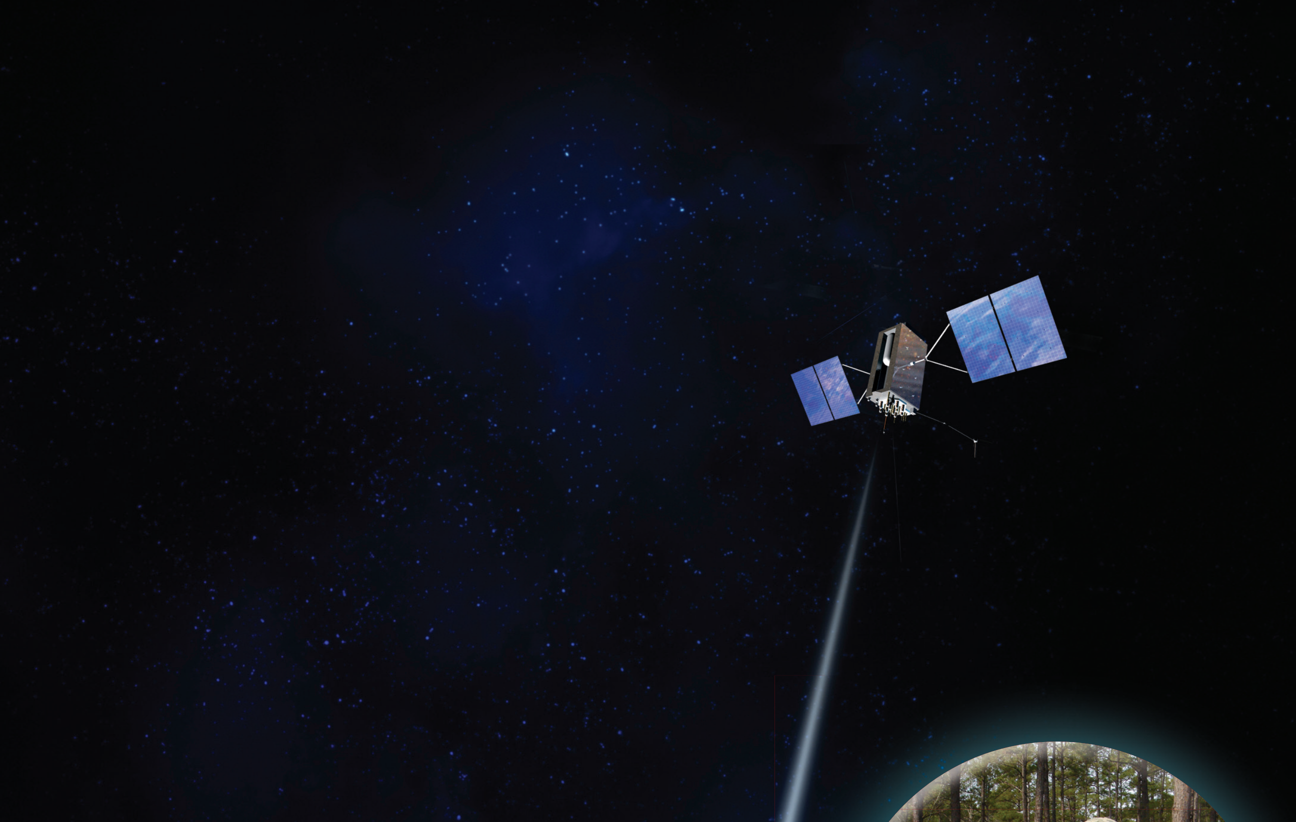


Figure 49 Combined GNSS+INS Solution



> “I don’t spend my time pontificating about high-concept things; I spend my time solving engineering and manufacturing problems.”
>
> –**Elon Musk**

7 *Chapter Seven*

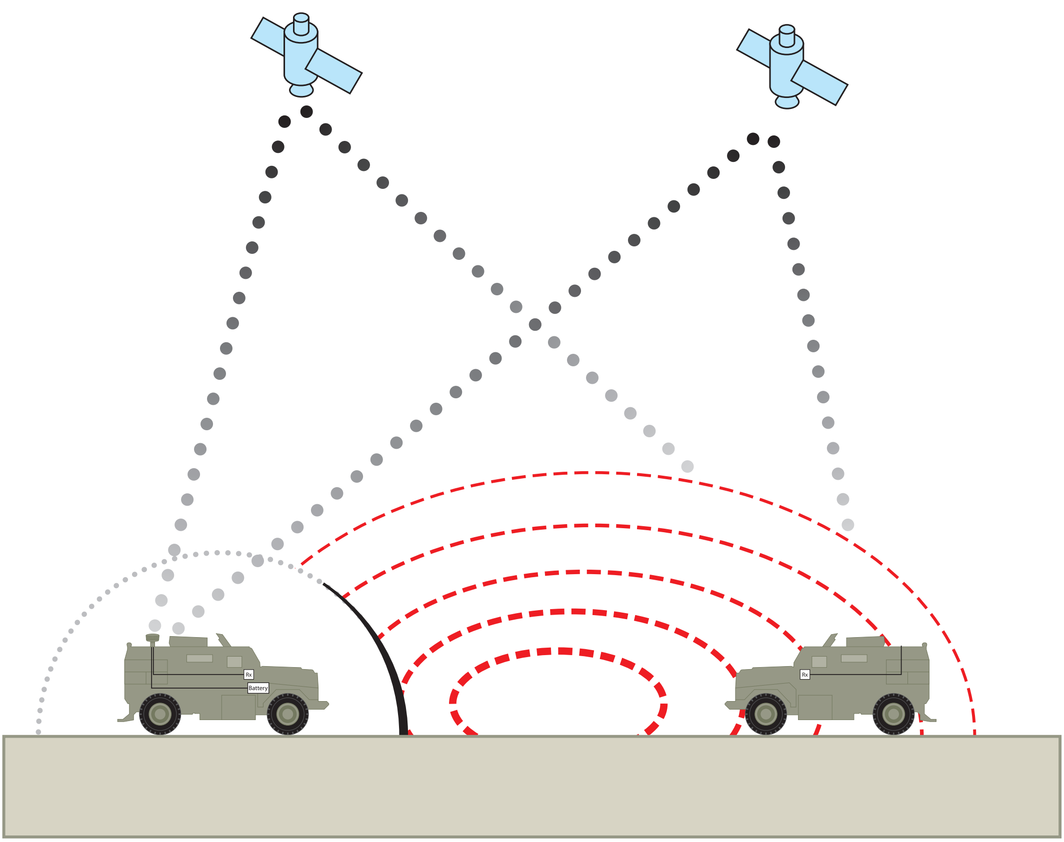
GNSS DENIAL

A receiver can not provide position, navigation or time because the GNSS signals are not available to the receiver due to interference, spoofing, signal blockage or constellation failure is said to be suffering from "GNSS Denial". The following sections describe the causes of GNSS denial and the methods used to mitigate them.

INTERFERENCE

By the time GNSS signals have travelled from the satellites to the receiver, the signals are at a very low power level. This low power level makes the signals susceptible to interference from other signals transmitted in the GNSS frequency range. If the interfering signal is suf-

Figure 50 Anti-Jam Antenna Protecting Against a Jammer



ficiently powerful, it becomes impossible for the receiver to detect the low power GNSS signal. An analogy is trying to have a conversation in a room with a stereo playing. If the stereo is playing very loud, it is impossible to hear the conversation over the music.

If the signal is from an unintentional source, such as faulty radio equipment, it is called interference. If the signal is intentionally transmitted in the GNSS frequency range, it is called jamming.

GNSS receivers use several methods to protect against interference and jamming.

Anti-Jam Antennas

Anti-jam antenna systems, comprised of Controlled Reception Pattern Antennas (CRPA) and sophisticated electronics, use the multiple antenna elements to control the amount of signal received from a particular direction. When an anti-jam system senses interference from one direction, it turns down the antenna gain, similar to turning down the volume, for that direction. This reduces the amount of interference received so that legitimate GNSS signals can be received from other directions.

Figure 50 shows two vehicles in range of a GNSS jammer. The vehicle on the right has a standard antenna and the GNSS signals are overpowered by the jammer. The vehicle on the left has an anti-jam antenna that blocks the jamming signal so GNSS signals can be received.

If the interfering signal has a narrow bandwidth, GNSS receivers can protect against the interference by tracking multiple frequencies and multiple constellations. For example, if the interference is in the 1550 to 1600 MHz range, GPS L1 would be blocked. However, a receiver can still provide position, navigation and time if the receiver can track GPS L2 or L5, GLONASS L2 or Galileo E5. A description of the existing and upcoming GNSS signals is given in Chapter 3.

Multiple Navigation Sensors

For short term interference, additional navigation sensors, such as Inertial Measurement Units (IMUs), odometers or altimeters can help the receiver bridge brief periods of GNSS outage. A discussion of systems that use GNSS receivers and IMUs, called GNSS+Inertial Navigation Systems (INS) is presented in Chapter 6.

SPOOFING

Unlike interference where GNSS is denied by overpowering the GNSS signal, spoofing tricks the receiver into reporting an incorrect location or time by introducing a false signal that is either created by a signal generator or is a rebroadcast of a real recorded GNSS signal. Also, unlike interference, spoofing is always an intentional attack.

To deny GNSS by spoofing, the attacker broadcasts a signal with the same structure and frequency as the GNSS signal. The spoofing signal controls its transmitted power level so the receiver will lock onto the spoofed signal rather than the real GNSS signal. In the spoofed signal, the message is changed so that the receiver will calculate an incorrect position or time.

The most effective way to protect against spoofing is to track an encrypted signal (such as the Y-code signal on GPS L1 and L2) that is broadcast by several of the GNSS constellations. Access to the encrypted signals is restricted and not available to all users, however there are mitigation methods that can be used with open signal receivers.

Spoofing GNSS signals is complicated and requires sophisticated equipment. It also generally needs information about the velocity of the target. The complexity of spoofing increases greatly if the attacker attempts to simultaneously spoof more than one GNSS frequency or constellation. So, a receiver that can track multiple frequencies and/or multiple constellations can be used to detect and overcome a possible spoofing attempt.

Also, other navigation sensors, such as GNSS+INS, can be used to detect and overcome a spoofing attempt as the signals from the IMU cannot be spoofed.

SIGNAL BLOCKAGE

A GNSS receiver needs a clear line of sight to the satellites it is tracking. If the line of sight to a satellite is blocked by objects such as buildings, trees, bridges, etc., the receiver cannot receive signals from that satellite. In locations that have a lot of obstructions, such as the downtown area of a large city, the obstructions can block so many satellites that the receiver cannot calculate its position or time.

One solution to signal blockage is for the receiver to track more than one constellation. By tracking more than one constellation, there will be more satellites available and a better chance of finding enough satellites to determine a position and time. The use of multiple navigation sensors, such as IMUs, helps not only in bridging outages such as those due to signal blockage, but also in reacquisition of the GNSS signals after the outage.

CONSTELLATION FAILURE

Although it is extremely unlikely that an entire constellation will fail, receivers that can track more than one constellation provide protection from this unlikely scenario.

CLOSING REMARKS

With the many technologies and applications depending on the GNSS to provide position, navigation and time, the topic of GNSS Denial is becoming increasingly important. If you want to learn more about this subject, we have provided a list of references at the end of the book.

8

> “Equipped with his five senses, man explores the universe around him and calls the adventure Science.”
>
> –Edwin Powell Hubble

Chapter Eight

8 GNSS APPLICATIONS AND EQUIPMENT

"Every generation needs a new revolution."

–Thomas Jefferson, influential Founding Father and third president of the United States.

We don't think it is an overstatement to say that the application of GNSS has revolutionized, and will continue to revolutionize, the way businesses and governments operate, and how we conduct our personal lives. This chapter highlights some of the incredible GNSS applications and equipment that are now available.

APPLICATIONS

In a short book, it is impossible to describe all GNSS applications. We will highlight some of the commercial applications, including:

- Consumer
- Transportation
- Machine Control
- Precision Agriculture
- Construction
- Mining
- Surveying
- Aerial Photogrammetry
- Ground Mapping
- GIS
- Port Automation
- Timing
- Marine
- Unmanned Vehicles
- Defense

CONSUMER

GNSS technology has been adopted by the consumer market, in an ever-increasing range of products.

GNSS receivers are now routinely integrated into smartphones, to support applications that display maps showing the location of and best route to stores and restaurants.

Portable navigation devices give drivers directions on road or off, as shown in **Figure 51.**

Geocaching is an outdoor activity in which participants use a GNSS receiver to hide and seek containers (called "geocaches" or "caches") around the world.

Currently, most GNSS consumer products are based on GPS, but this will change as more GNSS constellations are implemented.

TRANSPORTATION

"I knew I was going to take the wrong train, so I left early." **–Yogi Berra.**

In rail transportation, GNSS is used in conjunction with other technologies, to track the location of locomotives and rail cars, maintenance vehicles and wayside equipment, for display at central monitoring consoles. Knowing the precise location of rail equipment reduces accidents, delays, and operating costs, enhancing safety, track capacity, and customer service.

In aviation, GNSS is being used for aircraft navigation from departure, en route, to landing. GNSS facilitates aircraft navigation in remote areas that are not well served by ground-based navigation aids, and it is a significant component of collision-avoidance systems, and of systems used to improve approaches to airport runways. Refer to "Wide Area Augmentation System

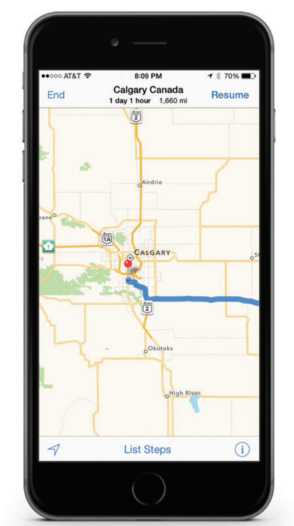


Figure 51 Portable Navigation Device

(WAAS)" in Chapter 5 for information about WAAS, a US system that delivers GPS corrections and a certified level of integrity to the US aviation industry, enabling aircraft to conduct precision approach to airports.

In marine transportation, GNSS is being used to accurately determine the position of ships when they are in open sea and also when they are maneuvering in congested ports. GNSS is incorporated into underwater surveying, buoy positioning, navigation hazard location, dredging, and mapping.

In surface transportation, vehicle location and in-vehicle navigation systems are now being used throughout the world. Many vehicles are equipped with navigation displays that superimpose vehicle location and status on maps. GNSS is used in systems that track and forecast the movement of freight and monitor road networks, improving efficiency and enhancing driver safety.

Port Automation

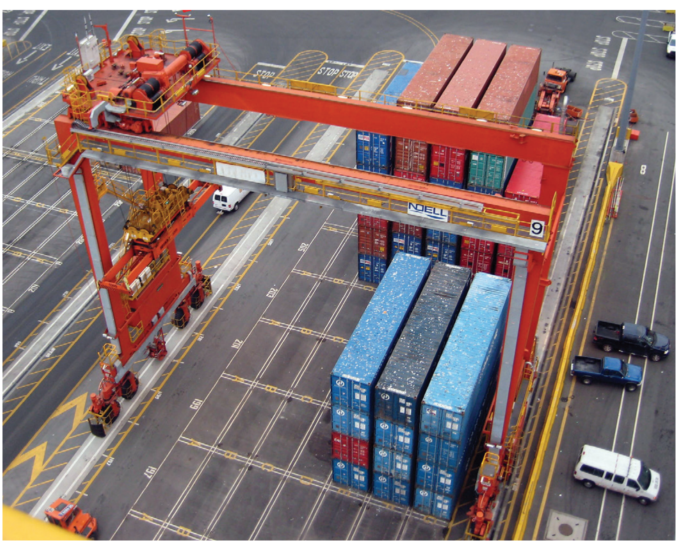
Using GNSS, shipping hubs can improve their operating efficiency by tracking the movement and placement of containers about their yards.

Gantry cranes are used in ports throughout the world to lift shipping containers, as shown in **Figure 52**. These cranes are large and sometimes difficult to steer accurately in a crowded shipping dock. Many cranes are equipped with GNSS-based steering devices that determine the crane's position and keep it travelling in the desired path, improving accuracy and productivity as well as the safety of operators and workers on the ground. A key benefit is the quick movement of containers about the port, which reduces food spoilage and gets toys delivered on time.

Driver Testing in China

The automotive market is booming in China. In 2001, there were only 5 million cars driving the roads in China. By the end of 2012, the number of cars had reached 120 million. This huge increase in cars also means a huge increase in new drivers. To manage the testing of all these new drivers, the Chinese government has instituted an automated test as part of the drivers license test. In the automated test, the new drivers are required to perform a series of standard driving tasks, such as parking, turning, stopping, etc., on a surveyed course at a licensing facility. To automate the test, the licensing facilities use a GNSS system installed in the car to monitor and evaluate the driver. The GNSS system installed on the car uses dual antennas so that the GNSS system can not only monitor the car's position and speed, but also detect the direction the car is going *(heading)*.

An article *(Road Test)* about how GNSS is used for driver license testing is in the 2013 Ve-



Adley Eng, NovAtel Inc.

Figure 52 Gantry Crane in the Port of Vancouver locity magazine available at: *www.novatel.com/technology-in-action/velocity/*.

Parking Automation

In the Canadian city of Calgary, paying for on street parking has become automated. Customers pay for parking at street side terminals or using their smartphone and monitoring of the parked vehicles is done from a vehicle equipped with cameras and GNSS receiver.

When a customer pays for parking, they enter the license plate of their vehicle, a code that identifies the parking area and the amount of parking time required. This information is sent to a database. As the monitoring vehicle drives along the street, the vehicle cameras capture the license plates of the parked cars. The license plate number, along with the time and position provided by the GNSS receiver, is compared to the database of paid parking. If a vehicle is not found in the database, the photograph is sent to a Calgary Parking Authority employee so they can determine if there is a just cause (e.g. people are just getting out of car), there is a mistake in identifying the license plate (e.g. a D is mistaken for an O) or if it is a parking violation.

Due to the tight urban corridors in downtown Calgary, the location reported by the GNSS only system on the monitoring vehicles was misplacing 6-7% of the vehicles (approximately 1,400 vehicles) per day and the vehicles could be misplaced by up to 600 metres. This misplacement caused many hours of extra work each day for Calgary Parking Authority employees, because they have to manually correct the vehicles position before they can determine if there was a parking violation.

By switching from a GNSS only system to a GNSS+INS system, the monitoring vehicle was able to overcome the GNSS challenges in downtown Calgary and provide a much more reliable position. The GNSS+INS system reduced the number of misplaced cars to 1% (less than 300) saving the Calgary Parking Authority enough work hours to pay for GNSS+INS system in all of their monitoring vehicles in under two years.

An article *(Calgary ParkPlus Program, City-Wide Positional Accuracy)* about how GNSS+INS has helped the Calgary Parking Authority is in the 2014 Velocity magazine available at: *www.novatel.com/technology-in-action/velocity/*.

MACHINE CONTROL

GNSS technology is being integrated into equipment such as bulldozers, excavators, graders, pavers and farm machinery to enhance productivity in the real-time operation of this equipment, and to provide situational awareness information to the equipment operator. The adoption of GNSS-based machine control is similar in its impact to the earlier adoption of hydraulics technology in machinery, which has had a profound effect on productivity and reliability.

Some of the benefits of GNSS-based machine control are summarized below:

EFFICIENCY: By helping the equipment operator get to the desired grade more quickly, GNSS helps speed up the work, reducing capital and operating costs.

ACCURACY: The precision achievable by GNSS-based solutions minimizes the need to stop work while a survey crew measures the grade.

JOB MANAGEMENT: Managers and contractors have access to accurate information about the jobsite, and the information can be viewed remotely.

DATA MANAGEMENT: Users can print out status reports, save important data and transfer files to head office.

THEFT DETECTION: GNSS GNSS allows users to define a "virtual fence" about their equipment and property, for the purpose of automatically raising an alarm when equipment is removed, then providing equipment tracking information to the authorities.

8 *Chapter Eight*

GNSS APPLICATIONS AND EQUIPMENT

"Farming looks mighty easy when your plough is a pencil, and you're a thousand miles from the corn field."

–**Dwight D. Eisenhower,** thirty-fourth U.S. president.

Thomas Morley, NovAtel Inc.

Figure 53 Precisely Aligned Crop Rows Planted by GNSS-guided Machinery

PRECISION AGRICULTURE

In precision agriculture, GNSS-based applications are used to support farm planning, field mapping, soil sampling, tractor guidance, and crop assessment. More precise application of fertilizers, pesticides and herbicides reduces cost and environmental impact. GNSS applications can automatically guide farm implements along the contours of the earth in a manner that controls erosion and maximizes the effectiveness of irrigation systems. Farm machinery can be operated at higher speeds, day and night, with increased accuracy. This increased accuracy saves time and fuel, and maximizes the efficiency of the operation. Operator safety is also increased by greatly reducing fatigue.

CONSTRUCTION

GNSS information can be used to position the cutting edge of a blade (on a bulldozer or grader, for example) or a bucket (excavator), and to compare this position against a 3D digital design to compute cut/fill amounts. "Indicate systems" provide the operator with visual cut/fill information, via a display or light bar, and the operator manually moves the machine's blade or bucket to get to grade. Automatic systems for bulldozers/graders use the cut/fill information to drive the hydraulic controls of the machine to automatically move the machine's blade to grade. Use of 3D machine control dramatically reduces the number of survey stakes required on a job site, reducing time and costs. Productivity studies have repeatedly shown that the use of 3D machine control results in work being completed faster, more accurately and with significantly less rework than conventional construction methods.

SURFACE MINING

GNSS information is being used to efficiently manage the mining of an ore body and the movement of waste material. GNSS equipment installed on shovels and haul trucks provides position information to a computer-controlled dispatch system to optimally route haul trucks to and from each shovel. Position information is also used to track each bucket of material extracted by the shovel, to ensure that it is routed to the appropriate location in the mine (crusher, waste dump, leach pad). Position information is used by blast hole drills to improve fracturization of the rock material and control the depth of each hole that is drilled, to keep the benches level. Multi-constellation GNSS is particularly advantageous in a surface mining environment due to the obstructions caused by the mine's walls. More satellites means more signal availability.

Automated Blast Hole Drilling

Automated drills are used in surface mines to increase safety and productivity. A single operator, located in the safer control room, can operate and monitor up to five automated drills.

The blast holes drilled by the automated drills must be very precise both horizontally and vertically. The position of the holes (horizontal accuracy) is critical in controlling rock fragmentation. Rock fragments that are too large or too fine can increase wear on the rock crushers used to process the material. Hole depth (vertical accuracy) is important for creating a flat bench.

Figure 54 Automatically Guided Trenching Machine

NovAtel Inc.

Three GNSS technologies are used on the automated drills, RTK, heading and multi-constellation. RTK provides the precise positioning needed to accurately locate the blast holes. Heading provides the alignment of the drill to ensure the holes are drilled perpendicular. Multi-constellation receivers compensate for signal blockages common in the high wall environment typical of surface mines.

An article *(The Pit, The Bit and The Benefit)* about how GNSS is used in automated drilling is in the 2013 Velocity magazine available at: *www.novatel.com/technology-in-action/velocity/*.

SURVEY

GNSS-based surveying reduces the amount of equipment and labour required to determine the position of points on the surface of the Earth, when compared with previous surveying techniques. Using GNSS, it is possible for a single surveyor to accomplish in one day what might have taken a survey crew of three people a week to complete.

Figure 55 GNSS-based Surveying Equipment

Figure 56 Aerial Image of Niagara Falls

Determining a new survey position once required measuring distances and bearings from an existing (known) survey point to the new point. This required measurements using theodolites to measure angular differences and metal "chains" (long heavy tape measures), pulled taught to minimize sag and accurately measure distances. If the new and existing survey points were separated by a large distance, the process would involve multiple setups of the theodolite, then multiple angular and distance measurements.

Using GNSS, surveyors can now set up a DGNSS or RTK base station over an existing survey point and a DGNSS or RTK rover over the new point, then record the position measurement at the rover. This simplification shows why the surveying industry was one of the early civilian adopters of GNSS technology.

Seismic Survey Sensors

In a seismic survey, sound waves are sent from a source (explosives or a thumper truck) through the ground to an array of sensors (geophones). Knowing the exact location and orientation of the geophones is critical for a successful survey.

Using traditional geophones, the placement of the geophones was a two step process. First a team surveys the area and places markers for each geophone. Later, a second team places the geophones precisely on the marked locations and then orients the geophones using a direction measuring device, such as a compass.

Using GNSS enabled geophones, eliminates the need to survey the area first. The GNSS enabled geophones have a GNSS receiver and dual antennas integrated in the geophone. The receiver and dual antennas allows the geophone to not only determine its exact location, but also its orientation.

An article *(Building a Better Geophone)* about how GNSS is used to simplify geophone placement is in the 2013 Velocity magazine available at: *www.novatel.com/technology-in-action/velocity/*.

AERIAL PHOTOGRAMMETRY

Aerial photogrammetry refers to the recording of images of the ground (photographs, for example) from an elevated position, such as an aircraft. Systems of this type are now more generally referred to as "remote sensing," since the images can be taken from aircraft or from satellites.

In the past, images would have to be manually corrected for orientation, perspective and the height of the camera and location, and manually "stitched" together. This manual process would be based on the accurate alignment of known points in adjacent pictures.

By integrating the camera with GNSS and INS, it is now possible to automate the process, in real time or post-mission, to "transfer" the location accuracy of the aircraft, determined from GNSS, to the image.

Aerial photographs are used in online map systems such as Google Earth. Many of us have found our houses, and perhaps even our cars, through these applications.

GNSS technology has also been integrated with LiDAR (Light Detection and Ranging), an optical remote sensing technology used to measure range to distant targets. It is possible to image a feature or object down to the wavelength, which at LiDAR frequencies is less than a millionth of a metre.

Mapping Wildfires

To battle wildfires, fire fighters need to know the locations of the fires and any hotspots. Using an airplane equipped with an infrared imaging sensor and a GNSS+INS system, the locations of the fires and hotspots can be projected on topographical or 3D terrain maps.

An article *(Custom Airborne Mapping Solutions)* about how GNSS is used in aerial mapping is in the 2014 Velocity magazine available at: *www.novatel.com/technology-in-action/velocity/*.

GROUND MAPPING

Products have been developed that take 360-degree panoramic photographs to support the presentation of geometrically correct images on a computer screen. These images are continuous and precisely positioned. GNSS and IMU data is recorded before the panoramic photographs are taken. Position and attitude data is programmed into the cameras, allowing on-screen determination of positions of objects in the photos, or measurements between objects.

Infrastructure Visualization

Using a LiDAR system combined with a GNSS+INS system, a user can capture comprehensive visual information of key infrastructure, such as oil and gas pipelines. This visual information provides the state, location and positioning of the infrastructure and its related assets. It also assists in planning for maintenance and modifications.

An article *(Seeing is Believing)* about how GNSS and LiDAR are used for infrastructure visualization is in the 2014 Velocity magazine available at: *www.novatel.com/technology-in-action/velocity/*.

GEOSPATIAL INFORMATION SYSTEMS (GIS)

A geospatial information system (GIS) captures, stores, analyzes, manages, and presents data that is linked to location. The data may consist of, for example, environmental or resource data. GIS is also used to map attributes for insurance companies, municipal planning, utility companies, and others. The positions associated with the data can be provided from a GNSS receiver. GIS applications

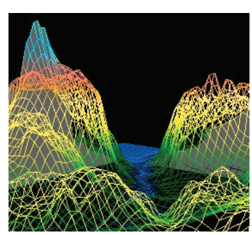

NovAtel Inc.

Figure 57 GIS Data Output

"The clock, not the steam engine, is the key-machine of the modern industrial age."

–**Lewis Mumford,** American historian of technology and science.

can generate detailed contour maps from the data and present these maps in a digital form, as illustrated in **Figure 57.**

TIME APPLICATIONS

As we mentioned in earlier chapters, time accuracy is critical for GNSS position determination. This is why GNSS satellites are equipped with atomic clocks, accurate to nanoseconds. As part of the position determining process, the local time of GNSS receivers becomes synchronized with the very accurate satellite time. This time information, by itself, has many applications, including the synchronization of communication systems, electrical power grids, and financial networks. GNSS-derived time works well for any application where precise timing is needed by devices that are dispersed over a wide area.

Seismic monitors that are synchronized with GNSS satellite clocks can be used to determine the epicenter of an earthquake by triangulation based on the exact time the earthquake was detected by each monitor.

www.wellandcanal.ca

MARINE APPLICATIONS

In the Foreword, we discussed the challenges that early explorers had determining their position when at sea. With the advent of GNSS, these problems have largely disappeared.

In addition to dramatically improving marine navigation, GNSS is also being applied to a broad range of marine applications, such as oilrig positioning, underwater cable and pipeline installation and inspection, rescue and recovery, and the dredging of ports and waterways.

GNSS-Equipped Sonobuoys

An interesting application of GNSS is the use of GNSS-equipped sonobuoys in underwater sonar systems.

Sonobuoys are dropped from aircraft over an area of interest, but are left to float autonomously. The sonobuoys detect approaching ships and other hazards in the water by transmitting sound waves through the water, detecting reflections from vessels and objects, and determining the time it takes for the "echo" to be received. The data comes up to the sonobuoy's float then is transmitted, with GNSS positioning data, over a radio link to a survey ship. The survey ship collects and analyzes sonar data from a larger number of sonobuoys then determines and displays the location of ships and objects in the area of interest.

Seafloor Mapping

Knowing the depth of the seafloor in ports and navigation channels is critical to safe marine navigation. Maps of the ports and channels are created using bathymetric sonar systems.

Figure 58 Marine Application of GNSS

Bathymetric sonar systems, mounted in a marine vessel, bounce sound waves off the seafloor to determine the depth of the water. Using these depth measurements, a map of the seafloor is created. For the seafloor maps to be accurate, the exact location of the vessel on the surface of the water must be known. A GNSS+INS system integrated with the sonar system provides the precise location of the vessel for each sonar measurement. The GNSS+INS system also provides the vertical location of the vessel to compensate for waves.

An article *(Sounding the Depths)* about how GNSS works with bathymetric sonar is in the 2014 Velocity magazine available at: *www.novatel.com/technology-in-action/velocity/.*


NASA

Figure 59 Predator Unmanned Aerial Vehicle (UAV)

UNMANNED VEHICLES

An unmanned vehicle is a vehicle that is unoccupied but under human control, whether radio-controlled or automatically guided by a GNSS-based application. There are many types of unmanned vehicles, including: Unmanned Ground Vehicle (UGV), Unmanned Aerial Vehicle (UAV), Unmanned Surface Vehicle (USV) and Unmanned Underwater Vehicle (UUV).

Initially, unmanned vehicles were used primarily by the defense industry. However, as the unmanned vehicle market has grown and diversified, the commercial use of unmanned vehicles has also grown and diversified. Some of the current civilian uses for unmanned vehicles are: search and rescue, crop monitoring, wildlife conservation, aerial photography, environmental research, infrastructure inspection, bathymetry, landmine detection and disposal, HAZMAT inspection and disaster management. As the civilian unmanned vehicle market expands, so will the civilian use of unmanned vehicles.

Hurricane Research

Knowing where a hurricane will make land fall and how powerful it will be are important to properly prepare for the storm. While meteorologists are good at predicting the potential path of a hurricane it is much harder to predict how powerful the storm will be when it arrives.

To learn more about what causes a hurricane to rapidly increase or decrease in intensity, NASA is using two long range UAVs to study the storms while they are still far out to sea. Onboard the UAVs are meteorological instruments that monitor the environmental conditions in and around the storm. The UAVs also have a GNSS+INS system that records the UAV location and attitude for each measurement taken by the meteorological instruments. An accurate UAV location and attitude is necessary for the measurement take to be useful.

An article *(Joining the Hunt)* about the NASA project to study hurricane intensification is in the 2014 Velocity magazine available at: *www.novatel.com/technology-in-action/velocity/*.

Orion Spacecraft Parachute Testing

Before the Orion spacecraft can be used for manned space missions, NASA must know that Orion can safely land on earth. A key aspect of returning the astronauts safely to earth is slowing the Orion spacecraft from its incredibly high re-entry speed of close to 32,000 km/h to less than 36 km/h. This is the job of the Capsule Parachute Assembly System (CPAS).

To test the CPAS, NASA created two unmanned test vehicles. These test vehicles are dropped out of a C-17 aircraft from altitudes as high as 35,000 feet. A GNSS+INS system installed in the test vehicles measures the vertical velocity of vehicle to test the effectiveness of parachute system.

An article *(Put to the Test)* about the Orion CPAS testing is in the 2014 Velocity magazine available at: *www.novatel.com/technology-in-action/velocity/*.

Landing an Unmanned Helicopter on a Ship

The autonomous landing of an unmanned helicopter is already challenging as the navigation system has to deal with the movement of the helicopter caused by the winds. This challenge is greatly increased when trying to land on a ship at sea. Not only is the helicopter's position changing based on its movement and the affects of the wind, the ship is moving independently based on its movement and the affects of both the wind and the sea.

When landing a helicopter on a ship, the relative distance between the helicopter landing gear and the flight deck of the ship is much more important than the absolute position of the helicopter and ship. GNSS+INS systems installed on both the helicopter and the ship are used to determine this relative distance. The GNSS+INS system on the ship calculates its position and sends that information to the GNSS+INS system on the helicopter. The GNSS+INS system on the helicopter uses the position sent from the ship along with its own position to calculate the relative distance and direction between the ship and helicopter. Using this relative distance and direction, the unmanned helicopter is able to autonomously approach and land on the ship's flight deck.

An article *(From Fledgling to Flight)* about the landing of the unmanned Little Bird helicopter on a moving ship is in the 2013 Velocity magazine available at: *www.novatel.com/technology-in-action/velocity/*.

DEFENCE

The defence sector makes broad use of GNSS technology, including:

NAVIGATION: Using GNSS receivers, soldiers and pilots can navigate unfamiliar terrain or conduct night-time operations. Most foot soldiers now carry hand-held GNSS receivers.

SEARCH AND RESCUE: If a plane crashes and that plane has a search and rescue beacon that is equipped with a GNSS receiver, it may be possible to more quickly locate it.

RECONNAISSANCE AND MAP CREATION: The military uses GNSS to create maps of uncharted or enemy territory. They can also mark reconnaissance points using GNSS.

UNMANNED VEHICLES: Unmanned vehicles are used extensively in military applications, including reconnaissance, logistics, target and decoy, mine detection, search and rescue, research and development and missions in unsecured or contaminated areas.

MUNITIONS GUIDANCE: Precision munitions use GNSS to ensure the munition lands on target.

GNSS EQUIPMENT

The first generations of commercial GNSS receivers cost well over $100,000. Now, GNSS receivers are built into smartphones. Equipment vendors have developed a wide array of equipment to support the incredible range of GNSS applications that are now available. As illustrated in **Figure 60,** GNSS equipment consists of receivers, antennas and supporting software, in varying levels of integration and performance.

Depending on the application, the antenna and receiver may be separate entities, or they may be integrated into a single package, as in a handheld GNSS receiver. GNSS equipment may be further integrated with application equipment such as a survey or hydrographic instrumentation or a transport vessel.

GNSS equipment specifications and features depend on the application. To illustrate, users need to consider the following when selecting GNSS equipment for a particular use:

ACCURACY: Applications such as survey may require centimetre-level accuracy. Others, such as positioning for hiking, may only require accuracy to within tens of metres. Some applications require absolute accuracy; that is, position defined accurately, relative to an actual reference point or location. Others may require accuracy relative to a previous position. If high-precision accuracy is obtained through the application of differential GNSS, it may be desirable that the differential service be integrated in the same package as the GNSS receiver, for example, the SBAS receiver or the radio link to the base station or rovers.

ACQUISITION TIME: For some applications, users may require a fast "time to first fix," the time required by a GNSS receiver to achieve a position solution. For other applications, it may not be important that the "fix" be available quickly. The trade-off to achieving fast acquisition time is increased probability of a wrong position/fix.

RELIABILITY: Addresses the question, "Do you need the answer (position and time) to be correct every time?"

AVAILABILITY: Equipment may be required to provide positioning service continuously, even in areas where signals from satellites are blocked. As we have discussed, these applications may best be served by equipment that integrates GNSS and INS equipment. Equipment may need to support multiple constellations and frequencies, and may need to perform well in environments characterized by a high level of multipath interference. Remember, from Chapter 4, multipath interference occurs because some of the signal energy transmitted by the satellite is reflected (and therefore delayed) on the way to the receiver.

In the selection of GNSS equipment, there will almost always be tradeoffs between accuracy, acquisition time, reliability and availability.

ENVIRONMENTAL: User equipment may have to operate over wide temperature and humidity ranges, at high altitudes, or in dusty environments. The equipment may need to be waterproof to rain or submersion.

SHOCK AND VIBRATION: Equipment may be subjected to high levels of shock and vibration, such as that which is characteristic of industrial vehicles.

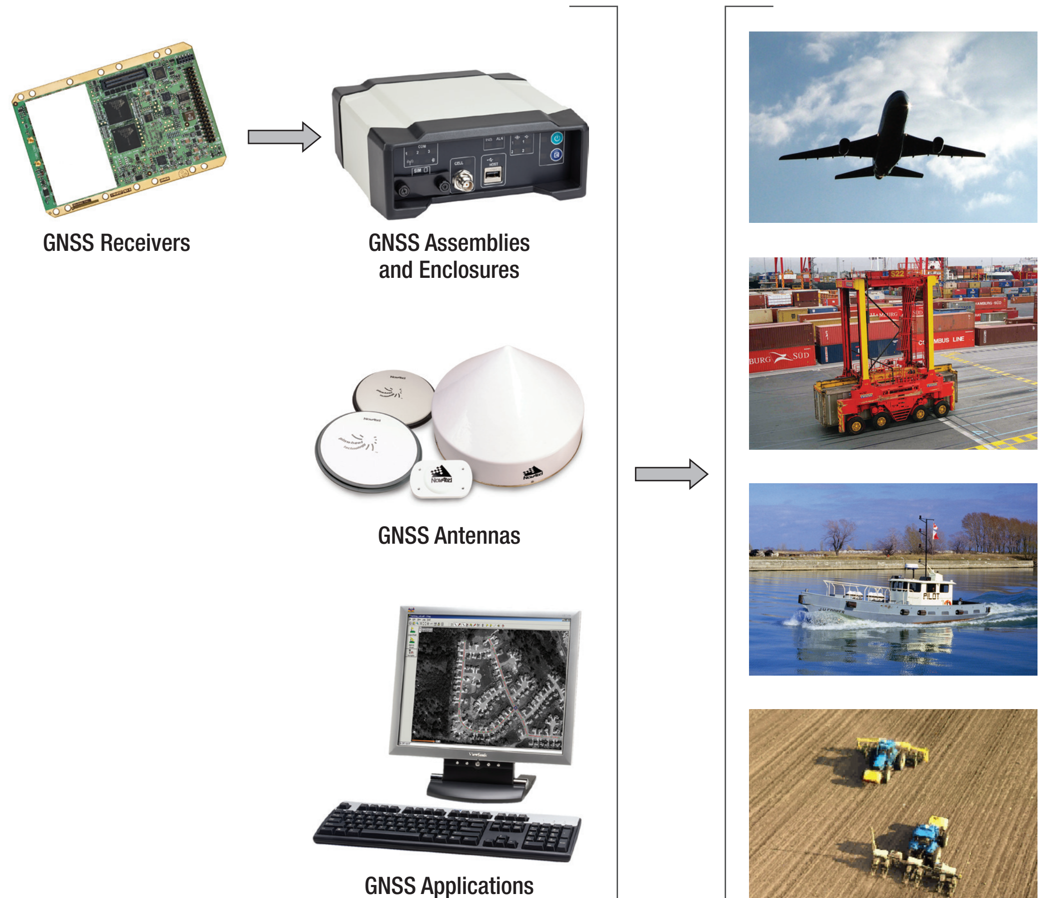


Figure 60 Examples of GNSS Equipment

PORTABILITY: Depending on the application, the equipment may need to be portable, such as hand-held device for hiking or survey.

REGULATORY: Regulatory compliance will vary with the jurisdiction in which the user is operating, for example:

- Emissions standards, such as FCC Part 15.
- Compliance with the European Union's Restriction of Hazardous Substances (RoHS) directive.
- WEEE, the European Community directive that imposes responsibility for the disposal of waste electrical and electronic equipment on the equipment manufacturer.

DATA STORAGE: Receivers may be required to store timestamped range or position information for applications that will use this information post-mission.

PHYSICAL SIZE AND POWER CONSUMPTION: The user may require a receiver or antenna with a small form-factor and low power consumption for integration in a particular application, such as UAVs.

USER INTERFACE: The manner through which the user interacts with the equipment is important; for example, a keypad for entering commands, a screen for viewing position data on a map, or connectors for outputting data to other devices.

COMPUTATIONAL REQUIREMENTS: Users may require that the equipment provide computed data such as velocity or heading.

COMMUNICATIONS: Position may only be useful if it is communicated to another device over, for example, a cellular radio link.

FUTURE-PROOF: Although some GNSS signals and constellations may not yet be available, users may require some assurance that they will be able to use these signals and constellations once they are available.

CLOSING REMARKS

Like "cyberspace," GNSS is already here, its broad acceptance and application is based on a track record of exceptional performance and reliability. Industry and government agencies are continually enhancing technology and infrastructure to enable the development of new GNSS-based solutions.

In this chapter, we have provided a broad sample of current GNSS applications to illustrate just how beneficial GNSS is–both in terms of cost efficiency and safety of life applications. GNSS technology is becoming truly ubiquitous—a prevalent, taken-for-granted technology in almost everything we do. GNSS anywhere, and anytime is here.

> "I used to think that cyberspace was fifty years away. What I thought was fifty years away, was only ten years away. And what I thought was ten years away… it was already here. I just wasn't aware of it yet."
>
> –**Bruce Sterling,** American science fiction author.

Appendices

This section includes the following appendices, which include general or supplementary information about GNSS:

- **Appendix A**–Acronyms
- **Appendix B**–GNSS Glossary
- **Appendix C**–Standards and References

1PPS	One Pulse Per Second
ADR	Accumulated Doppler Range
AFSCN	Air Force Satellite Control Network
AltBOC	Alternate Binary Offset Carrier
AMSAT	American Satellite
ARNS	Aeronautical Radio Navigation Services
ARP	Antenna Reference Point
AVL	Automatic Vehicle Location
BDS	BeiDou Navigation Satellite System
BOC	Binary Offset Carrier
C/A Code	Coarse/Acquisition Code
CASM	Coherent Adaptive Subcarrier Modulation
CD	Clock Drift
CDGPS	Canada-Wide Differential GPS
CDMA	Code Division Multiple Access
CE	Conformité Européenne (Also known as CE Mark)
CMG	Course Made Good
CNAV	Civil Navigation
C/No	Post Correlation Carrier to Noise Ratio in dB-Hz
COG	Course Over Ground
COGO	Coordinate Geometry
COSPAS	Cosmitscheskaja Sistema Poiska Awarinitsch Sudow (Russian: space system for search of vessels in distress)
CRPA	Controlled Reception Pattern Antenna
CS	Commercial Service
CTP	Conventional Terrestrial Pole
CTS	Conventional Terrestrial System
dB	Decibel
dBm	Decibel Relative to 1 milliWatt
DGNSS	Differential Global Navigation Satellite System
DGPS	Differential Global Positioning System
DOP	Dilution Of Precision
DR	Dead Reckoning
e	Eccentricity
EC	European Commission
ECEF	Earth-Centred-Earth-Fixed
EGNOS	European Geostationary Navigation Overlay System
ESA	European Space Agency
FAA	Federal Aviation Administration
FCC	Federal Communication Commission
FDMA	Frequency Division Multiple Access
FKP	Flachen Korrectur Parameter (Plane Correction Parameter) German
FOC	Full Operational Capability
FOG	Fiber Optic Gyro
GAGAN	GNSS Aided GEO Augmented Navigation (India)
GBAS	Ground Based Augmentation System
GCC	Galileo Control Centre
GDOP	Geometric Dilution Of Precision
GEO	Geostationary Earth Orbit
GIC	GNSS Integrity Channel
GIS	Geospatial Information System
GLONASS	Global Navigation Satellite System
GMS	Ground Mission Segment
GMT	Greenwich Mean Time
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRAS	Ground-based Regional Augmentation System (Australia)
GRC	Galileo Reception Chain
GRCN	Galileo Reception Chain Non-PRS
GSS	Galileo Sensor Stations
GSTB	Galileo System Test Bed
GTR	Galileo Test Receiver
GTS	Galileo Test Signal Generator
GUS	Ground Uplink Station
GUST	WAAS GUS-Type 1
GUSTR	WAAS GUST Type-1 Receiver
HDOP	Horizontal Dilution Of Precision
hex	Hexadecimal
HTDOP	Horizontal Position and Time Dilution Of Precision
Hz	Hertz
I and Q	In-Phase and Quadrature (Channels)
I Channel	In-Phase Data Channel
ICP	Integrated Carrier Phase

IEC	International Electrotechnical Commission
IERS	International Earth Rotation Service
IGP	Ionospheric Grid Point
IGRF	International Geometric Reference Field
IGS CB	International GNSS Service Central Bureau
IGSO	Inclined Geosynchronous Orbit
IMLA	Integrated Multipath Limiting Antenna
IMU	Inertial Measuring Unit
INS	Inertial Navigation System
I/O	Input/Output
IODE	Issue of Data (Ephemeris)
IOV	In-Orbit Validation
IRNSS	Indian Regional Navigation Satellite System
ITRF	International Terrestrial Reference System
L1	The 1575.42 MHz GPS carrier frequency including C/A and P-Code
L1C	Future GPS L1 civilian frequency
L1F	Future Galileo L1 civilian frequency
L2	The 1227.60 MHz 2nd GPS carrier frequency (P-Code only)
L2C	The L2 civilian code transmitted at the L2 frequency (1227.6 MHz)
L5	The 1176.45 MHz 3rd civil GPS frequency that tracks carrier at low signal-to-noise ratios
LAAS	Local Area Augmentation System
LIDR	Light Detection and Ranging
LGF	LAAS Ground Facility
LNA	Low Noise Amplifier
LORAN	LOng RANge Navigation System
MAT	Multipath Assessment Tool
mBOC	Multiplexed Binary Offset Carrier
MEDLL	Multipath Estimating Delay Lock Loop
MEO	Medium Earth Orbit
MHz	MegaHertz
ms	Millisecond
MSAS	MTSAT Satellite Based Augmentation System (Japan)
MSAT	Mobile Satellite
MSL	Mean Sea Level
MTSAT	Multi-Functional Transport Satellite
NASA	National Aeronautics and Space Administration (U.S.)
NAVSTAR	NAVigation Satellite Timing And Ranging (synonymous with GPS)
NMEA	National Marine Electronics Association
ns	Nanosecond
OEM	Original Equipment Manufacturer
OS	Open Service
PAC	Pulsed Aperture Correlator
PCO	Phase Center Offset
P-Code	Precise Code
PDOP	Position Dilution Of Precision
PDP	Pseudorange/Delta-Phase
PE-90	Parameters of the Earth 1990 (see PZ-90)
PIN	Position Indicator
PLL	Phase Lock Loop
PPM	Parts Per Million
PPP	Precise Point Positioning
PPS	Precise Point Positioning Service
PPS	Pulse Per Second
PRN	Pseudorandom Noise
PRS	Public Regulated Service
PSR	Pseudorange
PVT	Position Velocity Time
PZ-90	Parametry Zemli 1990 (see PE-90)
Q Channel	Quadrature Data-Free Channel
QSO	Quasi-Zenith Orbit
QZSS	Quasi-Zenith Satellite System
RCC	Rescue Coordination Centre
RF	Radio Frequency
RINEX	Receiver Independent Exchange Format
RLG	Ring Laser Gyro
RoHS	Restriction of the use of Hazardous Substances
RMS	Root Mean Square
RPDP	Relative PDP
RS	Restricted Service
RSS	Residual Solution Status
RTCA	Radio Technical Commission for Aviation Services
RTCM	Radio Technical Commission for Maritime Services
RTK	Real Time Kinematic
SA	Selective Availability
SAR	Search and Rescue
SARSAT	Search and Rescue Satellite Aided Tracking
SBAS	Satellite Based Augmentation System
SD	Standard Deviation
SDCM	System for Differential Corrections and Monitoring
SG	Signal Generator
SGS-90	Soviet Geodetic System 1990
SI	Système Internationale
SiS	Signal in Space
SNAS	Satellite Navigation Augmentation System (China)
SNR	Signal-to-Noise Ratio
SOL	Safety-of-Life
SPS	Standard Position Service
SPAN	Synchronized Position Attitude Navigation
SV	Space Vehicle
SVID	Space Vehicle Identifier
SVN	Space Vehicle Number
TDOP	Time Dilution Of Precision
TTFF	Time-To-First-Fix
TTNL	Time to Narrow Lane
UHF	Ultra High Frequency
USGS	United States Geological Survey
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
UNB	University of New Brunswick
USV	Unmanned Surface Vehicle
UTC	Coordinated Universal Time
UTC(SU)	Coordinated Universal Time (former Soviet Union, now Russia)
UUV	Unmanned Underwater Vehicle
VDOP	Vertical Dilution of Precision
VHF	Very High Frequency
VRS	Virtual Reference Station
VSWR	Voltage Standing Wave Ratio
WAAS	Wide Area Augmentation System
WMS	Wide Area Master Station
WRS	Wide Area Reference Station
WEEE	Waste Electrical and Electronic Equipment
WGS	World Geodetic System

Absolute Accuracy
In GNSS positioning, absolute accuracy is the degree to which the position of an object on a map conforms to its correct location on the earth, according to an accepted coordinate system.

Acquisition
The process of locking onto a satellite's C/A code and P-code. A receiver acquires all available satellites when it is first powered up, then acquires additional satellites as they become available and continues tracking them until they become unavailable.

Accumulated Doppler Range (ADR)
Carrier phase, in cycles. [See *Carrier Phase Measurements]*.

Almanac
A set of orbit parameters that allows calculation of approximate GNSS satellite positions and velocities. The almanac is used by a GNSS receiver to determine satellite visibility and as an aid during acquisition of GNSS satellite signals.

Almanac Data
A set of data which is downloaded from each satellite over the course of 12.5 minutes. It contains orbital parameter approximations for all satellites, GNSS to Universal Standard Time (UTC) conversion parameters, and single-frequency ionospheric model parameters.

Ambiguity
The integer number of carrier cycles between a satellite and receiver.

Anti-Spoofing
Denial of the P-code by the Control Segment is called Anti-Spoofing. It is normally replaced by encrypted Y-code. [See *P-Code* and *Y-Code*]

Antipodal Satellites
Antipodal satellites are satellites in the same orbit plane separated by 180 degrees in argument of latitude.

Baseline
The line between a pair of stations for which simultaneous GNSS data has been collected.

Base Station
The GNSS receiver which is acting as the stationary reference. It has a known position and transmits messages for the rover receiver to use to calculate its position.

Bearing
The horizontal direction of one terrestrial point from another terrestrial point, expressed as the angular distance from a reference direction, usually measured from 000° at the reference direction clockwise through 360°. The reference point may be true north, magnetic north or relative (vehicle heading).

BeiDou Navigation System (BDS)
BeiDou is China's navigation satellite system. Originally, a regional navigation satellite system with 14 satellites, BeiDou will be expanded to provide global coverage. The global system space segment will consist of 5 geostationary earth orbit satellites, 3 inclined geosynchronous orbit satellites and 27 medium earth orbit satellites.

Broadcast Ephemerides
A set of parameters which describes the location of satellites with respect to time, and which is transmitted (broadcast) from the satellites.

Carrier
The steady transmitted RF signal whose amplitude, frequency, or phase may be modulated to carry information.

Carrier Phase Ambiguity
The number of integer carrier phase cycles between the user and the satellite at the start of tracking (sometimes ambiguity for short).

Carrier Phase Measurements
These are "Accumulated Doppler Range" (ADR) measurements. They contain the instantaneous phase of the signal (modulo 1 cycle) plus some arbitrary number of integer cycles. Once the receiver is tracking the satellite, the integer number of cycles correctly accumulates the change in range seen by the receiver. When a "lock break" occurs, this accumulated value can jump an arbitrary integer number of cycles (this is called a cycle slip).

C-Band
C Band is the original frequency allocation for communications satellites. C-Band uses 3.7-4.2 GHz for downlink and 5.925-6.425 GHz for uplink.

Coarse Acquisition (C/A) Code
A pseudorandom string of bits that is used primarily by commercial GNSS receivers to determine the range to the transmitting GNSS satellite. The 1023 chip GPS C/A code repeats every 1 ms giving a code chip length of 300 m, which is very easy to lock onto.

Control Segment
The Master Control Station and the globally dispersed Reference Stations used to manage the GNSS satellites, determine their precise orbital parameters and synchronize their clocks.

Coordinated Universal Time (UTC)
This time system uses the second-defined true angular rotation of the Earth measured as if the Earth rotated about its Conventional Terrestrial Pole. However, UTC is adjusted only in increments of one second. The time zone of UTC is that of Greenwich Mean Time (GMT).

Course
The horizontal direction in which a vessel is to be steered or is being steered; the direction of travel through the air or water. Expressed as angular distance from reference north (either true, magnetic, compass or grid), usually 000° (north), clockwise through 360°. Strictly, the term applies to direction through the air or water, not the direction intended to be made good over the ground [See *Track Made Good*]. Differs from heading.

Course Made Good (CMG)
The single resultant direction from a given point of departure to a subsequent position; the direction of the net movement from one point to the other. This often varies from the track caused by inaccuracies in steering, currents, cross-winds, etc. This term is often considered to be synonymous with Track Made Good, however, Course Made Good is the more correct term.

Course Over Ground (COG)
The actual path of a vessel with respect to the Earth (a misnomer in that courses are directions steered or intended to be steered through the water with respect to a reference meridian); this will not be a straight line if the vessel's heading yaws back and forth across the course.

Cycle Slip
When the carrier phase measurement jumps by an arbitrary number of integer cycles. It is generally caused by a break in the signal tracking due to shading or some similar occurrence.

Dead Reckoning (DR)
The process of determining a vessel's approximate position by applying DR from its last known position a vector or a series of consecutive vectors representing the run that has since been made, using only the courses being steered, and the distance run as determined by log, engine rpm or calculations from speed measurements.

Destination
The immediate geographic point of interest to which a vessel is navigating. It may be the next waypoint along a route of waypoints or the final destination of a voyage.

Differential GNSS (DGNSS)
A technique to improve GNSS accuracy that uses pseudorange errors, at a known location, to improve the measurements made by other GNSS receivers within the same general geographic area.

Dilution of Precision (DOP)
A numerical value expressing the confidence factor of the position solution based on current satellite geometry. The lower the value, the greater the confidence in the solution. DOP can be expressed in the following forms.

GDOP: Uncertainty of all parameters (latitude, longitude, height, clock offset)
PDOP: Uncertainty of 3D parameters (latitude, longitude, height)
HTDOP: Uncertainty of 2D and time parameters (latitude, longitude, time)
HDOP: Uncertainty of 2D parameters (latitude, longitude)
VDOP: Uncertainty of height parameter
TDOP: Uncertainty of clock offset parameter

Doppler
The change in frequency of sound, light or other wave caused by movement of its source relative to the observer.

Theoretical Doppler: The expected Doppler frequency based on a satellite's motion relative to the receiver. It is computed using the satellite's coordinates and velocity, and the receiver's coordinates and velocity.

Apparent Doppler: Same as Theoretical Doppler of satellite above, with clock drift correction added.

Instantaneous Carrier: The Doppler frequency measured at the receiver, at that epoch.

Doppler Aiding
A signal processing strategy, which uses a measured Doppler shift to help a receiver smoothly track the GNSS signal, to allow more precise velocity and position measurement.

Double-Difference
A mathematical technique comparing observations by differencing between receiver channels and then between the base and rover receivers.

Double-Difference Carrier Phase Ambiguity
Carrier phase ambiguities which are differenced between receiver channels and between the base and rover receivers. They are estimated when a double-difference mechanism is used for carrier phase positioning (sometimes double-difference ambiguity or ambiguity, for short).

Earth-Centered-Earth-Fixed (ECEF)
This is a coordinate system which has the X-axis in the Earth's equatorial plane pointing to the Greenwich prime meridian, the Z-axis pointing to the north pole, and the Y-axis in the equatorial plane 90° from the X-axis with an orientation which forms a right-handed XYZ system.

Eccentricity (e)
A dimensionless measurement defined for a conic section where $e=0$ is a circle, $0<e<1$ is an ellipse, $e=1$ is a parabola and $e>1$ is a hyperbola. For an ellipse, larger values of e correspond to a more elongated shape. The eccentricity of GNSS satellite orbit is typically .02.

Elevation
The angle from the horizon to the observed position of a satellite.

Ellipsoid
A smooth mathematical surface which represents the Earth's shape and very closely approximates the geoid. It is used as a reference surface for geodetic surveys.

Ellipsoidal Height
Height above a defined ellipsoid approximating the surface of the Earth.

Ephemeris
A set of satellite orbit parameters that are used by a GNSS receiver to calculate precise GNSS satellite positions and velocities. The ephemeris is used in the determination of the navigation solution and is updated periodically by the satellite to maintain the accuracy of GNSS receivers.

Ephemeris Data
The data downlinked by a GNSS satellite describing its own orbital position with respect to time.

Epoch
Strictly a specific point in time. Typically when an observation is made.

Fixed Ambiguity Estimates
Carrier phase ambiguity estimates which are set to a given number and held constant. Usually they are set to integers or values derived from linear combinations of integers.

Fixed Discrete Ambiguity Estimates
Carrier phase ambiguities which are set to values that are members of a predetermined set of discrete possibilities, and then held constant.

Fixed Integer Ambiguity Estimates
Carrier phase ambiguities which are set to integer values and then held constant.

Galileo
Galileo will be the European Union's own global navigation satellite system, providing a highly accurate, guaranteed global positioning service under civilian control. The fully deployed Galileo system will consist of 27 satellites (with three active spares), positioned in three circular orbits, 23,222 km above the Earth, and at an inclination of the orbital planes of 56 degrees with reference to the equatorial plane.

Geometric Dilution of Precision (GDOP)
[See *Dilution of Precision (DOP)*]

Geoid
The shape of the Earth if it were considered as a sea level surface extended continuously through the continents. The geoid is an equipotential surface coincident with mean sea level to which at every point the plumb line (direction in which gravity acts) is perpendicular. The geoid, affected by local gravity disturbances, has an irregular shape.

Geodetic Datum
The reference ellipsoid surface that defines the coordinate system.

Geostationary
A satellite orbit along the equator that results in a constant, fixed position over a particular reference point on the Earth's surface.

Geosynchronous
A satellite orbit with an orbital period matching the Earth's sidereal rotation period. This synchronization means that for an observer at a fixed location on Earth, a satellite in a geosynchronous orbit returns to exactly the same place in the sky at exactly the same time each day.

Global Navigation Satellite System (GLONASS)
GLONASS is a radio satellite navigation system, the Russian counterpart to the United States' GPS and the European Union's Galileo positioning systems. The GLONASS space segment consists of 24 satellites (with three active spares) in three orbital planes, with eight satellites per plane. The satellites are placed into nominally circular orbits with an inclinations of 64.8 degrees and an orbital height of about 19,140 km, which is about 1,050 km lower than GPS satellites.

Global Positioning System (GPS)
Full name is NAVSTAR Global Positioning System. A space-based radio positioning system which provides suitably equipped users with accurate position, velocity and time data. GPS provides this data free of direct user charge worldwide, continuously, and under all weather conditions. The GPS constellation consists of 27 satellites in six different orbital planes. The system is developed by the Department of Defense under U.S. Air Force management.

GPS L1 Frequency
The 1575.42 MHz GPS carrier frequency, which contains the course acquisition (C/A) code, as well as encrypted P-code, and navigation messages used by commercial GPS receivers.

GPS L2 Frequency
The 1227.60 MHz secondary GPS carrier frequency, containing only encrypted P-code. Currently, GPS satellites transmit the civilian C/A code on the L1 frequency, and the military P(Y) code on both the L1 and L2 frequencies. Block IIR-M GPS satellites transmit the same signals as previous GPS satellites, but will also have a new signal, called L2C, on the L2 frequency.

GPS L5 Frequency
The third civil GPS frequency at 1176.45 MHz is transmitted beginning with the Block IIF GPS satellites. This frequency is located within the 960-1215 MHz frequency band. The L5 signal is equally split between an In-phase (I) data channel and a Quadrature (Q) data-free channel, which improves resistance to interference, especially from pulse emitting systems in the same band as L5.

Great Circle
The shortest distance between any two points along the surface of a sphere or ellipsoid, and therefore the shortest navigation distance between any two points on the Earth. Also called Geodesic Line.

Heading
The direction in which a vessel points or heads at any instant, expressed in degrees 000° clockwise through 360° and may be referenced to true north, magnetic north, or grid north. The heading of a vessel is also called the ship's head. Heading is a constantly changing value as the vessel oscillates or yaws across the course due to the effects of the air or sea, cross currents and steering errors.

Horizontal Dilution of Precision (HDOP)
[See *Dilution of Precision (DOP)*]

Horizontal and Time Dilution of Precision (HTDOP)
[See *Dilution of Precision (DOP)*]

Integer Ambiguity Estimates
Carrier phase ambiguity estimates which are only allowed to take on integer values.

Iono-Free Carrier Phase Observation
A linear combination of L1 and L2 carrier phase measurements which provides an estimate of the carrier phase observation on one frequency with the effects of the ionosphere removed. It provides a different ambiguity value (non-integer) than a simple measurement on that frequency.

Kinematic
The user's GNSS antenna is moving. In GNSS, this term is typically used with precise carrier phase positioning and the term dynamic is used with pseudorange positioning.

L-Band
L-Band is a frequency range between 390 MHz and 1.55 GHz which is used for satellite communications and for terrestrial communications between satellite equipment. L-Band includes the GNSS carrier frequencies L1, L2, L5 and several Precise Point Positioning service providers satellite broadcast signals.

Lane
A particular discrete ambiguity value on one carrier phase range measurement or double-difference carrier phase observation. The type of measurement is not specified (L1, L2, L1-L2, iono-free).

Magnetic Bearing
Bearing relative to magnetic north; compass bearing corrected for deviation.

Magnetic Heading
Heading relative to magnetic north.

Magnetic Variation
The angle between the magnetic and geographic meridians at any place, expressed in degrees and minutes east or west to indicate the direction of magnetic north from true north.

Mask Angle
The minimum GNSS satellite elevation angle permitted by a particular receiver design. Satellites below this angle will not be used in position solution.

Misclosure
The gap between a receiver's predicted and actual position.

Moving Base Station
The GNSS receiver which is acting as the reference point but is in motion. It has an estimated position and transmits messages for the rover receiver to use to calculate its position.

Multipath Errors
GNSS positioning errors caused by the interaction of the satellite signal and its reflections.

Nanosecond
1×10^{-9} second.

Narrow Lane
The GPS observable obtained by summing the carrier phase observations on the L1 and L2 frequencies. The narrow lane observable can help resolve carrier-phase ambiguities.

Network RTK
With Network RTK, corrections are generated from a base station network instead of from a single base station. These corrections can remove more spatially correlated errors and thus improve the RTK performance as opposed to the traditional RTK. Network RTK uses permanent base station installations, allowing kinematic GNSS users to achieve centimetre accuracies without the need for setting up a GNSS base station on a known site.

Observation
Any measurement.

Observation Set
A set of receiver measurements, taken at a given time, that includes one time for all measurements, and the following for each satellite tracked: PRN code, pseudorange or carrier phase or both, lock time count, signal strength and tracking status.

Parity
The even or odd quality of the number of ones or zeroes in a binary code. Parity is often used to determine the integrity of data especially after transmission.

P-Code
Precise code or protected code. A pseudorandom string of bits that is used by GPS receivers to determine the range to the transmitting GPS satellite. P-code is replaced by an encrypted Y-code when Anti-Spoofing is active. Y-code is intended to be available only to authorized (primarily military) users. [See *Anti-Spoofing, (C/A) Code and Y-Code*]

PDOP
Position Dilution of Precision [See *Dilution of Precision (DOP)*]

Post-processing
A processing mode in which a base station is placed at a known reference point and a rover is used for gathering positions. Accurate coordinates are generated by taking data stored from the receivers and processing them using post-processing software.

Precise Positioning Service (PPS)
The GNSS positioning, velocity and time service which is available on a continuous, worldwide basis to users authorized by the U.S. Department of Defense (typically using P-code).

Pseudorandom Noise Number
A number assigned by the GPS system designers to a given set of pseudorandom codes. Typically, a particular satellite will keep its PRN (and hence its code assignment) indefinitely, or at least for a long period of time. It is commonly used as a way to label a particular satellite.

Pseudolite
An Earth-based transmitter designed to mimic a satellite.

Pseudorange
The calculated range from the GNSS receiver to the satellite determined by taking the difference between the measured satellite transmit time and the receiver time of measurement, and multiplying by the speed of light. Contains several sources of error.

Pseudorange Measurements
Measurements made using one of the pseudorandom codes on the GNSS signals. They provide an unambiguous measure of the range to the satellite including the effect of the satellite and user clock biases.

Radio Technical Commission for Aeronautics (RTCA)
An organization which developed and defined a message format for differential positioning.

Radio Technical Commission for Maritime Services (RTCM)
An organization which developed and defined the SC-104 message format for differential positioning.

Real-Time Kinematic (RTK)
A type of differential positioning based on observations of carrier phase.

Receiver Channels
A GNSS receiver specification which indicates the number of independent hardware signal processing channels included in the receiver design.

Reference Satellite
In a double-difference implementation, measurements are differenced between different satellites on one receiver in order to cancel the correlated errors. Usually one satellite is chosen as the “reference”, and all others are differenced with it.

Reference Station
[See *Base Station*]

Relative Bearing
Bearing relative to heading or to the vessel.

Remote Station
[See *Rover Station*]

Residual
In the context of measurement, the residual is the difference between the measurement predicted by the computed solution and the actual measurement.

Route
A planned course of travel, usually composed of more than one navigation leg.

Rover Station
The GNSS receiver which does not know its position and needs to receive measurements from a base station to calculate differential GNSS positions. (The terms remote and rover are interchangeable.)

Satellite-Based Augmentation System (SBAS)
A type of geostationary satellite system that improves the accuracy, integrity and availability of the basic GNSS signals. This includes WAAS, EGNOS and MSAS.

Selective Availability (SA)
The method used in the past by the United States Department of Defense to control access to the full accuracy achievable by civilian GPS equipment (generally by introducing timing and ephemeris errors).

Sidereal Day
A sidereal day is the rotation period of the Earth relative to the equinox and is equal to one calendar day (the mean solar day) minus approximately four minutes.

Spheroid
Sometimes known as ellipsoid; a perfect mathematical figure which very closely approximates the geoid. Used as a surface of reference for geodetic surveys.

Standard Positioning Service (SPS)
A positioning service made available by the United States Department of Defense which is available to all GPS civilian users on a continuous, worldwide basis (typically using C/A Code).

Space Vehicle ID (SV)
Sometimes used as SVID. A unique number assigned to each satellite for identification purposes. The 'space vehicle' is a GNSS satellite.

TDOP
Time Dilution of Precision [See *Dilution of Precision (DOP)*]

Time-To-First-Fix (TTFF)
The actual time required by a GNSS receiver to achieve a position solution. This specification will vary with the operating state of the receiver, the length of time since the last position fix, the location of the last fix, and the specific receiver design.

Track Made Good
The single resultant direction from a point of departure to a point of arrival or subsequent position at any given time; may be considered synonymous with Course Made Good.

True Bearing
Bearing relative to true north; compass bearing corrected for compass error.

True Heading
Heading relative to true north.

Undulation
The distance of the geoid above (positive) or below (negative) the mathematical reference ellipsoid (spheroid). Also known as geoidal separation, geoidal undulation, geoidal height.

Update Rate
The GNSS receiver specification which indicates the solution rate provided by the receiver when operating normally.

UTC
[See *Coordinated Universal Time*]

VDOP
Vertical Dilution of Precision [See *Dilution of Precision (DOP)*]

Waypoint
A reference point on a track.

Wideband Antenna
A GNSS antenna that is capable of receiving multiple Global Navigation Satellite Systems (GNSS) including GPS, GLONASS, BeiDou and Galileo frequencies.

Wide Lane
A particular integer ambiguity value on one carrier phase range measurement or double-difference carrier phase observation when the difference of the L1 and L2 measurements is used. It is a carrier phase observable formed by subtracting L2 from L1 carrier phase data: F' = F1 - F2. The corresponding wavelength is 86.2 cm.

World Geodetic System 1984 (WGS84)
An ellipsoid designed to fit the shape of the entire Earth as well as possible with a single ellipsoid. It is often used as a reference on a worldwide basis, while other ellipsoids are used locally to provide a better fit to the Earth in a local region. GNSS uses the centre of the WGS84 ellipsoid as the centre of the GNSS ECEF reference frame.

Y-Code
An encrypted form of P-code. Satellites transmit Y-Code in replace of P-code when Anti-Spoofing is in effect. [See *P-Code* and *Anti-Spoofing*]

This appendix provides links to companies and agencies engaged in activities related to GNSS. Web site addresses are subject to change; however, they are accurate at the time of this book's publication.

NovAtel Inc.

Contact your local NovAtel dealer first for more information. To locate a dealer in your area or to resolve a technical problem, contact NovAtel Inc. directly.

Customer Service Department
1120 - 68 Avenue NE
Calgary, AB., Canada, T2E 8S5
Phone: 1-800-NOVATEL (International), +1-403-295-4900 (U.S. & Canada)
Fax: +1-403-295-4901
E-mail: support@novatel.com
Web site: http://www.novatel.com

Other sources of information about GNSS:

Arinc: http://www.arinc.com

BeiDou Navigation Satellite System: http://en.beidou.gov.cn/

European Space Agency (Galileo and EGNOS information): http://www.esa.int/Our_Activities/Navigation

Geodetic Survey of Canada: http://www.geod.nrcan.gc.ca/

GPS System: http://www.gps.gov/

Indian Space Research Organisation (IRNSS information): http://www.isro.org/index.aspx

National Geodetic Survey: http://www.ngs.noaa.gov

National Marine Electronics Association (NMEA): http://www.nmea.org

NAVSTAR GPS Operations: http://tycho.usno.navy.mil/gpsinfo.html

Quasi-Zenith Satellite System (QZSS): http://www.qzs.jp/en/

Radio Technical Commission for Aeronautics (RTCA): http://www.rtca.org

Radio Technical Commission for Maritime Services (RTCM): http://www.rtcm.org

Russian Federal Space Agency (GLONASS information): http://glonass-iac.ru/en/

Signals Chart: http://www.novatel.com/signalschart

Society of Automotive Engineers (SAE): http://www.sae.org/

TerraStar: http://www.terrastar.net/

VERIPOS: http://www.veripos.com/