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The Global Positioning System

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The Global Positioning System

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Abstract

      This research study explores the Global Positioning System (GPS), its history, and the process of discovery needed to create the most accurate GPS possible, as well as the contemporary applications of GPS technology. Starting with the first satellite in space, GPS has been a work in progress. Originally pursued by the military for improvements to military tactics, GPS has become integrated into the everyday lives of millions of people around the world. How GPS determines location is a dichotomy, with simplistic theory and complex application. Many factors go into GPS to provide a consistent, accurate location. The orbital planes the satellites are placed in provide 24/7 coverage globally, the L-band frequencies used were chosen specifically for the characteristics they possess, and the multiple atomic clocks installed on each satellite provide incredible accuracy down to the nanoseconds, which is quintessential in GPS accuracy. The applications in GPS are far reaching and more applications are continually being discovered. With as far as GPS technology has progressed, there are still several factors that degrade the signal and are a challenge to overcome. Many of these challenges can be corrected efficiently, however, others, such as scintillation and total electron content variability in the ionosphere, create major hurdles to overcome. Luckily, there are many programs that aid in the correction process of these hurdles.

The History of GPS

      According to R. Saunders' article *A Short History of GPS Development,* The Global Positioning System (GPS) has a long history of trial and error and refinement and improvement. It's purpose has shifted from being a military strategic asset to commonplace among the general public with its use in traveling, farming, and even banking. The beginning of GPS, introduced with a simple idea, can be traced back to the Soviet Union in the late 1950's.

      In 1957, the Soviet Union made history with successfully launching the first satellite in space. To track the satellite Sputnik, Physicists and Scientists at John Hopkins University's Applied Physics Laboratory listened to the beeps Sputnik's signals produced. They noticed that the beeps had a Doppler Effect or Doppler Shift as the satellite passed by. Much like the sound a siren makes as a fire truck approaches, then as it passes, the sound of the siren seems different. The change in timing between the beeps let the scientist know Sputnik's location. This led to the idea of reversing that process, to give a location on the Earth. Using radio frequencies to determine location in a two dimensional plane had been around since WWII, but using satellites would push this technology into the three dimensional realm.

      The United States Navy, Army, and Air Force all began developing their own GPS satellites in the 1960's, but this was no small task. In the early 1960's, the Navy launched its first Transit Satellite. The failure of this satellite, however, was due to

researchers neglecting to add a timing signal. They failed to take into account the effects of Special and General relativity as well as signal delay from the effects of the ionosphere. These effects which will be discussed further on in this article, proved how imperative it is to have an accurate timing signal.

After the initial Transit Satellite launch, the Navy then went on to develop the Timing and Navigation (TIMATION) satellite. This solidified the importance of a highly accurate timing system on the satellites to provide an accurate 3D location.

The Army's Sequential Collation of Range Satellites (SECOR) used several ground stations to assist in providing an accurate location, which would later be useful in producing the modern GPS.

The Air Force was working on the 621B when the decision was made to merge it with the Navy's TIMATION system. This would come to be known as the Navigation Satellite Timing and Ranging (NAVSTAR) program. In Feb 1978, The Air Force launched its first NAVSTAR GPS satellite. Over the next seven years, The Air Force would launch 10 more. In Feb 1989 The Air Force began launching the new Block II satellites. Within one and a half years, the Air Force had eight operational Block II satellites used in coalition with the eight already orbiting Block I satellites. Due to the US' involvement in Desert Shield in Iraq, the Air Force pushed for an accelerated launch schedule of the eight remaining satellites. These satellites were expected to complete a 24 satellite constellation around the Earth. This was completed by the end of Nov 1990.

Over the next four years, the military began incorporating GPS technology into all aspects of warfare, from tracking ground units, to guiding missiles through windows of buildings. This demonstrated the lethal capability and precision of GPS guided munitions and introduced the dawn of a new era in war tactics.

GPS achieved full operational capability in April 1995, and over the course of the next two decades - became a part of everyday life in communications, sports and recreation, banking, and many other fields. GPS has come a long way from being a beep in space, and the possibilities with which it can be used are numerous. (*A Short History of GPS Development,* R. Saunders)

Determining Location

GPS receivers are able to determine a location by a process called trilateration, commonly mistaken for triangulation. (*Trilateration vs. Triangulation - How GPS Receivers Work*, gisgeography.com). Trilateration measures distances whereas triangulation measures angles. GPS works in a three dimensional world measuring longitude, latitude, and altitude. However, it may be easier to imagine how it works using two dimensions. Say you are some distance *x* away from a satellite.
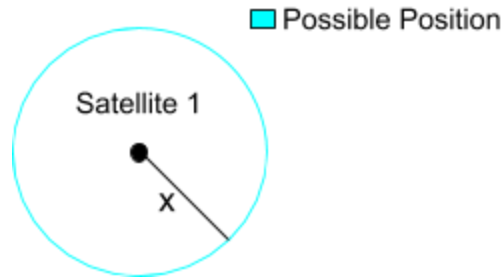
You know how far you are somewhere on the circle *x* distance from the satellite, however, you don't know exactly where. This is where the second satellite comes in. Now you know you are distance *x* from the first satellite and distance *y* from the second satellite.
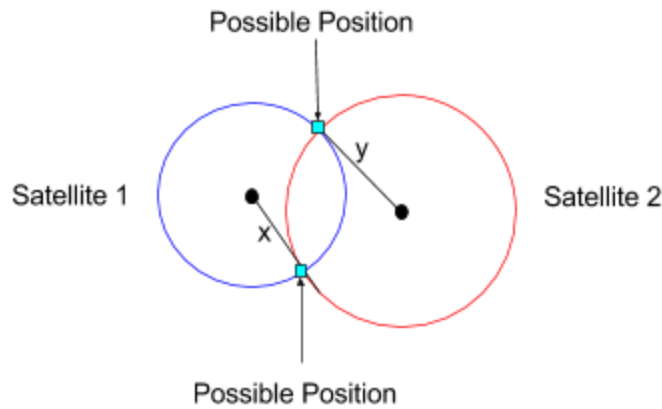
As you can see, this already narrows down our possible position to just two locations. We need the distance *z* from the third satellite to tell us which of those two locations we are actually at.
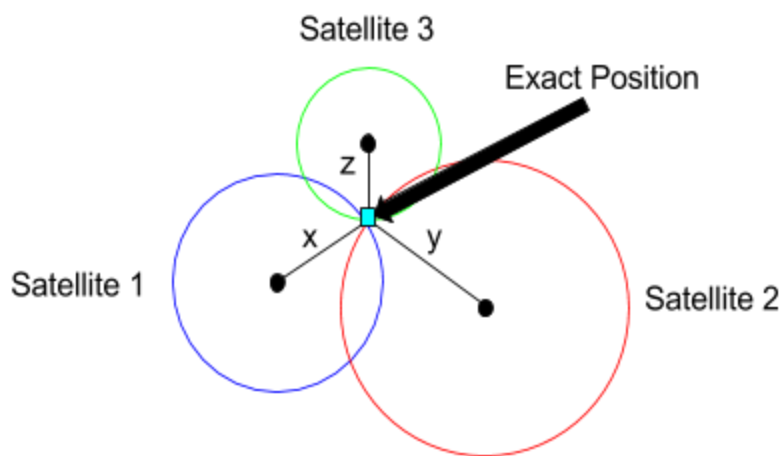
Imagining how this works three dimensionally isn't much different, however, now you are positioned on a sphere *x* distance from satellite 1, y distance from satellite 2, z distance from satellite 3, and a fourth satellite is required to account for the added dimension, w distance from satellite 4. (*Trilateration vs. Triangulation - How GPS Receivers Work*, gisgeography.com)

GPS satellite Orbit

If four satellites are required to give an accurate location, that means a GPS receiver must be in line of sight of at least four satellites at all times. In order to accomplish this, GPS satellites are placed in a medium Earth orbit (MEO) of 20,200 km at 3.9 kilometers per second and a nominal period of 12 sidereal hours (11h 58m 2s). Sidereal hours are the time it takes the Earth to rotate a full 360 degrees, whereas normal days are based on the time it takes for one point of the Earth to completely face the Sun again. The satellites are placed in a near circular orbit around the earth with an eccentricity of less than 0.02. The constellation they orbit in consist of six orbital planes with an inclination of 55 degrees relative to the equator. Each orbital plane contains at least four GPS satellites with slots to place additional satellites in the future. This constellation ensures a GPS receiver will have four satellites within sight at any time. (GPS Space Segment, navipedia.net)

The Unites States seeks to maintain this 24 satellites constellation at all times, so the US Air Force has been flying and operating 31 GPS satellites for the past few years. They do this to ensure coverage is maintained when the baseline satellites are being serviced or when older satellites get decommissioned. (Space Segment, gps.gov)

The orbital period of these satellites can be obtained first by recognizing the attractive force between two objects.

$$F = \frac{GM_E m_O}{r^2} \quad \text{Eq 1}$$

Where F is mass x acceleration, G is the universal gravitation constant of 6.67×10^{-11} N·m^2/kg^2, r = the distance between the two object's center of gravity, M_E = M = mass of the Earth 5.972×10^{24} kg, and m_O = mass of an object.

Newton's second law states that the force is equal to the product of mass and acceleration for a body in free fall so we can say m_O = m. Thus we get

$$ma = \frac{GMm}{r^2} \quad \text{Eq 2}$$

Which reduces to

$$a = \frac{GM}{r^2} \quad \text{Eq 3}$$

Utilizing circular orbit which GPS satellites nearly maintain, we can say the force of magnitude required to keep an object of mass m and speed v in a circular path of radius r is

$$\frac{mv^2}{r} \quad \text{Eq 4}$$

We can set equations 2 and 4 equal to each other in order to determine the velocity needed to set an satellite in circular orbit.

$$\frac{GMm}{r^2} = \frac{mv^2}{r} \quad \text{Eq 5}$$

Through simple algebra, this can reduce to

$$v^2 = \frac{GM}{r} \quad \text{Eq 6}$$

The period can be determined simply by realizing that

$$v = \frac{d}{T} \quad \text{Eq 7}$$

Where d is the the distance, v is the velocity, and T is the time or orbital period. Knowing that the distance needed to travel is the circumference of a circle which is $2\pi r$, we can substitute in for velocity to get

$$\left(\frac{2\pi r}{T}\right)^2 = \frac{GM}{r} \quad \text{Eq 8}$$

With some simple algebra we can solve for the period T to get

$$T^2 = \frac{4\pi^2 r^3}{GM} \quad \text{Eq 9}$$

From this we can see that as an object gets farther from the Earth (r increases), the period gets longer (T increases) and the less effect the Earth's gravitational force has on the object. This is significant in determining the distance at which GPS satellites should be placed in order to maintain the orbital period of 12 sidereal hours.

The next question to be answered is, how is the distance from satellites determined? It was stated earlier that scientists were able to track the satellite Sputnik by the time between beeps. (*A Short History of GPS Development*, R. Saunders). Sputnik had several scientific functions, two of which were to test radio and optical methods of orbital tracking, and determine the effects of radio wave propagation through the atmosphere. (*Sputnik 1*, nasa.gov). Knowing that radio waves travel at the speed of light, 3×10^8 m/s, (*Communication System*, qrg.northwestern.edu), and using the equation

$$d = v \times t \quad \text{Eq 10}$$

Where d is the the distance, v is the velocity, and t is the time, (*Distance Speed Time Formula*, softschools.com), the distance can be solved with simple algebra. Tracking the distance from a satellite isn't quite that simple, as there are several natural and unnatural hindrances that can alter the radio wave quite dramatically. These hindrances will be discussed later on in this article.

GPS Signals
The radio waves GPS satellites use are on the L-band. L-band refers to the operating frequency range of 1–2 GHz in the radio spectrum with a wavelength range of 15 - 30 cm. (*L Band,* techopedia.com). L-band wavelengths were chosen due to their ability to penetrate clouds and all types of weather phenomena, as well as vegetation. They have a high bandwidth which is ideal for code modulation, and they have a wide beam width which makes it easier for antennae to receive the signal and requires low directionality. (*Why GPS Carrier Signals are in the L-Band*, ascelibrary.org)
The frequencies used are L1, L2, and any GPS satellite model Block IIF[1] or newer also use L5. The L1 frequency is 1,575.42 MHz with a wavelength of 19.05 cm, the L2 frequency is 1,227.60 MHz with a wavelength of 24.45 cm, and the L5 frequency is 1,176.45 MHz with a wavelength of 25.48 cm. (*Why GPS Carrier Signals are in the L-Band*, ascelibrary.org)

[1] The term "Block" refers to the generation of GPS satellite with Block I being the first generation, Block II being the second generation, with sub generations IIF, IIR-M, etc; and Block III being the third generation.

The L1 band is the most important band for navigation and most applications in the world are based off the signals transmitted from this frequency. Four signals are transmitted from this frequency, the Coarse Acquisition (C/A) code, the Precision P(Y) code, the L1 Civil signal (L1C), and the Modernized Military Signal (M-Code). These codes will be described in detail further on in this section. (*GPS Signal Plan*, Navipedia.net)

The L2 band provides for better accuracy and correction due to errors in the ionosphere. There are also four signals transmitted at this frequency. The P(Y) code, the M-code, and two new signals, the L2 Civil Moderate (L2 CM) code, and the L2 Civil Long (L2 CL) code. The two new signals are multiplexed so that the chipping rate is twice as high as that of each individual signal. Again these two new codes will be described in detail further on. (*GPS Signal Plan*, Navipedia.net)

This L5 band "is protected worldwide for aeronautical radionavigation use, and will support aviation safety-of-life applications. The addition of L5 will make GPS a more robust radionavigation service for many aviation applications, as well as all ground-based users (maritime, railways, surface, shipping, agriculture, recreation, etc.)" (*GNSS Frequently Asked Questions - GPS*, faa.gov)

There are only two signals transmitted on the L5 band, the in-phase (I5 code or L5 I code) and the quadraphase (Q5 code or L5 Q code). (*GPS Signal Plan*, Navipedia.net)

The C/A code, once primarily used for acquisition of the P(Y) code, is now used in most mass market applications. It has a code length 1 millisecond with a chipping rate of 1.023 Mbps[2]. The code sequence $G_i(t)$ is a linear pattern split into two subsequences G_1 and G_{1i}. The epochs of this code synchronize with the epochs of the P(Y) code. From the very beginning of GPS, the C/A code has been open to all users, however, an artificial degradation was implemented by means of selective availability. This meant that the military could prevent certain people or groups from having an accurate reading if they were a non-desired user. This lasted until May 2000. Now, With the implementation of the M-Code this is no longer necessary. The C/A code is only utilized in the L1 band. (*GPS Signal Plan*, Navipedia.net)

The P(Y) code is a precision code with a code length of seven days, and a chipping rate of 10.23 Mbps. This code has two subsequences X_1 and X_{2i}. This setup allows for the basic code generation technique to produce a set of 37 mutually exclusive code sequences seven days long.

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[2] **Chipping Rate** refers to pulse sent out from a transmitter. A chip is usually a rectangular pulse of +1 or -1 amplitude. It is multiplied by the message bits to form a complete signal. In other words, a chip is a bit sequence of a code, it is called a chip to avoid confusion with message bits. The higher the chipping rate, the better the bandwidth, which will produce a more accurate location in GPS. (*Satellite Communications Systems,* Gerard Maral and Michel Bousquet)

The Y code is an anti-spoofing code and used in place of the P code whenever necessary. The P(Y) code is used in both the L1 and L2 bands with only slight variations adjusted for the band in which they operate.(*GPS Signal Plan*, Navipedia.net)

The L1C code consists of two main components, the $L1C_P$ which is a time-multiplexing channel for the pilot signal and does not transmit a data message. It is modulated by a unique overlay secondary code. The $L1C_D$, which is the data channel, is a ranging code modulated by a data message.(*GPS Signal Plan*, Navipedia.net)

The M-Code is strictly for military use and may eventually replace the P(Y) code. It provides better jamming resistance than the P(Y) code, by transmitting at a much higher power without interference of the C/A code or P(Y) code receivers. It has a more robust signal acquisition than the C/A and P(Y) codes with better security in exclusivity, authentication, and confidentiality. It has a streamlined key distribution, with better performance and flexibility than the P(Y) code. The M-Code maintains its confidentiality by a modulation of a non-return zero Pseudo-random noise spreading code. (*GPS Signal Plan*, Navipedia.net). This essentially means that the signal is encrypted, and only military systems containing the proper key for the pseudo-random code can decrypt the signal. This helps the military maintain the M-code for military purposes only. Just as the P(Y) code operates under both the L1 and L2 bands with only slight adjustments for their respective L bands, the M-code is adjusted for these conditions as well.

The L2 CM code is transmitted from satellite blocks IIR-M, IIF, and subsequents blocks. It has a ranging code $CM_i(t)$ with a linear pattern sequence which is 20 milliseconds in length and a chipping rate of 511.5 Kbps. The epochs of the L2 CM are synchronized with the epochs of the X1 epochs of the P code. (*GPS Signal Plan*, Navipedia.net)

The L2 CL code is also a newer signal transmitted on the IIR-M block satellites, IIF block satellites, and subsequent blocks. It has a linear pattern sequence which is 1.5 seconds in length and a chipping rate of 511.5 Kbps. The epochs of the L2 CL are synchronized with the epochs of the X1 of the P code. The linear sequence pattern is generated from the same code generator polynomial as the $CM_i(t)$, however, the $CL_i(t)$ sequence is short cycled. (*GPS Signal Plan*, Navipedia.net)

L5 I and L5 Q codes are modulated by two bit trains in phase quadrature: the L5 pilot channel and the L5 data channel. "The (...) L5-codes for (…) are independent, but time synchronized ranging codes $X_i^i(t)$, and $X_Q^i(t)$, of 1 millisecond in length at a chipping rate of 10.23 Mbps. For each code, the 1-millisecond sequences are the modulo-2 sum of two sub-sequences referred to as XA and XBi with lengths of 8,190 chips and 8,191 chips respectively, which restart to generate the 10,230 chip code. The XBi sequence is selectively delayed, thereby allowing the basic code generation technique to produce the different satellite codes." (*GPS Signal Plan*, Navipedia.net)

The signal is broadcast from the satellite by the use of transmitters. The transmitters use an electrical signal in the stated frequencies to produce a carrier wave. The frequencies are modulated with information and the signal is sent. The GPS receiver acquires the signal, and demodulates it to relay the information to the user. (*Why GPS carrier signals are in the L-band*, ascelibrary.org)

GPS Timing

As stated earlier, the Navy's first navigational satellite was a failure due to the lack of a timing component. Not just any timing component will do either, it needs to be incredibly accurate and have little to no deviation. This is achieved by adding atomic clocks to all GPS satellites. "Each GPS satellite contains multiple atomic clocks that contribute very precise data to the GPS signals." (*Timing*, GPS.gov) The use of atomic clocks in GPS satellites has been crucial in its success and has added benefits and applications.

Atomic clocks work by utilizing the changing between two states of electrons in atoms as they are bombarded with certain frequencies of radiation or radio waves. The jumping between states of these electrons is so precise that it is an effective way to count seconds. It is so precise that it is now an international standard for counting the length of one second which is 9,192,631,770 cycles per second. (How does an atomic clock work, livescience.com)

In Cesium atomic clocks, Cesium atoms pass through radio waves as they are funneled down a tube. With the right frequency, the electrons in the cesium will resonate and jump between the two states at the desired 9,192,631,770 cycles per second. (How does an atomic clock work, livescience.com)

A detector at the end of the tube keeps track of the atoms that have changed their energy state. The detector sends the information back to the radio wave generator to synchronize the best frequency with the desired number of Cesium atoms. When the desired number of cycles is met, the clock counts 1 second. These atomic clocks are so accurate that they only have an error of 0.03 nanoseconds, meaning they would only lose one second in 100 million years. (How does an atomic clock work, livescience.com)

The reason timing is so important in the GPS is because of it's importance in determining our distance from the satellite. The signal GPS satellites transmit contains the time that it was sent. When your GPS receiver acquires the signal, it reads the time the satellite sent it, and calculates how far your are from that satellite. This is why atomic clocks are used, they provide a more precise time for the receiver to use to calculate that distance. (*A Question of Timing*, Physics.org). An error of one nanosecond can decrease accuracy by 0.3 meters or 1 foot. Thus an error of 1 second can decrease accuracy by kilometers. (*Understanding the Global Positioning System*, montana.edu)

Special and general relativity have a lot to do with the difficulty in providing accurate time. This is because relativity helps us realize that time is not constant, thus making it harder to obtain an accurate measurement of distance from the satellite. (*Understanding the Global Positioning System*, montana.edu)

Special relativity states that a clock in motion runs slower with respect to an observer in a fixed position. It is inherently obvious the more an object approaches the speed of light. GPS satellites don't travel near the speed of light, but they still travel relatively fast compared to an observer on the surface of the Earth. The effects this has on the atomic clocks on a satellite is measureable and can therefore be adjusted for corrections. (*Understanding the Global Positioning System*, montana.edu)

General relativity, much like special relativity states that time moves slower, the closer a clock is to an object with massive gravity, much like the Earth. The time for a satellite travelling a good distance from the Earth will move much faster than that of an observer on the Earth. It would be convenient if the effects of special and general relativity canceled each other out, sadly this is not the case. (*Understanding the Global Positioning System*, montana.edu)

Time for the satellite due to special relativity runs approximately 7,200 nanoseconds slower per day than an observer on the Earth. Time for the same satellite due to general relativity runs approximately 45,900 nanoseconds faster per day than that of an observer on the Earth. Fortunately, because these times can be measured, they can be easily adjusted for by simply subtracting 7,200 from 45,900 to get 38,700 nanoseconds faster per day than that of an observer on Earth. With a little correction, GPS accuracy can be greatly improved. (*Understanding the Global Positioning System*, montana.edu)

Applications of GPS

The applications for GPS are quite extensive, and the Global Positioning System has far outreached its original purpose of determining a location on the surface of the Earth. Listed below are many of those applications, some of which be described in detail. (*Applications*, GPS.gov)

- Agriculture

    By combining GPS and the Geographic Information System (GIS), large amounts of geospatial data has become available. This has aided in farm planning, field mapping, soil sampling, tractor guidance, crop scouting, variable rate applications, and yield mapping. Farmers previously having to treat their farms uniformly are now able to micromanage their fields for better crop output and soil viability. They are able to make better farm maps and plan irrigation techniques that will best benefit their farm and the environment.

- Aviation

    GPS provides for better safety and efficiency in flight by providing three dimensional position determination for all phases of flight. Aircraft and pilots are now able to fly their prefered routes rather than basing them on ground based way points. This is specifically helpful when flying over data sparse areas such as oceans. GPS can also improve approaches to runways which increases safety and operational benefits. With the implementation of the Wide Area Augmentation System (WAAS) and the new L5 frequencies, Errors in GPS due to the ionosphere are greatly reduced improving all aspects of aviation.

- Environment

    Much like in agriculture, GPS can greatly improve data collection across many kilometers of terrain. Many environmental problems can be studied from a new perspective, and provide a more complete understanding.

- Marine

    From the open sea to congested harbors, marine vessel navigation has never been for precise. Accurate position, speed, and heading can be obtained to ensure a vessel reaches its destination in a safe and timely route. GPS aids Search and Rescue to determine the location of a ship in need. It provides greater surveying techniques for marine biologist, oceanographers, and mariners. The timing factor in GPS, provides better port facility time management shipping routines.

- Public Safety and Disaster Relief

    "Knowing the precise location of landmarks, streets, buildings, emergency service resources, and disaster relief sites reduces that time -- and saves lives." (*Public Safety and Disaster Relief*, GPS.gov). GPS has played a critical role in providing relief for many natural disasters as well as wildfire management. It is helping scientist determine fault lines and anticipate earthquakes. For local emergency response systems, it has provided better navigation and travel to many medical emergencies providing better response times.

- Rail

    Railways use GPS to track locomotives, and automated systems can be incorporated to vary train speeds in high traffic areas.

- Recreation

     Many hazards such as getting lost in the wilderness have been greatly reduced thanks to GPS. Fishermen can have a better idea of where fish are congregating, and golfers can better track their game. New sports have been invented with the use of GPS, such as geocaching which is a form of treasure hunting.

- Roads and Highways

     One of the most obvious uses for GPS is of course navigation, but GPS can aid in much more than getting you from point A to B. It can provide details on road congestion and direct you onto more efficient routes to decrease travel time and increase travel safety. It is also an essential part of the future of travel with the use of automated vehicles. Although, not in public use yet, automated vehicles use GPS to navigate through large cities and vast deserts with incredible precision.

- Space

     GPS even has many uses in space like, high precision orbit determination, timing solutions for other spacecraft, constellation control, formation flying, and launch vehicle tracking.

- Surveying and Mapping

     GPS provides accurate modeling and mapping of the physical world from mountains and rivers to buildings and streets.

- Timing

     Precise timing is crucial to many aspects of economic activities. "Communication systems, electrical power grids, and financial networks all rely on precision timing for synchronization and operational efficiency." (*Timing*, GPS.gov). Wireless telephone and data networks synchronize base stations off the GPS timing system. Many companies use GPS to time stamp transactions, such as at ATMs. The Federal Aviation Administration (FAA) using GPS timing to synchronize the reporting of hazardous weather conditions.

There are many more uses for GPS that have yet to be discovered, and as GPS accuracy improves and the timing gets more precise, these uses will become more coherent.

GPS Signal Degradation

GPS signals can be degraded by many factors, These degradations can decrease accuracy of the GPS signal. Listed below are some of those factors. (*Overview of GNSS Signal Degradation and Phenomena,* Glenn MacGougan, Gerard Lachapelle, Rakesh Nayak, and Alexander Wang)

- Evil Waveforms/Spurious Signals

   These can occur when a satellite transmits an anomalous waveform with a distorted PRN[3] code or by second order filtering of the waveform. This was observed in 1993 by and operating satellite which lead to a better derivation of the mathematical model of the waveform.

- The Ionosphere

   One of the largest sources for error in GPS accuracy, The Ionosphere is made up of four layers or regions D,E,F1,F2. Each containing different types and quantities of Ions and free electrons. The layer's thickness can vary and differs from day to night.

   The D and E Layers have little to negligible effects on GPS signal or frequencies. The F1 layer has a significant impact on GPS frequencies and accounts for about 10% daytime error in GPS accuracy. The F2 layer is responsible for most effects on GPS frequencies, However it is most active in the evening.

- Scintillation

   Scintillation is the rapid modification of the amplitude and/or phase of radio waves in the ionosphere. This can greatly reduce accuracy and can even block GPS receivers from attaining a signal.

   What causes scintillation is the wave diffraction and reflection in the ionosphere. Because the ionosphere has an inconsistent ion and electron density, the predictability of the when and how much diffraction and reflection will take place is near impossible to predict.

[3] Pseudo-Random Noise (PRN) also known as Pseudo-Random Code (PRC) is complicated sequence of 1s and 0s. Because the digital code is so complicated it can be confused as electrical noise. Both the C/A and P(Y) codes are PRNs and are what relay the information about the satellite to the GPS receiver. The code is intentionally complicated to prevent the receiver from syncing to the wrong signal and helps prevent jamming. (*Psuedo Random Code*, gps2008.wordpress.com), (*Pseudo Random Code*, Trimble.com)

Scintillation is even more greatly affected or changed by solar winds, geomagnetic activity, latitude (greater effect near high and low latitudes), time and season. This is why using multiple wave frequencies can help combat error and provide a more accurate location. (*Ionospheric Scintillation*, SWPC.NOAA.gov), (*Overview of GNSS Signal Degradation and Phenomena,* Glenn MacGougan, Gerard Lachapelle, Rakesh Nayak, and Alexander Wang)

- Troposphere

The Earth's surface to 50 km in altitude, contributes in small part to GPS signal degradation. The contributing factors being attenuation, signal delay, and a much smaller amount of scintillation.

Attenuation is the loss of intensity of the signal mostly caused by O_2 in the atmosphere. Water vapor, rain and Nitrogen have negligible effects. Degradation due to attenuation varies by elevation angle of the satellite.

Signal Delay is caused by refraction in the atmosphere and is divided into two components, wet and dry.

The dry component accounts for 80%-90% of signal delay. It corresponds to a delay of 2.3m at the zenith and varies by about 1% over a few hours. The wet component although accounts for much less delay, it varies by about 10%-20% at the zenith and corresponds to a delay of 1-80cm at the zenith,

Tropospheric scintillation is very small and easily correctable by differencing. It is caused by weather conditions, changes in the refractive index, and elevation angle.

- Doppler Shift

A change in frequency is perceived due to the motion of the source relative to the receiver. Most Doppler shift effects are contributed to the motion of the satellite relative to the receiver and to a lesser extent, the motion of the receiver relative to the satellite. Doppler shift can attribute to +/- 5 kHz for a stationary or static receiver. Receivers at a higher altitude can be affected even more.

- Signal Masking

Signal masking is the GPS signal being blocked by physical obstructions, such as buildings or dense foliage. Attenuation in this area can vary due to density, height, and material of obstructions.

- Multipath

    A larger source of signal error and differential GPS. Multipath is reflected signals entering the same RF front end mixing with the direct signal. The effects are even greater for static receivers near a large reflective source so care must be taken when installing static receivers.

- Jamming Interference

    Intentional or unintentional interference with the L1 or L2 or both frequencies causing a loss of signal. Types of interference are Continuous Wave, Wideband, narrowband, and pulsed.

Sourcers can be

    -Intentional noise jammers

    -Television transmitter's harmonics or near band microwave link transmitters overcoming front-end filter of the GPS receiver

    -Intentional spread spectrum jammers or near-field of pseudolites

Radar transmissions

    -AM stations transmitter's harmonics or CB transmitter's harmonics

    -Intentional CW jammers or FM stations transmitter's harmonics

    -Intentional CW jammers or near-band unmodulated transmitter's carriers

- Ionosphere Effect on Aviation GPS

    Ionosphere Scintillation causes major issues for GPS receivers in aviation. The effects of scintillation on receivers are compounded immensely. Deep amplitude fades in signal can be in excess of 20 dB-Hz. This can cause poor inaccurate signals or loss of signal entirely for intermittent periods of time.

    The use of two bands L1 and L2, provide provide a source for corrections as the signal gets altered through the ionosphere. However, with the intermittent loss of signal to either the L1 or L2 bands even for just a few seconds, prevents corrections from being made. Without these corrections, navigational accuracy is unreliable. In aviation, with the aircraft moving at higher speeds the total distance a receiver can be off is exponential to that of what might happen on the ground in an automobile. (*Impacts of ionospheric scintillations on GPS receivers intended for equatorial aviation applications*, A. O., P. H. Doherty, C. S. Carrano, C. E. Valladares, and K. M. Groves)

GAIM

    GAIM is a process used to help correct for degradations in the ionosphere due to space weather variability. It stands for Global Assimilation of Ionospheric Measurements. GAIM was developed at Utah State University (USU) and works by

assimilation and models the Total Electron Content (TEC) in the Ionosphere. The models of the ionosphere are produced with observations of physics based theoretical models, and combine numerical data assimilation techniques.

Due to the TEC variability in the ionosphere, it is difficult to predict the corrections that need to be made to adjust for its effects. By assimilating the information given by these models, GAIM can produce near real-time 3-dimensional data of the Ionosphere. This has large implications for providing greater accuracy to GPS. The Air Force Weather Agency has been utilizing GAIM and working with USU since 2006 to make corrections in real time to adjust for ionospheric variability. (*Utah State University Global Assimilation of Ionospheric Measurements Gauss-Markov Kalman Filter Model of the Ionosphere: Model Description and Validation,* Scherliess, Schunk, Sojka, Thomson, Zhu)

Summary

There is a rich history in GPS that capstones the efforts of thousands of military and civilian scientists through decades of research. The Calculated distance from a series of satellites set in orbit around the Earth provides precision accuracy. The 6 orbital planes the 24 plus satellites are placed in provide signal coverage 24/7 so there is no gap in position location. The L1, L2, and L5 signals have optimal frequencies for GPS to function in all weather conditions, and aid in correction for scintillation. Atomic clocks installed on all GPS satellites are the timing components that maintain the accuracy of GPS. If a clock were off by even 1 second, the location position could be off by kilometers. There are many applications to GPS that are being exercised today that improve many aspects of our everyday lives. GPS is not without its faults as several factors can degrade the GPS signal decreasing accuracy substantially with scintillation in the Ionosphere being the biggest contributing factor. There are programs implemented to account for the variable TEC in the ionosphere, such as USUs GAIM that provides near real time data on what is currently going on in the ionospher.

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