Global Positioning Systems – An Introduction

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Synonyms
- GPS, NAVSTAR

Definition
Global Positioning System a.k.a. GPS is a navigational system involving satellites and computers that can determine location (latitude, longitude and altitude) of any point on Earth. The satellite transmits signals which are received on earth by relatively inexpensive receiving device. By calculating the distance between four or more satellites and a receiver, a three-dimensional position on Earth is determined.

As described in [2], this system allows you to figure out where you are with the help of a simple radio receiver. The accuracy of the data (i.e. co-ordinates of a location) depends upon the quality of the receiver and procedures applied to collect the data. It can range from as good as few millimeters to around hundred meters. In addition to giving the current location, some GPS receivers can also store past data by transferring the data collected at a regular interval to a computer memory. This data can then be utilized for other applications like in Geographic Information Systems (GIS).

GPS usually implies NAVSTAR (NAVigation System with Time And Ranging), which is a constellation of 27 Earth-orbiting satellites (24 in operation and three extras in case one fails), developed by US Department of Defense (DOD). GLONASS (GLObal NAvigation Satellite System) and Galileo Positioning System are the Russian and European Union counterparts of NAVSTAR respectively.

Historical Background
Navigation has been an area of marked interest for human beings. People have been looking for and discovering easy and dependable ways to navigate from one place to another quickly. In the earlier days, position of stars was used for navigation. Then the magnetic compass and sextant came into picture; compass could not tell the exact position of the traveler but used to provide information on which direction he is moving and early sextant used to give only latitude of the position. Thereafter the concept of chronometer made it possible to measure the longitude of a particular point. So sextant along-with chronometer could give the longitude as well as latitude of a particular point. Radio-based navigation systems were developed in the early twentieth century, and were used extensively for military purposes in World War II. The drawback in such systems was the tradeoff between the area that can be covered and accuracy as high frequency radio-waves are accurate but can cover only a small area.

Satellite navigation systems were built to overcome the drawback of radio-based navigation systems. The idea of satellite based navigation using radio waves started when
Sputnik was launched into space by Russia. After the launch researchers of the Massachusetts Institute of Technology determined the orbit of the Russian satellite by noting that the Sputnik's radio signal increased as it approached and decreased as it left. So the fact that a satellite's position could be tracked from the ground was the first step in recognizing that a subject's whereabouts on the ground could be determined using radio signals from the satellite [5].

The U.S. Navy experimented with satellite navigation. In the mid-sixties there was the Transit System that was developed to cater to navigational needs of submarines carrying Polaris nuclear missiles. Earlier method used in submarines called gyroscope-based navigation was not accurate enough. The Transit system comprised half-dozen satellites that would circle the earth continuously in polar orbits. In measuring the Doppler shift of the radio signals the submarines could locate its position within fifteen minutes. But this method was not fool proof.

To develop a foolproof (and/or error-proof) system, various ideas based on the earlier satellite navigation systems developed by or for the US DOD, were brain-stormed in 1973 and the result was: NAVSTAR Global Positioning System, now commonly known GPS. In the beginning, three satellites which were called ‘Block I’ were launched to test the proposed system, thereafter in 1989 another set of ‘Block II’ satellites were launched. As mentioned in [4], current GPS installation consists of 24 Block II/II A satellites and 1 Block I experimental satellite. Next generation of satellites named Block IIR are also in orbit.

**Scientific Fundamentals**

**Architecture of GPS:**
The technical and operational characteristics of GPS are organized into three distinct segments: the space segment, the operational control segment, and the user equipment segment. The GPS signals, which are broadcast by each satellite and carry data to both user equipment and the ground control facilities, link the segments together into one system. Figure 1 below briefly characterizes the signals and segments of the Global Positioning System:
**Space Segment**

The space segment consists of 24 earth-orbiting satellites. Each satellite orbits the earth in a way so that every point on the planet is in radio contact with at least four satellites. A GPS satellite broadcasts three different kinds of signals as explained below:

1. **Almanac**: This includes coarse time information (upto seconds precision) and status information about the satellite.
2. **Ephemeris**: This sends the information using which a receiver can determine the exact position of the satellite. This is also called Navigation Message or NM.
3. **Coarse Acquisition Code (C/A) and Precise code (P Code)**: These two are the form of two accurate clock information; former is used for civilian purpose and later for governmental purposes. Each satellite sends a distinct C/A code, which allows them to be identified. C/A is broadcasted at 1.023 MHz and P-code at 10.23 MHz. Also, in normal mode, the P code is first encrypted into the Y-code, or P(Y), which can only be decrypted by units with a valid decryption key.

All three signals, NM, C/A and P(Y), are mixed together and sent on the primary radio channel, L1, at 1575.42 MHz. The P(Y) signal is also broadcast alone on the L2 channel, 1227.60 MHz ([5]).

**Operation Control Segment**

As in [4], Operational control segment (OCS) consists of the master control station (MCS), located at Falcon Air Force Base in Colorado Springs, Colorado; remote monitor stations, located in Hawaii, Diego Garcia, Ascension Island, and Kwajalein; and uplink antennas located at three of the four remote monitor stations and at the MCS. The four remote monitor stations track and send information about the satellite to the MCS. The frequency with which this is done varies from 20 to 21 hours per day. Land-based and
space-based communications are used to connect the remote monitoring stations with the 
MCS. The MCS is responsible for overall satellite command and control, which includes 
maintaining the exact orbits of each satellite and determining any timing errors that may 
be present in the highly accurate atomic clocks aboard each satellite. Errors in a satellite's 
orbital position or in a satellite's timing are determined by analyzing the same signal and navigation message from each satellite that is used by GPS receiver equipment.

**User Segment**

GPS user equipment varies widely in cost and complexity, depending on the receiver design and application. Receiver sets, which currently vary in price from approximately $400 or less to $30,000, can range from simple one-channel devices that only track one satellite at a time and provide only basic positioning information, to complex multi-channel units that track all satellites in view and perform a variety of functions. Most GPS receivers, however, consist of the same three basic components: (1) the antenna, which receives the GPS radio signal and in some cases provides anti-jamming capabilities; (2) the receiver-processor unit, which converts the radio signal to a useable navigation solution; and (3) a control/display unit, which displays the positioning information and provides an interface for receiver control.

GPS positioning capability is provided at no additional cost to civilian and commercial users worldwide but the accuracy level is restrained. The accuracy levels are of two types:

1. **Standard Positioning Service (SPS):** Provided for civilian and commercial users and involves accuracy level of 100 meters.
2. **Precise Positioning Service (PPS):** The U.S. military and its allies, and a select number of other authorized users, receive a specified accuracy level of 16 meters.

The full accuracy capability of GPS is denied to users of the SPS through a process known as Selective Availability, or SA. SA is the purposeful degradation in GPS navigation accuracy that is accomplished by intentionally varying the precise time of the clocks on board the satellites, which introduces errors into the GPS signal, and by providing incorrect orbital positioning data in the GPS navigation message. SA is normally set to a level that will provide 100-meter positioning accuracy to users of the SPS. PPS receivers with the appropriate encryption keys can eliminate the effects of SA.

**How GPS works:**

This section describes how the above individual segments gel together and function:

1. **Locating the User Device:** The basis of GPS is ‘triangulation’ from satellites. It is a method of determining the relative positions of objects using the geometry of triangles. This can be thought of as a venn diagram as follows:
Figure 2: Venn diagram showing how 3 satellites cover a particular area on earth’s surface.

S1, S2 and S3 are three satellites and User represents a GPS user on earth’s surface. In a Figure 2 shown above, the intersection of 3 circles is a collection of points but when this diagram is extrapolated to 3-dimensional surface; it can be found that 3 spheres intersect at 2-points. By measuring distance from one other satellite (S4), the accurate position of the User on earth can be found as geometrically distances from 4 spheres will intersect at only one point.

2. **Measuring Distance from Satellite:** Distance to a satellite is determined by measuring how long a radio signal takes to reach the receiver from that satellite. Multiply that travel time by the speed of light gives the distance.
   a. Each satellite in the message it sends, includes the time (T1) at which it sends message based on the atomic clock inside the satellite. When the signal hits the receiver, that time T2 is noted. T2-T1 gives the total time (T) taken by the signal in space.
   b. Speed of light is taken to be $3 \times 10^8$ m/sec
   c. Distance (in meters) = Speed X T

As in formula presented for calculating distance, it is obvious that finding distance accurately is dependent upon measuring time accurately. Satellites are accurate because they have atomic clocks on board. But receivers generally have a Quartz clock which is not as accurate as an atomic clock. However, to rectify this problem of inaccuracy at the receiver’s end, signals are exchanged between satellite and receiver to synchronize the clocks. The receiver calculates the necessary adjustment in its clock that will cause the four spheres (as described in #1) to intersect at one point. Based on this, it resets its clock to be in sync with the satellite's atomic clock. The receiver does this constantly whenever it's on, which means it is nearly as accurate as the expensive atomic clocks in the satellites.

3. **Measuring Satellite Positions:** To use the satellites as references for range measurements, their exact position is required to be known. GPS satellites are so high up that their orbits follow the same designated path almost all the times. Minor variations in their orbits are measured by the Department of Defense and the error information is sent to the satellites, to be transmitted along with the timing signals.

4. **Error Corrections:** Finally the delay that the signal experiences, has to be corrected. There can be a number of reasons for the delay which are explained in
the next sections. The delay in the signal in turn affects the distance calculation and hence the calculation of the triplet (longitude, latitude, altitude).

**Sources of Error:**
There can be mainly three sources of errors in the position as calculated by any GPS receiver: the current time, position measurement of satellite and delay in the signal. Errors in the current time can generally be reduced as described in previous section, so the accuracy of GPS device is generally affected by later two factors. Following lists different kind of errors that can affect GPS accuracy:

a. **Selective Availability:** Selective availability is the intentional error introduced to prevent the system to be exploited by hostile agents; this is explained in Users Segment section.
b. **Clock and Ephemeris errors:** This deals with the errors that prop up due to erroneous clock time and position of the satellite.
c. **Atmospheric Delays:** The signal sent from the satellite gets delayed as it passes through various layers of atmosphere (mainly troposphere and ionosphere layers). This form of error can be eliminated using something called dual-frequency observation which however is not accessible to the civil users.
d. **Multi-path errors:** These errors occur when GPS signals gets reflected from the obstacles (like buildings etc.) on the way to the receiver.
e. **Receiver’s noise:** Thermal noise produced at the receiver’s end can cause faulty observations, hence amounting to inaccurate output by GPS receiver.
f. **Poor satellite geometry:** Satellite geometry in GPS allows any user to have access to signals from four satellites; however, based on the position on earth, this might not be possible for a simple reason that due to obstacles, a receiver can not access the four satellites whose distances converge at a single point.

**Measures of Capability of GPS:**
GPS capability can be measured not only in terms of accuracy as described above but also in terms integrity, availability, continuity of service, and resistance to radio frequency (RF) interference.

a. **Accuracy:** Ability to provide accurate coordinates of a point on earth.
b. **Integrity:** This is the ability of GPS to broadcast timely warnings to the receiver if the system is not to be used.
c. **Availability:** This is defined as percentage of time the system can be used (i.e. is available).
d. **Continuity of Service:** This is the ability of the system to provide continuous service without interruption for a specified interval of time, this is also referred to as reliability.
e. **Resistance to Radio Frequency:** If there are unwanted radio signals, the accuracy of GPS receiver can be degraded. Hence this refers to the ability of the receiver to cancel out the effects of noise signals while calculating the position co-ordinates.

**Enhancements to GPS:**
Many techniques have been designed to improve the accuracy of GPS. Some of them are:
a. Differential GPS  
b. Carrier Phase (Interferometric) GPS  
c. Pseudolites  
d. Receiver Autonomous Integrity Monitoring (RAIM)  
e. Combined Use of GPS and GLONASS  
f. GPS/Inertial Navigation System (INS) Integration  
g. GPS and Loran-C

For more discussion on this topic, refer to [4].

**Key Applications**

GPS has become a vital global utility finding its use in many of arenas, some of which are described below:

1. **Military**: GPS allows accurate targeting of various military weapons including cruise missiles and precision-guided munitions, as well as improved command and control of forces through improved locational awareness.

2. **Navigation**: GPS is used by people around the world as a navigation aid in cars, airplanes, and ships. Personal Navigation Device (PND) such as hand-held GPS is used by mountain climbers and hikers.

3. **Location-based services**: GPS functionality can be used by emergency services and location-based services to locate mobile phones. Assisted GPS is a GPS technology often used by the mobile phone because it reduces the power requirements of the mobile phone and increases the accuracy of the location obtained.

4. **Road and Highways**: GPS can be used to route the traffic effectively to avoid congestion on the busy highways in conjunction with GIS.

5. **Space**: GPS has provided many low-cost alternatives to the activities in the space domain, for e.g.: The need of having costly atomic clocks in the space craft is abolished by substituting them with relatively low-cost GPS receivers.

6. **Aviation**: Aviators use Global Positioning System (GPS) to increase the safety and efficiency of flight. Space-based position and navigation enables three-dimensional position determination for all phases of flight from departure, en route, and arrival, to airport surface navigation.

7. **Marine**: GPS provides the fastest and most accurate method for mariners to navigate, measure speed, and determine location. This enables increased levels of safety and efficiency for mariners worldwide.

8. **Environment**: GPS when coupled with GIS can provide better data which can be very helpful in predicting and reacting to the environment conditions.

9. **Surveying**: More costly and precise receivers are used by land surveyors to locate boundaries, structures, and survey markers, and for road construction.

10. **Agriculture**: GPS Machine Guidance is used for tractors and other large agricultural machines via auto steer or a visual aid displayed on a screen, which is extremely useful for controlled traffic and row crop operations and when spraying.

11. **Precise time reference**: Many systems that must be accurately synchronized use GPS as a source of accurate time. For instance, the GPS can be used as a
reference clock for time code generators or NTP clocks. Also, when deploying sensors (for seismology or other monitoring application), GPS may be used to provide each recording apparatus with a precise time source, so that the time of events may be recorded accurately.

12. Public Safety and Disaster Relief: Time plays an important part in the rescue operations to be effective after the disaster. Knowing the precise location of landmarks, streets, buildings, emergency service resources, and disaster relief sites reduces that time -- and saves lives. GPS has made accurate data available easily.

Future Directions

GPS is a relatively new technology and there are many improvements being suggested and implemented in the current system. Following is the focus of currently in GPS:

1. As described by US government: Future work is to do an extensive modernization program, including the implementation of a second and a third civil signal on GPS satellites. The second civil signal will improve the accuracy of the civilian service and supports some safety-of-life applications. The third signal will further enhance civilian capability and is primarily designed for safety-of-life applications, such as aviation

2. Improving the Accuracy: As described in [4], Though GPS provides information fairly accurately; it still requires improvement to be put into use in certain operations like: all-weather aircraft carrier landings, surveying and mapping etc.
   a. Use of a 24-Satellite Ensemble Clock: Currently, clock offset corrections are determined on the ground and then sent to the individual satellites once a day as they pass over a GPS monitoring station. The Block IIR satellites will have the capability to determine their clock offsets autonomously relative to a space-based ensemble clock and exchange clock information with other satellites via cross-links every 15 minutes.
   b. Satellite-Based Integrity Monitoring: Perhaps the most innovative and promising method of signal integrity monitoring is through space-based monitoring, rather than ground-based monitoring. This capability known as Satellite Autonomous Integrity Monitoring or SAIM would require the instrumentation of GPS satellites to monitor transmitted L-band signals from each other for accuracy and usability.

3. Development of new Applications and GPS products: New applications need to be developed that make use of the data provided by GPS and build upon the key applications explained in the last section

4. Structure of Satellites: How satellites are structured in space can have a considerable impact on how efficiently a user can location their positions and calculate the mutual distance. This is a rich area for future research.

5. Integration of several satellite navigation systems: There have been many satellite navigations systems that have been built so far, each having their pros and cons. This information can be utilized in developing a fool-proof system which uses a mix of principles used in the past.

Cross References
Satellite Navigation Systems, GIS, GLONASS, Galileo

**Recommended Reading**


