

# A Civil Engineer's Guide to GPS and GNSS

## Abstract

The usage of the Global Positioning System (GPS) and other developing Global Navigation Satellite Systems (GNSS), for example the Russian GLONASS system and the emerging European Galileo and Chinese BeiDou systems is expanding exponentially. Current and future utilization, research, and application developments are becoming key to most walks of life and hence prevalent within government, commercial industry, research communities as well as for the citizen. The ability to accurately locate and relocate, to navigate and track and to synchronize data streams has made this a technology that we all utilise, whether we are aware of it or not.

Current GNSS drivers within the engineering community are to improve efficiency, to provide better customer service, to enhance health and safety provision and as an aid to meet industry regulation. Augmenting GNSS devices with other positioning tools (whether they be ground penetrating radar, inertial devices, lasers, tachographs, etc) can provide a total solution when they are appropriately combined together.

This paper aims to provide some background information on GNSS through concentrating on the



basic technology, issues and applications of GPS. A view to the future of GNSS will be given at the end.

## Overview of GPS

GPS is a constellation of orbiting satellites that provides navigation data to military and civilian users all over the world. The system is operated and controlled by the 50th Space Wing of the U.S. Air Force located at Schriever Air Force Base, Colorado, USA. GPS is a global 24-hour, all-weather, navigation system which can provide extremely accurate three-dimensional location information (latitude, longitude and altitude), velocity and timing.

GPS was designed as a dual-use military / civilian system, but its primary purpose was to enhance the effectiveness of U.S. and allied military forces. GPS has its origins in the 1970s and it became fully operational in 1995. Since that period however, GPS has rapidly become integral to the global information economy and hence civilian users and commercial communities have gained much influence over the development of GPS. This was outlined by the U.S. Policy Statement Regarding GPS Availability in March 2003; "The United States Government recognizes that GPS plays a key role around the world as part of the global information infrastructure and takes seriously the responsibility to provide the best possible service to civil and commercial users worldwide. This is as true in times of conflict as it is in times of peace."

Currently (2014) 31 GPS satellites orbit the earth in one of six orbital planes at an inclination of 55 degrees to the equator, there are also around four residual spare satellites in orbit. A GPS orbit has an altitude of around 20,200km above the Earth. As a result it takes about 11 hours and 56 minutes for a satellite to complete one orbit.

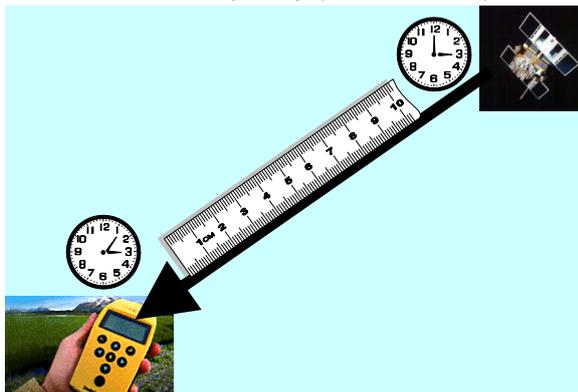
## The Growth in GNSS

One straightforward way of depicting the growth in the use of GNSS is through looking at the predicted revenue from GNSS receiver sales over the next 15 years. In 2001 this stood at €15 billion, by 2020 this is predicted to be €150 billion. The mass markets will be in personal navigation and telematics, followed by transport, emergency services and the surveying / engineering / asset management industries. The accurate timing that GNSS also provides is exploited to enable the synchronization of communications networks, electric power distribution and banking.

This current popularity and future explosion in the use of GNSS can partly be traced to the coming together of a variety of factors; the advances and increased use of telecommunication technologies and geographic information systems, together with the availability of geospatial information. This has combined with the overall decrease in cost, size and power consumption of satellite navigation receivers.

## The Basic GPS Measurements

The basic measurement in GPS positioning is the calculation of the receiver to satellite distance. The most fundamental method to do this uses very accurate satellite atomic clocks to generate a unique coded signal (Coarse Acquisition (C/A) Code) for each satellite. This signal is sent on one of the two signal frequencies broadcast by the satellites, the L1 frequency (1575.42 MHz).



C/A Code sequence: 

The receiver on the ground generates the same coded signal, at the same time, and compares the received code with the one being generated. The time offset between the two codes gives the time of travel of the signal between the satellite and receiver. The distance can then be calculated by:

$$\text{(pseudo-)range to satellite} = \text{signal travel time} \times \text{speed of light}$$

This measurement is called a pseudo-range because not all the errors in the measurement are taken into account at this stage.

The receiver knows 'when and where to look' in the sky for the signal from the satellite because orbital information is transmitted from the satellites and stored in the receiver memory. Each satellite generates a different coded signal and if measurements are made to enough satellites a position for the receiver can be computed. There are four unknowns (latitude, longitude, height and time offset) so ranges to four, or more, satellites at once have to be observed to determine a position.

Raw plan positional accuracy with a single receiver, for civilian users, is around 5m to 10m, 95% of the time. Height accuracy in GPS is generally two to three times worse than plan whatever technique is used. Before the 2<sup>nd</sup> May 2000, the accuracy was far worse (100m, 95%) because during the 1990s the U.S. DoD deliberately degraded the GPS signals to limit the real-time accuracy to civilian users. Military users had, and still have, access to a more accurate coded signal from the satellites.

The positional accuracy is affected by a variety of different sources of error. These include the imprecise knowledge of the GPS satellite orbits, small timing errors in the satellite & receiver clocks, the atmosphere (slowing down the signal and so producing a range that is too long), receiver biases and reflected indirect signals arriving at the antenna (multipath).

## Improving Raw GPS Positioning

To obtain improved accuracy, the errors must be calculated or modelled. For basic L1 code positioning, this process is known as Differential Code GPS or dGPS. DGPS involves the computation of corrections to the code-based pseudo-ranges.

Summary of GPS Error Sources	Magnitude (approx) m
Orbit Errors	3
Clocks	1.5
Ionosphere	6.0
Troposphere	0.5
Receiver Noise	0.2
Multipath	1

The corrections counteract the effect of the major errors in the GPS position (orbit, clocks and atmosphere). These corrections are then combined with GPS signals from the receiver to improve the computed position. Multipath errors are not reduced by dGPS, but are generally reduced by good siting of the GPS antenna, software in the receiver or antenna design which either detects the reflected signals and ignores them or reduces their effect.

The dGPS corrections are generally computed by using another GPS receiver at a known point. This receiver compares the measured and computed pseudo-ranges and uses the differences to compute the corrections to the GPS signal. The dGPS corrections can be combined with the user's receiver either in real-time through delivering them over a communications link or after the fact in post-processing software. Accuracy from this technique is typically around 50cm-5m, depending on the conditions and equipment used.

Two examples of free dGPS services are the General Lighthouse Authority (GLA) medium wave radio broadcast service aimed at mariners (but also available throughout mainland United Kingdom) and the European Geostationary Navigation Overlay Service (EGNOS) which transmits corrections to users via satellites. These two systems should provide 2-5m positional accuracy. There are also a number of commercial systems available which can produce better accuracy.

### **Carrier Phase Positioning**

Up until now we have just been dealing with the measurements of the satellite-receiver range through using the timing codes on the L1 frequency. It is however possible to measure the range more accurately through using measurements of the phase of the carrier waves on both the GPS frequencies; L1 and L2.

Carrier Phase: 

The 19cm or 24cm wavelength carrier waves can be used as an accurate ruler to measure the range to the satellites. In simple terms, by counting the number of whole cycles between the satellite and the receiver and multiplying by the wavelength (plus the additional fraction of a wavelength) gives the range. This gives a more accurate range than a code derived pseudo-range. Determining the whole number of wavelengths between the receiver and the satellite is where the problem lies however as each wavelength looks just like the last (unlike in the L1 C/A Code which is a very complex sequence and therefore it is relatively easy to determine specific points along its series). If a code position is used as a starting point to determine position, the number of satellite-receiver wavelengths is then known to probably +/- 20 wavelengths. This 'carrier phase ambiguity' is then easier to calculate to determine a final end user position.

A carrier phase derived range has all of the same errors as a code-based pseudo-range. Either real-time or post-processed differential techniques therefore have to be performed to obtain a highly accurate position. This again generally involves a receiver at a known point (base station) collecting data at the same time as a user's receiver, but this time instead of deriving a correction, a receiver to

receiver baseline is computed, either in real-time or after the fact during post-processing. The technique of real-time carrier phase positioning is also called Real Time Kinematic (RTK) if the user is moving.

It is possible to obtain extremely high levels of positional accuracy by using code and L1/L2 carrier phase GPS positioning. It is easily possible for an RTK user to obtain 2cm level positioning in plan, and even better if they are careful. In RTK however, the distance from the reference station affects the final positional accuracy that can be achieved.

If a receiver is left at a location for many months, it is possible to determine positions down to the few millimetre level – ideal for bridge monitoring or plate tectonic studies for example.

A technique known as Networked RTK has developed which links together data from a number of dual frequency GPS receivers in real-time – providing a regional dGPS or RTK correction solution. The main advantages of Networked RTK are cost savings, as there is no need to set up a local base station and the accuracy is not dependant on the base – rover receiver distance. Examples of a Networked RTK systems are the commercial services built on the Ordnance Survey OS Net™ national GPS infrastructure.

Carrier-smoothed code positioning provides a half-way house between just code and dual frequency carrier phase positioning. Plan accuracy levels are at the 20cm-80cm level.

### **Coordinates**

GPS provides coordinates in the World Geodetic System 1984 (WGS84). WGS84 consists of a three-dimensional cartesian coordinate system and an associated ellipsoid whose origin is at the centre of the Earth's mass. It is ideally suited for positioning anywhere on the Earth. The coordinate system defined and adopted for Europe however is the European Terrestrial Reference System 1989 (ETRS89) which is basically WGS84 at its' position on January 1<sup>st</sup> 1989. ETRS89 is used across Europe as the primary coordinate system instead of WGS84 because WGS84 is fixed to the earth's plates and so moves over time. In fact the divergence of ETRS89 and WGS84 is approximately 2.5cm / year. This may not sound very much, but over the last 24 years this has amounted to 90cm. This becomes important when National Mapping Agencies and others wish to provide a coordinate transformation between their GPS derived positions and mapping / plans.

If WGS84 was used, these transformations would have to change every few years to take into account the movement of WGS84. ETRS89 is therefore used as standard for high accuracy GPS work across the United Kingdom.

Briefing sheets are provided free of charge to help increase knowledge and awareness. They may be freely copied. Care is taken to ensure information is correct, however readers are advised to consult source documents for authoritative information.

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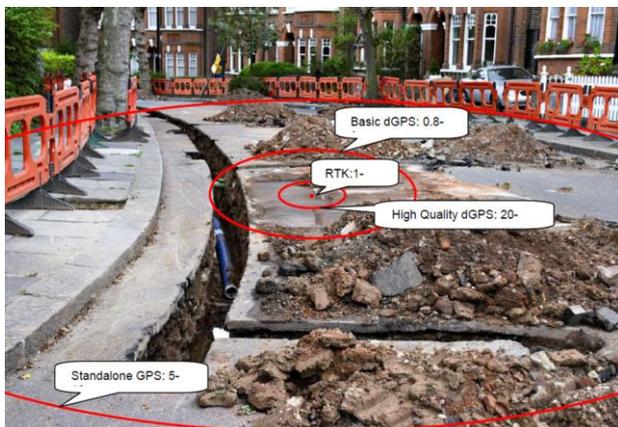
The most accurate transformation available in Great Britain from ETRS89 coordinates to the National mapping coordinate system (OSGB36 National Grid) is OSTN02™. For height this is the ETRS89 to height above sea level correction surface, currently OSGM02™.

Alternatively, if a local grid is being used, a local transformation model needs to be established. To do this at least 4 points with known local coordinates should be observed with GPS across the site. The GPS to local grid transformation parameters can then be established.

### User Applications

GNSS has a plethora of possible applications; from road (road user charging and navigation), rail (safety and positioning), offshore (navigation) and air (routing), to construction and engineering positioning to the location and relocation of utility assets.

The figure below illustrates a water industry application example. Raw stand-alone GPS positioning could be used to navigate an engineer to the correct road where a leak has occurred. Basic or high quality dGPS could be used to position assets into a database and RTK to locate or relocate a specific valve or pipe within a network.



Technique	Summary of GPS Plan Accuracy (m)	Approximate One Receiver Cost
Raw GPS	5-10	£70+
DGPS	0.8-3	£90+
Phase smoothed code	0.2-0.8	£1500+
RTK	0.01-0.05	£6000+
Long period static carrier phase	0.001-0.01	£5000+

Broader civil engineering GNSS applications are now widespread across the industry and have developed a long way over the last 10 years. This is especially so with the deployment of RTK for setting-out, profiling, as well as for the automatic guidance of plant for piling, grading, cutting and filling applications.

### The Future

The future for GNSS is very exciting over the next ten years where we could see more than 120 positioning satellites available to be used. GPS is slowly being *modernised* as new satellites are launched with new signals. This will mean GPS positions will become increasingly more accurate and quicker to determine. The Russian GLONASS navigation system was under funded for many years but was returned to a full constellation of 24 satellites by the end of 2012. A full modernisation programme is also planned for GLONASS over the coming years. Many survey grade receivers are now operating with both GPS and GLONASS, and indeed the Network RTK services based on OS Net™ now provide corrections for both GPS and GLONASS satellites. The European satellite navigation system Galileo will consist of 30 satellites and will provide a range of open (free) and restricted services. Four Galileo validation satellites are now in orbit with the remainder due to be launched from 2014 onwards with a full constellation expected by 2020. The Chinese BeiDou system became operational over South East Asia in 2012 and should be available as a global system also around 2020.

There are techniques that now enable very fast acquisition (sub-second) of the GPS satellites (*Assisted GPS* or *AGPS*). After first power, the receiver is sent orbital and timing information via a mobile phone - enabling the receiver to very quickly track the satellites. It is also possible to obtain a position, quite inaccurately currently, whilst indoors. *High Sensitivity GPS* works by detecting the very low strength GPS signals that permeate indoors – typically 20dB and 30dB lower. If an inertial system is coupled with the GPS receiver, positioning is possible in places where the receiver cannot see the four satellites it needs (in tunnels for example). Map matching techniques can be used which exploit the intelligence within digital mapping to align a user's GNSS track onto the right road – useful in vehicle tracking applications.

The acceptance and use of GNSS within civil engineering, often when combined with other measurement or sensor technology, will continue to flourish. GNSS is now used to control plant across the site, leading to the potential for it to become truly autonomous.

## **Reference Material:**

There are numerous text books and websites related to GPS and GNSS, including online tutorial material.

## **About the Authors:**

The first edition of this guide was written by Dr Paul Cruddace and James Brayshaw of the Ordnance Survey. It was updated in 2013 by Professor Terry Moore of the University of Nottingham

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