# 1. GLOBAL NAVIGATION SATELLITE SYSTEMS

The Global Navigation Satellite System (GNSS) is a constellation of satellites, transmitting signals for use in navigation and positioning applications, anywhere on the surface of the earth. There are currently two Global Navigation Satellite Systems in operation: the U.S. Global Positioning System (GPS) and the Russian Global Navigation Satellite System (GLONASS). A third system, Galileo, is currently under development in Europe. Galileo will provide a wide range of positioning signals and services including the high-reliability service required by safety-of-life-critical applications. Galileo will also provide a high level of integrity on the global scale and without any additional augmentation system. All the three systems will be interoperable. Combined use of Galileo and GPS will provide unprecedented increase in the availability of positioning.

Another name for GPS (Global Positioning System) given by its owner, the U.S. Department of Defense, is NAVSTAR (Navigation Satellite Timing and Ranging). GPS is a satellite based navigation system, operational since late 1995. Its constellation consists out of 24 satellites, which transmit ranging signals and navigation data 24 hours a day free of charge. GPS receivers obtain their locations on earth by measuring the distance from the satellites and computing their position relative to the Earth-fixed coordinate frame, WGS-84. GPS is funded and controlled by the U.S. Department of Defense (DoD) and was originally intended for military applications. In the 1980s, the U.S. government made the GPS system available for civilian use. It was the first system widely available to civilian users.

The Russian Global Navigation Satellite System GLONASS is similar in operation as GPS and may prove complimentary to the NAVSTAR system. Launched in 1996, its constellation is orbiting 19,100 Km above the earth in three orbital planes.
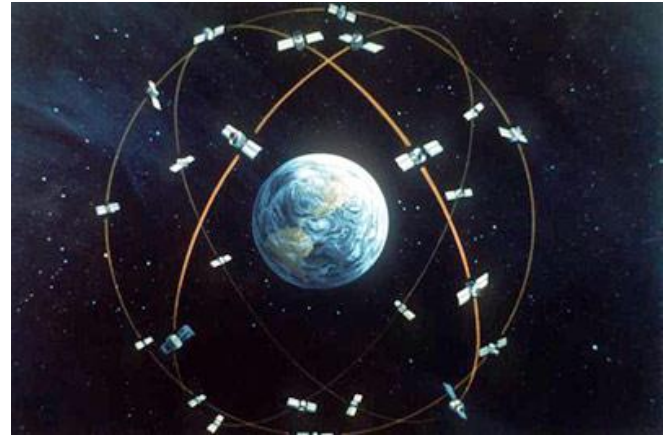
The development of the European GNSS system, GALILEO, began in 1999. It is scheduled to be fully operational in 2012. In its full constellation, Galileo will consist of 30 satellites, continuously transmitting high-frequency ranging signals, containing time and distance data tracked by a Galileo receiver. The future Galileo satellites will transmit a variety of signals modulated on four different carriers: E5a, E5b, E6 and L1. New signal processing techniques are required in order to track Galileo signals due to the new modulation types BOC and AltBOC and the presence of Pilot and Data channels at all frequencies. Galileo will provide a wide range of services including open, safety-of-life, commercial, and publicly regulated service. Galileo will guarantee the reliability of its signal anywhere on earth.

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2. WHAT IS GPS? HOW DOES IT WORK?

The Global Positioning System (GPS) is a worldwide radio-navigation system formed from a constellation of 24 satellites and their ground stations. The basic GPS then uses satellites within the constellation as reference points to calculate positions accurate to a matter of meters.

The GPS satellites transmit low power radio signals on multiple frequencies. L1 and L2 are the two basic carrier frequencies that contain the navigation signals. The L1 frequency is 1575.42 MHz in the UHF band while the L2 frequency is 1227.6 MHz. The signals travel by line of sight (the signal passes through clouds, glass, plastic and other lightweight materials but does not go through buildings, mountains or other enclosed spaces). The L1 signal contains two pseudorandom signals: the P (Protected) code and the C/A (Coarse/Acquisition) code.

A receiver can identify the signals because each GPS satellite transmits a unique code. The P code can be scrambled to prevent unauthorised access (=Anti-spoofing), it is then referred to as P(Y) code or Y code. A GPS signal contains a pseudorandom code, ephemeris data and almanac data. The first code identifies the satellite that is transmitting information. Ephemeris data contains information about the status of the satellite (healthy or unhealthy), current date and time. The almanac data informs the receiver where each GPS receiver should be at any time throughout the day.

Three satellites are used to triangulate a position (longitude, latitude and height), and a fourth satellite needs to be in line of sight in order to calculate time. The more satellites in view, the more accurate the positioning will be.
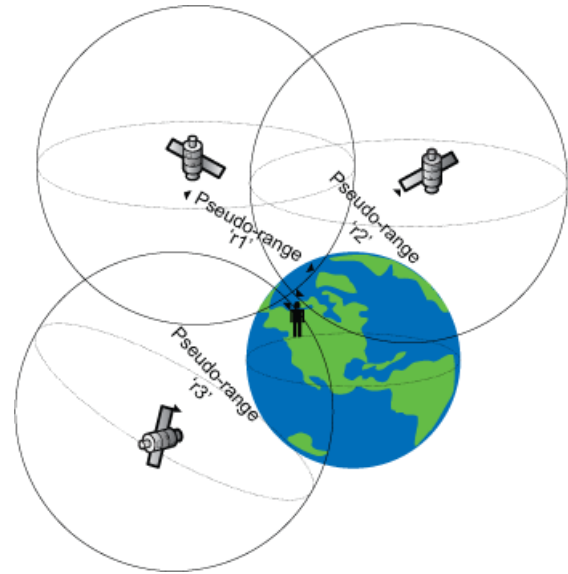
# 3. Triangulating From Satellites

The calculation of a location on earth relies on the GPS receiver accurately measuring its distance from four or more of the GPS satellites.

In the first instance, if the distance from a GPS satellite to a GPS receiver was measured at 18,000km, the possible locations of the receiver is somewhere on the surface of a sphere that has a radius of 18,000km.

If the measured distance from the receiver to a second satellite was 20,000km, the possible location of the GPS receiver is its position on the first sphere *and* on a sphere with a radius of 20,000km, i.e. within an area where the spheres intersect.

If the measured distance to a third satellite was 15,000km, the only possible locations for the GPS receiver is one of two points where the sphere of radius 15,000km cuts through the intersection of the first two spheres.

Although in theory no further satellites are required (as one of the triangulated points will have its location somewhere in space, i.e. not on the earth's surface) a fourth satellite is required in practice, and each additional satellite acquired by the GPS receiver increases the accuracy of the positioning.
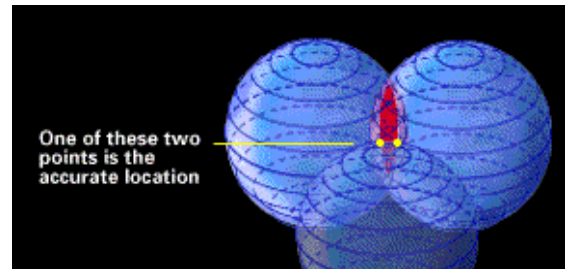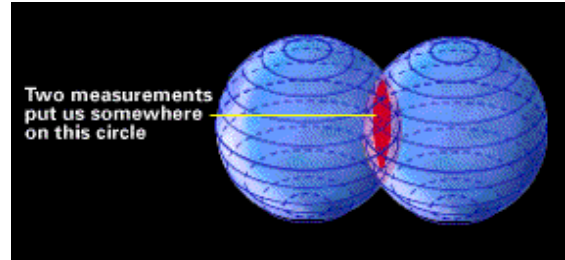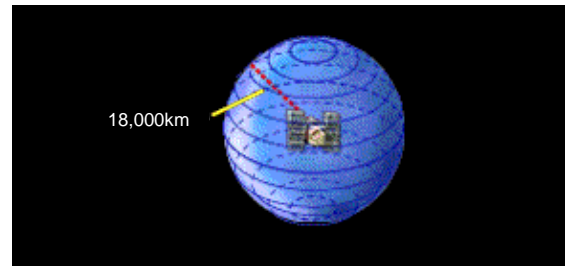
4. How The Distances To Satellites Are Measured

The distance from the GPS receiver to each of the GPS satellites relies on accurately measuring the time taken for a radio signal transmitted by a satellite to reach the receiver on earth, i.e.:

> **Velocity ×Time = Distance**
> GPS radio signals travel at the speed of light e.g. 300,000km/s.

The fact that GPS signals travel at the speed of light presents two problems:

Firstly, the times measured are going to be very short, i.e. if a satellite were directly over-head a receiver, the travel time of the signal would be ~0.06 seconds.

Secondly, to accurately measure these times requires very accurate clocks; (a GPS satellite is equipped with two atomic clocks but these are prohibitively expensive for use in hand-held receivers).

To overcome this each GPS satellite transmits its own individual pseudo-random code and two other pieces of information:
GPS Almanac – This is a data file that contains orbit information on all satellites, clock corrections, and atmospheric delay parameters. Each GPS satellite transmits this information to a GPS receiver, thereby facilitating rapid satellite vehicle acquisition within GPS receivers.
Ephemeris - The ephemeris contains predictions of the current satellite position.

In addition, the GPS receiver transmits the same pseudo-random codes as the GPS satellites; however, as the satellites' signals have to travel through space, they experience a slight delay when compared to those generated by the receiver.

The receiver therefore delays its pseudo-random codes until they fell into synchronisation with those of the satellites. The amount by which signal is delayed is therefore equal to the travel time of the satellites' versions.
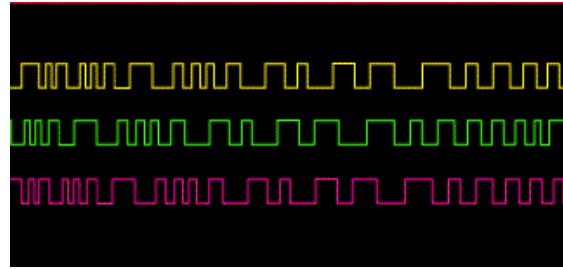
5. GETTING PERFECT TIMING

As the location of the GPS receiver is determined by the measured time taken by a signal transmitted by a GPS satellite to reach that receiver, it is essential that the timing is accurate.

However, although the clocks on board GPS satellites giving them almost perfect timing, the clocks on GPS receivers are no more than the quartz devices found in wristwatches. As both the satellite and the receiver need to precisely synchronise their pseudo-random codes to make the system work, a discrepancy of just $1/1000^{th}$ of a second between them would result in a positional error of >320km.

To overcome the limitations of the GPS receiver's imperfect clock, the GPS receiver takes the measurements from three satellites to calculate its position. It then takes a measurement from a fourth satellite as a cross check, as this position will NOT intersect with the first three, i.e. the receiver detects a discrepancy in its measurements.

The receiver then recognises that its clock is not synchronised to universal time. The receiver therefore looks for a single correction factor that it can subtract from all its timing measurements that would cause them all to intersect at a single point.

That correction brings the receiver's clock back into sync with universal time providing atomic clock accuracy. Once the receiver applies that correction to the signals received from all the satellites in view, precise positioning becomes possible.

One consequence of this principle is that any decent GPS receiver will need to have at least four channels so that it can make the four measurements simultaneously.
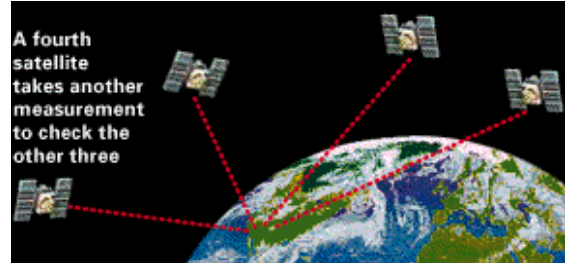
6. THE QUEST FOR GREATER ACCURACY

The quest for greater and greater accuracy has now spawned an assortment of variations on basic GPS technology. One technique, called **"Differential GPS,"** involves the use of two ground-based receivers. One monitors variations in the GPS signal and communicates those variations to the other receiver. The second receiver then corrects its calculations for better accuracy.

Another technique called **"Carrier-phase GPS"** takes advantage of the GPS signal's carrier signal to improve accuracy. The carrier frequency is much higher than the GPS signal, which means it provides measurements of timing that are far more precise.

The aviation industry is developing a type of GPS called **"Augmented GPS"** which involves the use of a geostationary satellite as a relay station for the transmission of differential corrections and GPS satellite status information. These corrections are necessary for the development of GPS for instrument landing systems with the geostationary satellite providing corrections across entire continents.

Constant Base Line
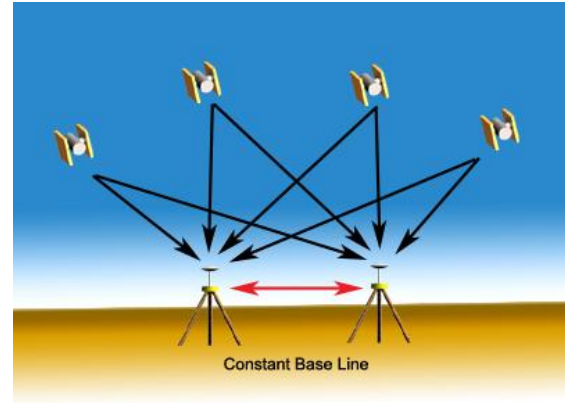
	C/A GPS	DGPS	RTK	PP
Position (m)	4.0-6.0	0.5-2.0	0.1-0.5	0.05-0.30
Velocity (m/s)	0.050	0.050	0.05	0.01
Roll/Pitch (deg)	0.05	0.050	0.05	0.040
True Heading (deg)	0.15	0.100	0.10	0.08

Accuracy of position using GPS processing in an airborne position and attitude navigation system

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7. COORDINATE SYSTEMS - GEODATA

Geo-coordinate systems give the position of an object on the surface of the Earth. However, the Earth is not a perfect sphere and in reality is an undulating oblate spheroid, also known as a Geoid. It is possible to represent the planimetric position of a point on the surface of a spheroid by two coordinates, which typically are a measure of latitude and longitude.

The altitude is a value with respect to a gravitational equipotential surface, which is commensurate with sea level on the oceans. The exact position of this equipotential surface, which represents zero altitude, is more difficult to delineate exactly on land surfaces, and hence, the determination of altitude by a GPS unit has a greater uncertainty than of the planimetric coordinates.

For reasons that are a mixture of valid science and historical accident, there is no one agreed latitude and longitude coordinate system. There are many different meridians of zero longitude (prime meridians) and many different circles of zero latitude (equators), although the former generally pass somewhere near Greenwich, and the latter is always somewhere near the rotational equator. The result is that different systems of latitude and longitude in common use today can disagree on the coordinates of a point by more than 200 metres. For any application where an error of this size would be significant, it is important to know which system is in use and its exact definition

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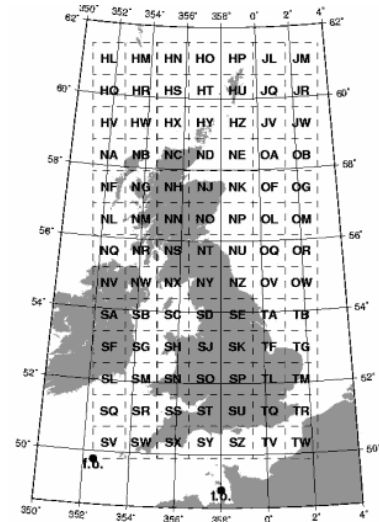
OS National Grid

The latitudes and longitudes of all features shown on Ordnance Survey maps are determined with respect to a terrestrial reference framework called OSGB36.
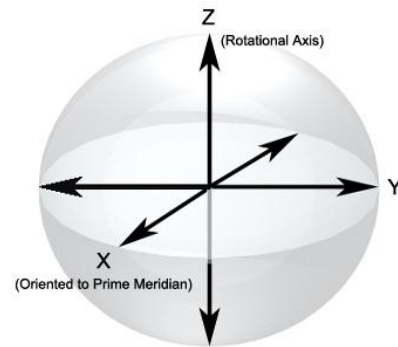
World Geodetic System 1984 (WGS84)

For real-time measurements and calculations, GNSS use the WGS84 reference system, with the resultant coordinates related to the WGS84 ellipsoid model. The origin of WGS84 ellipsoid coincides with the centre of the Earth's mass. The perpendicular X and Y-axes form the equatorial plane. The Z-axis is perpendicular to this plane, and coincides with the Earth's rotational axis. The X-axis is oriented to the Prime Meridian. The reference system for the data in Google Earth is WGS84 with a Plate Carree (world) projection.

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8. GPS FOR MEASURING MOTION

The highest sampling rate of a typical GPS unit is 1 point per second. At each point, the receiver records the latitude, longitude and altitude.

Therefore, the GPS unit captures the position vector of an object moving on the surface of the Earth, every one second. The rate of change of this position gives the 3D velocity vector of the object. The rate of change of velocity is the 3D acceleration of the object. The time dependent position, velocity and acceleration contain the complete description of the motion of the object.

Knowledge of the mass and the time varying position vector of an object allows the calculation of the time variation of the net force vector acting on the object. This is summarised by Newton's second law of motion, which states that the net force of an object is equal to its rate of change of momentum, which is also equal to the product of the mass and the acceleration.

Similarly, it is possible to calculate the physical effort or work expended by forces on objects causing them to change position. Taking the Geoid to be the location of zero altitude, the potential and kinetic energies of a moving object can be readily calculated from its time varying position vector and mass. The sum of potential and kinetic energies gives the total mechanical energy of the object. The change in the total mechanical energy is equal to the total work done by non-conservative forces, which typically in this case are external engines and the force of friction.

Therefore, the knowledge of variation of total energy opens up many possibilities for the examination of the law of conservation of energy. The time variation of total energy allows the exploration of the concept of net power impelling the motion.