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Global Positioning System - GPS

The Global Positioning System, frequently known as GPS is an Earth-satellite-based navigation system made up of a synchronized network constellation of at least 24 satellites which have been placed in Earth orbit by the U.S. Department of Defense (DoD). GPS was intended originally for military applications, but the U.S. government made the system available for civilian use purposes in 1984.

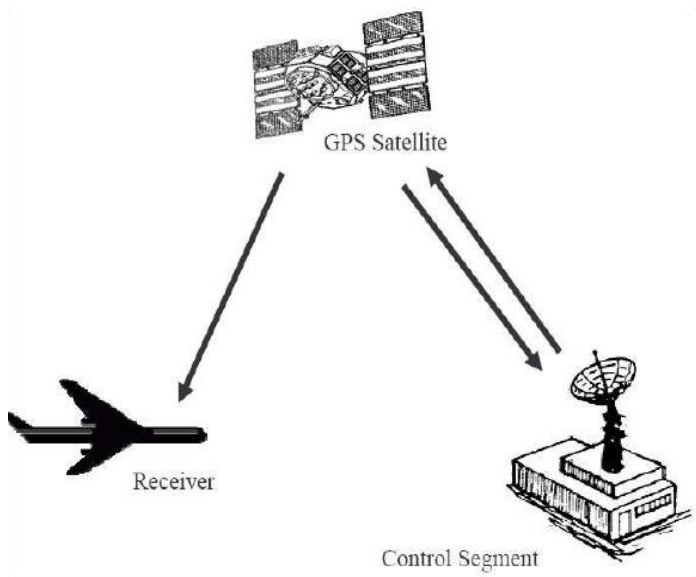


Figure 1: GPS Segment

The GPS system provides coded satellite signals which can be processed in a GPS receiver, allowing the receiver to estimate its current position and velocity. The system accuracy is not fixed, but the GPS should work in any climate situations and in any place on Earth, at any time. It is based on three active segments: Space, Control and User segment.

Control Segment

The Control Segment based on a system of tracking stations placed in different locations around the world. The main station is the Master Control facility, which is found at Schriever Air Force Base in Colorado.

These stations sustain and observe the Space segments (Satellites) in its proper orbit, produce corrections to its clocks, generate and upload Navigation (NAV) data to the satellites, in order they can transmit these NAV data to the End user.

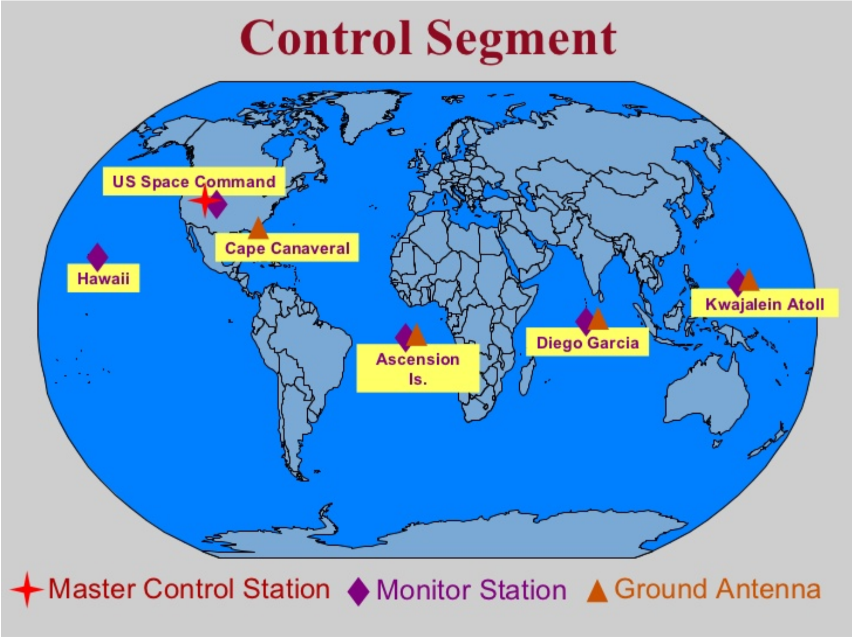


Figure 2: GPS Control Segment

Space Segment

The Space Segment of the GPS system are the GPS satellites, which send radio signals from there orbits to the users.

The first GPS satellite was launched in 1978 and a full constellation of 24 satellites was accomplished in 1994 (now 29 Satellites). The orbit altitude was chosen such that the satellites repeat the same track and configuration over any point roughly each 24 hours (4 minutes earlier each day). There are six orbital planes (with nominally four Satellites in each), equally spaced (60^{o} apart), and inclined at about 55^{o} with respect to the Earth equatorial plane.

Each satellite is built to last about 10-15 years and replacements are constantly being manufactured and launched.

A GPS satellite weights nearly 900kg and is about 5 meter long with the solar panels expanded. Its power transmitter has only up to 50 watts.

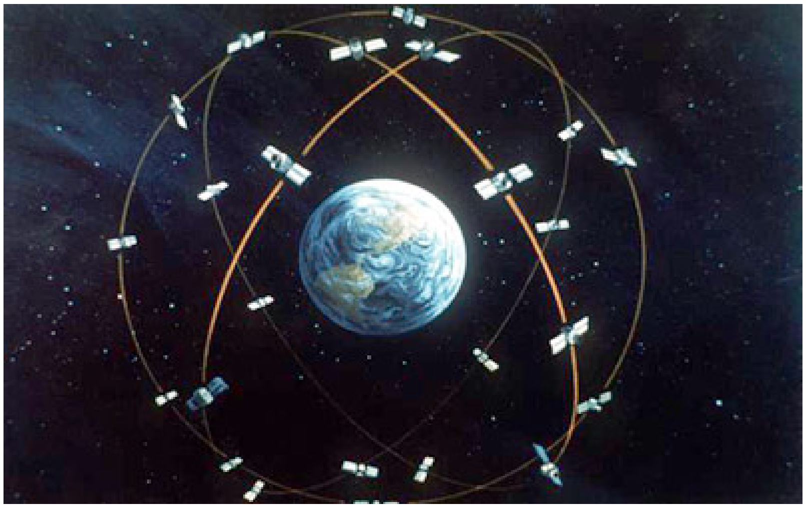


Figure 3: GPS Space Constellation (24 Satellites in 6 Orbital Planes)

User Segment

The User Segment involves the GPS receivers which are available anywhere without charge or limits. Basically, the GPS receiver competes the time difference between a GPS-signal sent from a GPS satellite with the time it was received. This time difference is used to calculate how far the satellite is. By measuring the distance of several satellites (at least 4), the user segment position and time can be computed.

Once the user’s position has been computed, the receiver unit can determine other information, like velocity and track. The calculated position, velocity and time of the user, all related to the Earth-Centered Earth-fixed (ECEF) frame. In some cases, even the angular rates can be provided through GPS antenna positioning techniques.

Figure 4; A GPS Receiver Example

Since the GPS receiver determines the states directly, it does not need information about previous states in order to calculate the current states, which means, it is not dependent on initial conditions. Hence the GPS receiver is considered to be a stand-alone sensor with limited error in time. This feature gives long operation time stability, what is not provided by any other reckoning sensor like IMU.

Nevertheless, unlike the IMU, it cannot provide a fast navigation solution because of its low sample rate and the fact that the vehicle must have at least 4 GPS satellite signals presented. The VectorNav sensor VN-200 combines the IMU and GPS measurements and provides a fast navigation solution up to 200Hz, the VN-200 provides industrial users with access to a continuous stream of low latency high accuracy position velocity and attitude measurements.

Therefore, although the advantage of being a standalone sensor and the long operation time stability, it has also associated imprecision due to the path of the satellite signals to the receiver, which suffer the influence of the atmosphere, multipath effects and clock bias and drift. Therefore, the navigation solution provided by the GPS receiver cannot reach high accuracy requirements. However, the measurements can be used in estimation processes as aiding sensor, where they help inertial sensors keeping the track to the actual position, velocity and attitude. In the GPS applications, the standard measure for accuracy is the Root-mean-square (RMS) error, which is the value of one standard deviation (68 %) of the error in one, two or three dimensions.

Nowadays, GPS receivers are particularly accurate (10 meters in average), and capable of tracking several satellites simultaneously, because of the utilizing of their parallel multi-channel strategy. For instance, 12 parallel channel receivers can lock up to 12 satellites simultaneously, and keep them locked even in urban settings with tall buildings, atmospheric factors and other sources of error.

GPS measurements

In absence of clock bias, three measurements are enough to determine the position in a three-dimensional space. However, in the presence of clock bias, 3 measurements only give a region which contains the position, without the possibility to determine the specific position. Thus, a fourth measurement is needed to determine the position within this region.

The complete range description, which takes the clock bias into account, is called pseudo range.

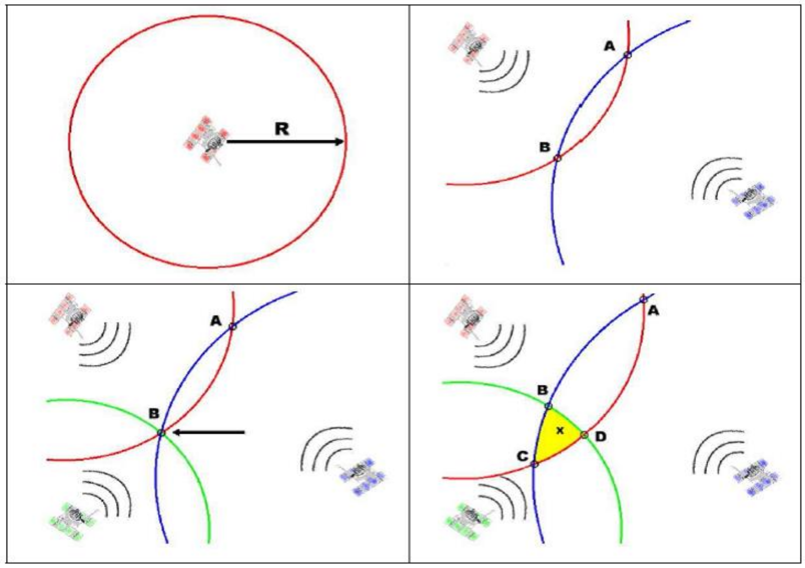


Figure 5: Pseudo-range concept

From the signal correlation performed in the electronic, the GPS receiver is capable of providing two types of measurements for GPS signals: Pseudorange and Doppler.

The raw measurement of the pseudorange and delta-pseudorange due Doppler are

$$\tilde{PR} = (\tilde{t}_R - \tilde{t}_T) \cdot c$$
$$d\tilde{PR} = -(D\tilde{C}O - IF_{L1}) \cdot c/L1$$

To determine the position and speed, a model for the GPS measurements is needed.

The measurement models for the pseudorange and delta-pseudorange due Doppler are

$$\hat{PR} = \hat{R} + \hat{R}_{bc} - \Delta\hat{T} \cdot c$$
$$\hat{R} = |\hat{\underline{r}}_S^i - \underline{r}_R^i|$$
$$\Delta\hat{T} = \hat{b}_{SV} + \Delta\hat{t}_r - \Delta\hat{T}_I - \Delta\hat{T}_T - \Delta\hat{T}_M$$

$$d\hat{P}R = (\hat{\underline{v}}_S^i - \underline{v}_R^i)^T \cdot \frac{(\hat{\underline{r}}_S^i - \underline{r}_R^i)}{\hat{R}} + (V_{bd} + \mu_{bd}) - \frac{d(\Delta\hat{T})}{dt} \cdot c$$
$$\frac{d(\Delta\hat{T})}{dt} = \frac{\Delta\hat{T}(t_{k+1}) - \Delta\hat{T}(t_k)}{t_{k+1} - t_k}$$

where µbd represent the associated noise around the real clock drift speed Vbd such as

$$\hat{V}_{bd} = V_{bd} + \mu_{bd}$$

and the delays are:
• Dtr - Relativistic delay
• DTI - Ionospheric delay
• DTT - Tropospheric delay
• DTM - Multipath effect delay

Note: The satellite clock bias is represented by bSV which is not included in the clock bias term Rbc that represents only the receiver clock bias.

It is possible to note that the pseudorange equation contributes with the same 4 unknowns rX, ry, rz and Rbc for each observed satellite while the delta-pseudorange equation contributes with the same 4 unknowns vX, vy, vz and Vbd. Thus, if at least 4 satellites are available, the position, clock bias, speed and clock drift can be determined and thus it is possible to determine the user positioning for both static and kinematic cases.

GPS Error Sources

There are several sources of error in any GPS reading, the typical GPS error sources are:

• **At Transmission:**
Satellite Clock errors - Deviations in the satellite clock with respect to the global GPS System Time due associated biases, drifts and when the message does not transmit the correct clock correction terms. For 12 hours update, the average error is about 1 − 2 m without SA.
- SA errors - Occur due introduced deviations for non-authorized users. The typical RMS for SA is about 20 m.

• **On Travel:**
– Ionosphere errors - Occur due the deviation of the travel of GPS signals through the ionosphere, which is a function of the frequency of the carrier.
The average error is about 2−5 m depending on sight elevation with minimum at zenith.
– Troposphere errors - Occur due the deviation of the travel of GPS signals through the troposphere, which is a function of the pressure, temperature and humidity. The average error is about 1 m depending on sight elevation with minimum at zenith.
– Multipath errors - Occur due signals multi-reflection paths, which masks the signal code correlation pick. This effect is more present for receivers near ground and reflective surfaces. In the case of navigating aerospace vehicles, this effect is reduced. The average error can range from about 1 m for moving receivers to about 15 m for static receivers in extreme cases.

• **At Reception:**
– Receiver Clock errors - Deviations in the receiver clock with respect to the global GPS System Time due associated biases and drifts. Typical values are around 300.0 m.
– Receiver Noise and resolution errors - Deviations in the receiver due receiver clock resolution and associated measurement noises. Typical values are around 11.0 m.
– Satellite Ephemeris errors - Occur when the message does not transmit the correct satellite location (Ephemeris or Almanac). The principal effects occur in the radial position, orbit inclination and argument of latitude. They tend to grow since the last uploaded correction and are closely correlated to the clock errors. For prediction of up to 24 hours, the RMS ranging error is about 2.1 m.
Not considering receiver clock errors, if all errors are taken into account, excluding SA, the average error will be about 1 ¾ = 12.8 m for vertical errors and about 1 ¾ = 10.2 m for horizontal errors, where the ionosphere is the dominant contribution. Including SA, the average error will grow up to about 1 ¾ = 51.4 m for vertical errors and about 1 ¾ = 41.1 m for horizontal errors.The errors can be summarized in the following table:

Domain	**Error**	**1σ user equivalent range error (m)**
At transmission	Satellite clock	2.0
	SA	20.0
On Travel	Ionosphere	5.0
	Troposphere	1.0
	Multipath	1.0
At Reception	Receiver Clock	300.0
	Receiver Noise	11.0
	Ephemeris	2.1

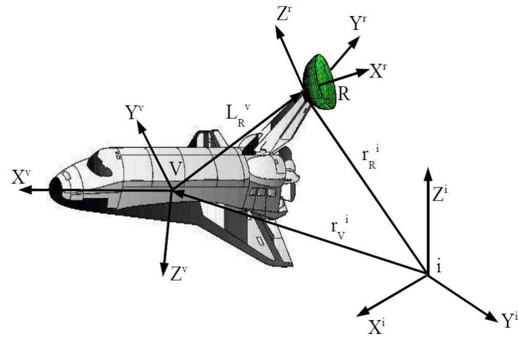
– Troposphere errors - Occur due the deviation of the travel of GPS signals through vehicle navigation.

Antenna Installation on the Vehicle

Although the GPS measurements give a navigation solution for the antenna, what is of real interest, is the navigation solution for user vehicle, on which the antenna is installed.

Hence the antenna navigation must be translated to the vehicle navigation. Hence, the system must be able to change among vehicle and receiver antenna navigation variables.

This task is accomplished through the installation relationship equations. Depending on the design of the user vehicle, the installation position of the antenna and its angular alignment with respect to the vehicle reference frame can be diverse. In the next figure the installation relationship is sketched for the antenna.



Since the antenna navigation solution is influenced by vehicle motions and antenna motions with respect to vehicle, and that the antenna is not necessarily installed on vehicle. Note that not all of the following navigation variables are capable to be determined by single receiver GPS measurements. However, since GPS receivers are frequently applied together with inertial measurement units, known as platforms, for vehicle navigation, the antenna navigation variables, other than position and velocity, can be also determined from the vehicle navigation variables through the vehicle installation relationships. These variables can then be used to help on the GPS measurements, as for example in better Doppler effects computations by taking the attitude motion into account.