GPS/GNSS Meteorology

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1. Introduction

The Global Positioning System more popularly GPS was deployed by the Department of Defence USA for improved navigation, positioning, and timing purposes. The term 'global navigation satellite system' (GNSS) refers to a constellation of satellites providing signals from space transmitting positioning and timing data. By definition, a GNSS provides signals on global coverage for example GPS (USA), GLONASS (Russia), Galileo (Europe) and Compass or Beido (China).

IRNSS (Independent Regional Navigation Satellite System – India) and QZSS (Quasi Zenith Satellite System (JAPAN) are examples of Regional Navigational Satellite System for India and Japan and does not have global coverage.

Precise location information of interest to geophysicists required correction of position errors due to atmospheric delays. In the early 1990's, scientists developed techniques to use these same atmospheric delay errors as signals to determine the amount of Integrated Precipitable Water Vapor (IPWV) in the troposphere. The result of these efforts created a new science, GPS/GNSS Meteorology.

This lecture notes discuss in brief about GPS principles and its application in Meteorology. The principle is same for all other GNSS satellite systems except the position, inclination of satellite orbits and satellite signal structure.

2. What is GPS?

GPS mainly consists of three segments

1. Space Segments
2. Control/Ground Segment
3. User Segments

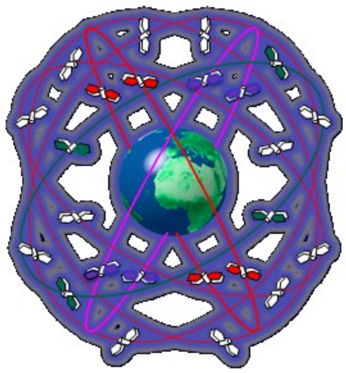


Fig -1. GPS constellation

Space Segments

- The Global Positioning System (GPS) is a satellite-based navigation system made up of a network of 24 satellites moving in six orbital plane (fig 1).

- Each orbit contains 4 satellites at 20,200 km height from the surface of the earth and the orbit is inclined at 55 degree to the plane of earth equator (Fig 2). The orbital period of the satellites is 12 hours.

Fig 2. GPS Satellite Orbits

- Total number of satellites are 27 (6 X4 = 24 + 3 spares to replace deteriorating satellite if any during operation)

- GPS satellites Caries Atomic Clock onboard and transmit two low power radio signals, L1=1575.42 MHz and L2 =1227.60 MHz . Base frequency (L = 10.23 MHz).

Control/Ground Segment

- Control Segment is responsible for the proper operation of the GPS system.

- The Control Segment (Fig 3) is composed by a network of Monitor Stations (MS), a Master Control Station (MCS), a backup of the MCS and the Ground Antennas (GA).

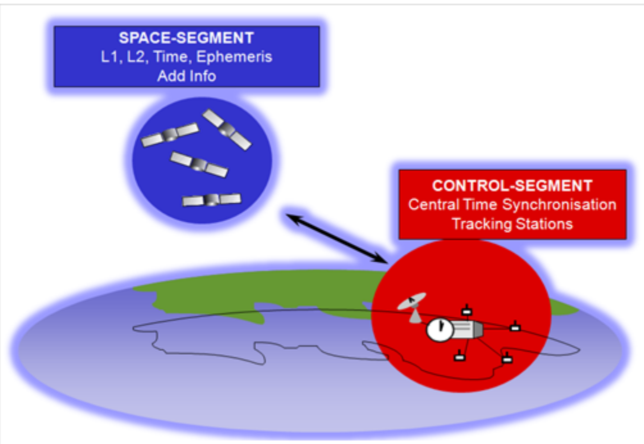


Fig 3. Ground Segment or Control Segment

- The MCS processes the measurements received by the MS to estimate satellite orbits (ephemerides) and clock errors, among other parameters, and to generate the navigation message. These corrections and the navigation message are uploaded to the GPS satellites through the GA, which are co-located in four of the Monitor stations.

User Segments

- The GPS User Segment consists on L-band radio receiver/processors and antennas which receive GPS signals, determine pseudorange.
- (and other observables), and solve the navigation equations in order to obtain user coordinates and provide a very accurate time (Fig 4).

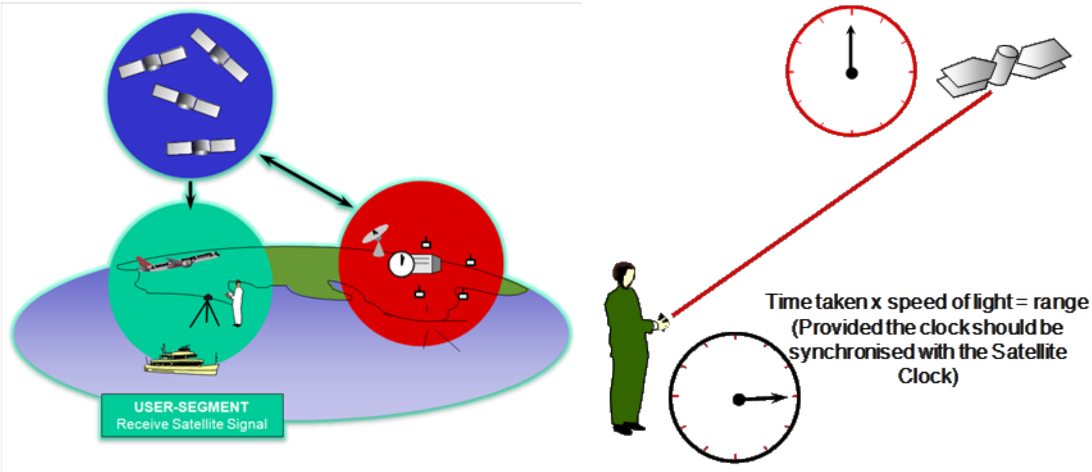


Fig 4. User Segments. User finding his range from the GPS satellite.

- By finding the pseudoranges from three different satellites simultaneously the user coordinates obtained by triangulation as shown below (Fig 4B).

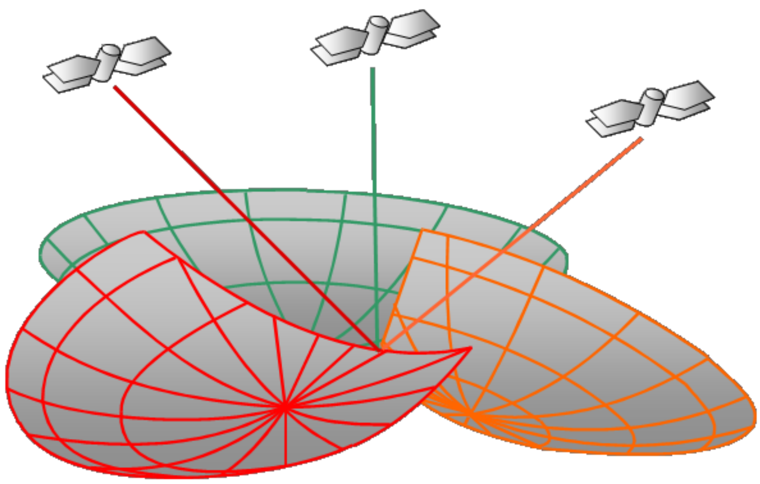


Fig 4B. 3 Ranges to resolve – latitude, longitude and height of the user with respect to earth axis. 4th Range to resolve receiver clock offset.

- But in reality the GPS signal gets affected by the presence of matter along its path: the atmosphere (ionosphere and troposphere).

➢ The atmosphere affects the signal propagation by

- Extra delay (slowing effect)
- Curved path (bending effect)

Therefore the excess time travelled by the signal leads to inaccuracy in finding the range of the satellite.

For example as in figure below, let as assume the signal takes 0.1 sec to reach a user. The user estimate the range between satellite and receiver is about 30,000 Km. (Distance = velocity of light ($3X10^8$ m/s) X 0.1 sec). This is true for free atmosphere or vacuum. But our atmosphere is composed of water vapour, ions and polar molecules, the GPS signal for the same range takes longer time to reach the user. For example, if the user receives the signal after 0.2 sec, then the user estimate range 60,000 Km from the satellite instead of 30,000 Km.

3. GPS Meteorology

Water vapor is the key element in the hydrological cycle and the main driver of atmospheric events. Water vapor is not evenly distributed over the earth because of the hydrological cycle and variations of temperature, pressure and geography. The distribution varies both horizontally on earth's surface and vertically as well. Nearly 50% of the water in the atmosphere is between sea level and 1.5 km above sea level. Less than 5% is between 5 to 12 km and less than 1% is in the stratosphere. Horizontally, on earth's surface, average IPWV is less than 5 mm near the poles and greater than 50 mm near the equator. Active weather is strongly correlated to the distribution of water vapor in the atmosphere.

The ability to improve weather forecasts is currently hindered by the lack of timely and accurate water vapor observations, especially under severe weather conditions. Current moisture observations in the atmosphere made with weather balloons are inadequate because the balloons are sparsely launched and are not frequent enough to provide reliable, accurate moisture data. Other ground or space-based systems can give PW only in cloud free regions. Over the land due to large variation in surface temperature, the accuracy of PW is largely compromised over land region. The space based The National Weather Service's (NWS) existing systems measure moisture with 3 mm accuracy inland and 5 mm accuracy along the coasts (cloud free region). Ground-based GPS Meteorology utilizes GPS receivers co-located with surface Meteorological sensors to calculate the total precipitable water vapor directly above the site at 1 mm accuracy.

As depicted in Figure 5, the total GPS signal delay (error) in the atmosphere is composed of ionospheric and tropospheric delays. The largest atmospheric signal delays come from the ionosphere. These delays can be compensated with dual frequency GPS receivers. GPS satellites send radio signals at two frequencies, L1 (1.6 GHz) and L2 (1.2 GHz). The delay in the ionosphere is inversely proportional to the frequency of the radiowaves. Thus, the delay can be calculated by measuring the difference between the two frequencies. The tropospheric delay cannot be corrected by using the dual frequencies since the electrically neutral atmosphere (troposphere) is nondispersive below 30 GHz (Fig 6). The tropospheric delay has two components: hydrostatic and wet components. The dry delay is due to the total mass of the atmosphere above the GPS antenna, and wet delay is caused by the total amount of water vapor along the GPS signal path. To calculate wet the delay, first the dry delay (ZHD) is calculated from surface pressure measurements.

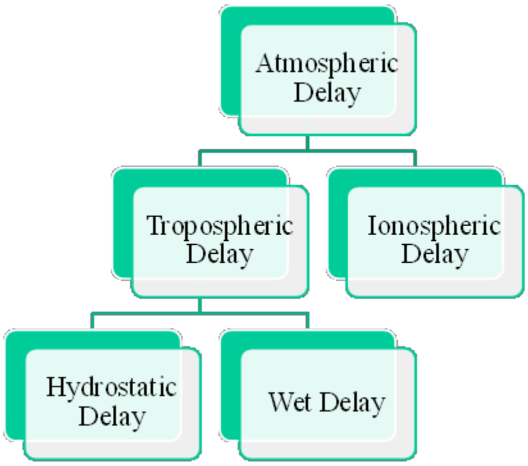


Fig 5. GPS Signal Delay

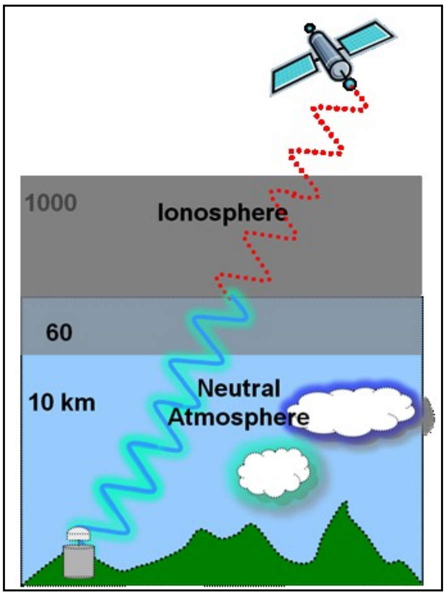


Fig 6.

$$\text{ZHD} = \frac{(2.2768 \pm 0.0005) P_s}{f(\phi, H)} \quad (1)$$

with ZHD in mm and P_s in hPa. The term

$$f(\phi, H) = 1.00266 \cos 2\phi - 0.00028 H \quad (2)$$

accounts for the variation in gravitational acceleration with latitude ϕ and the height *H* of the surface above the ellipsoid (in kilometres). The ZTD of the GPS signal is the integral of the refractivity N along the ray path. Neglecting liquid water contribution and ionospheric effects

$$\mathrm{N} = k_1\left(\frac{P_d}{T}\right)+k_2\left(\frac{P_w}{T}\right)+k_3\left(\frac{P_w}{T^2}\right)$$

The ZWD is obtained by subtracting the ZHD from ZTD (observed). The PW estimates were then obtained by scaling the ZWD with the multiplication factor Π given by

$$PW = \Pi * ZWD \qquad (3)$$

$$\Pi^{-1} = 10^{-6}\rho R_v[(k_3 / T_m)+k_2^{'}]$$

where ρ is the density of liquid water, R_v is the specific gas constant for water vapour, k_3 *and* $k_2^{'}$ are physical constant. The water-vapour weighted mean temperature of the atmosphere is defined and approximated as

$$Tm \equiv \frac{\int \frac{Pv}{T} dz}{\int \frac{Pv}{T^2} dz} \qquad (4)$$

can be calculated from vertical profiles of water vapour pressure P_v and temperature T, usually derived from NWP analysis fields. Assuming a linear relation with surface temperature it is also possible to approximate T_m from station surface temperature observations T_s

$T_m = 55.8 + 0.77T_s$.

3. Current GPS Networks: The promise of GPS-MET to determine the amount of IPWV and improve short-term weather forecasts attracted the attention of groups all around the world. The initial goal for most of these networks was geodetic applications. Over time, as GPS-MET techniques were refined, most of these networks started co-locating MET packages with the existing GPS receivers to perform IPWV calculations. IMD initiated the project with 5 GPS stations and now

commissioning 25 more stations. This network likely to increase to 50 by end of year 2015. With an experimental network, NOAA has demonstrated that inclusion of GPS observations into numerical weather prediction methods improves forecast accuracy.

4. Current GPS Meteorology Applications:

a) Near-Real-Time Weather Prediction: The main goal of GPS Meteorology has been to provide improved short-term weather prediction, especially in severe weather such as thunderstorms or flash flood. See the fig, the PW measured by GPS continuously increasing since 00 UTC onwards followed by heavy rain. During convective system, the PW values increases before the formation of convective clouds. The GPS data may help in predicting the duration and magnitude of a rain event. If it starts to rain and the IPWV is still climbing, we can conclude it is going to continue to rain and probably get more intense. This valuable information is not easily available from other meteorological sources that are sparser spatially and temporally.

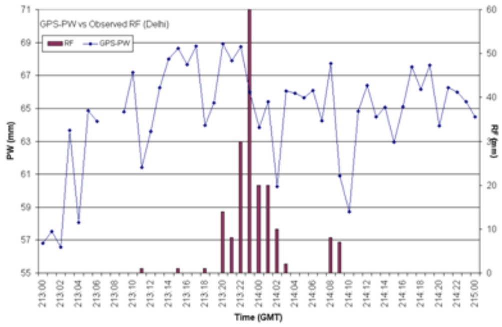
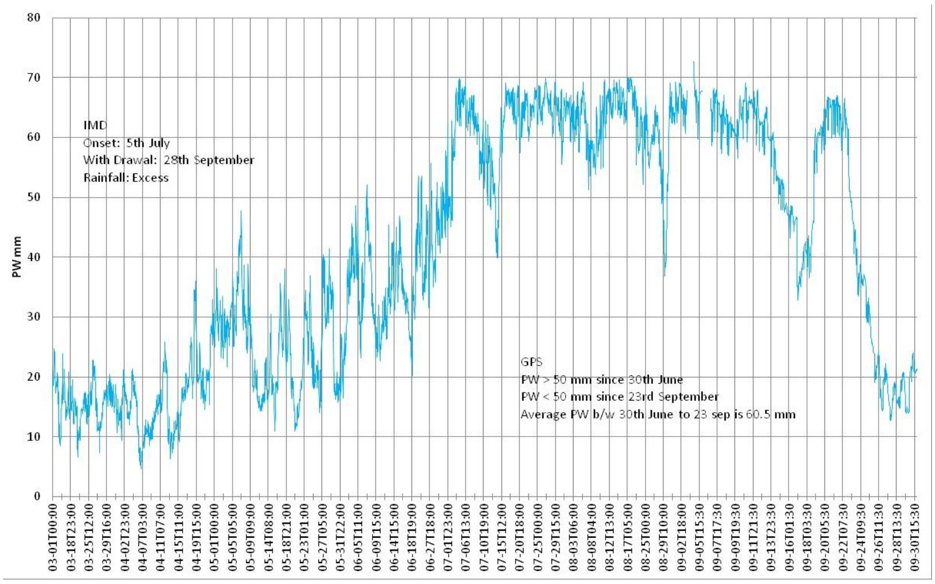


Fig 7. Time series of PW variation and observed Rainfall

b). Monsoon Arrival and withdrawal. Fig 8. shows the continuous variation of PW during premonsoon, monsoon and post monsoon. The onset of monsoon over New Delhi is noticed on 5th July against the normal date of 29th June. On 5th the PW increased from 50 mm to 70 mm. It is also seen that PW remains 65 mm throughout the monsoon season and decreased rapidly to 20mm in 25th September.



C). Climatology: Since GPS Meteorology is a tool to determine the amount of PWV in the atmosphere, this concept can also be applied to long-term weather studies (climatology). A study was done by the University of Hawaii and the Jet Propulsion Laboratory in 1998 to determine if the GPS-MET concept was applicable to long-term weather studies. During this study, GPS receivers recorded the influence of El Nino precipitable water vapor in the tropic Pacific Ocean. The IPWV drop from these receivers coincided with the drop in seasurface temperature. During the mature phase of El Nino, atmospheric drying associated with El Nino was clearly visible from GPS readings.

D. Major other Applications of GPS Network

1. Meteorological Satellite Sensor calibration and Validation

2. Soil moisture estimation

3. CORS (Continuously operating Reference Station) used to monitor crustal deformation (Seismology) and seismic observation.

4. Land Slide, Sea level raise,

5. Time transfer and Positioning,

6. Ionospheric /TEC study

5. Satellite Based Augmentation System (SBAS). The **GPS aided geo augmented navigation** is an implementation of a regional SBAS by India. It is a system to improve the accuracy of GNSS receiver by providing reference signals. The Airport authority of India's efforts towards implementation of operational SBAS can be viewed as the first step towards introduction of modern communication, navigation, surveillance/**Air Traffic Control** system over Indian airspace.

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