A Broad Overview of GPS Fundamentals: Now and Future

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***Abstract*— GPS (Global Positioning System) is a satellite based navigation system and is used in a variety of applications such as mapping, vehicle navigation and surveying. In this work, a detailed background of GPS is included. First, historical development of GPS technology is provided. This is followed by a detailed theoretical background of GPS and GNSS (Global Navigation Satellite System). Afterwards, the topics of "GPS estimation error" and "increasing GPS position accuracy" are covered. Then, various counterparts of GPS technology, developed by rival countries are discussed. Finally, future expectations of scientific world from the GNSS technology are presented.**

***Index Terms*— GPS, satellite, GNSS, PRN, trilateration**

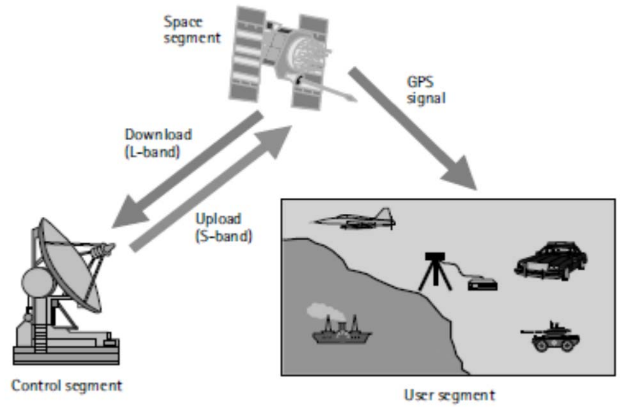

Fig. 1: GPS Segments [4]

I. Introduction

GNSS (Global Navigation Satellite System) is a system that supplies geospatial positioning with a coverage all around the world [1]. GPS (Global Positioning System) is the first GNSS which is designed and released by DoD (Department of Defense) of the U.S. in 1970s [2]. Although it was originally built for military purposes, it became available to civilian users' access in the early 1980s [3]. The GPS supplies timing and positioning data globally for both military and civilian access, though by means of distinct carrier frequency use [4]. It is used in a variety of applications including personal navigation, aviation navigation, vehicle navigation, marine navigation, mapping, survey and infrastructure.

GPS system is comprised of at least 24 active satellites orbiting about 19,000 kilometers above the earth and they are arranged in a form that any GPS receiver at any time and any point around the world sees or has a line of sight to at least 4 GPS satellites. 24-hour-a-day coverage is supplied by these satellites [5]. A couple of extra satellites are reserved in the system in idle mode in case of any active satellite failure so that full coverage anywhere in the world is sustained.

In GPS system, atomic clocks are used as they are extremely accurate [6]. Ranging code and navigation data are broadcast by each satellite with the use of CDMA (Code Division Multiple Access) [6]. The Coarse/Acquisition (C/A) ranging code, also called PRN (Pseudorandom Noise) code is 1,023 bits unique sequence repeating every millisecond. A receiver contains all of the PRN codes belonging to any satellite and by means of cross correlation of each with the received PRN code it determines from which satellite the signal is transmitted. A peak cross correlation-coefficient is obtained only with the matching satellite code. The ranging code also allows the receiver to measure the time of the flight of the signal and thereby estimating the range from the satellite to the receiver. In the receiver side, a crystal clock is generally utilized so as to keep the size, cost and complexity low. As a crystal clock is not as accurate as an atomic clock, a minimum of four satellites are needed for user position coordinates to be estimated meaningfully [6].

Amongst the GPS counterparts, GLONASS, Russian Global Navigation Satellite, is the only one which is in full operational mode. By means of interoperability of GPS with other GNSS systems, the position accuracy could be increased significantly.

A. History of GPS Development

In 1973, the GPS proposal was officially accepted. In 1978, the first satellite was sent into space and in 1993, the launch of 24 satellites, which was the requisite for a reliable and consistent GNSS system, was completed. In early 1994, by the Federal Aviation Agency (FFA), it was announced officially and publicly that GPS was prepared for aviation utilization [7].

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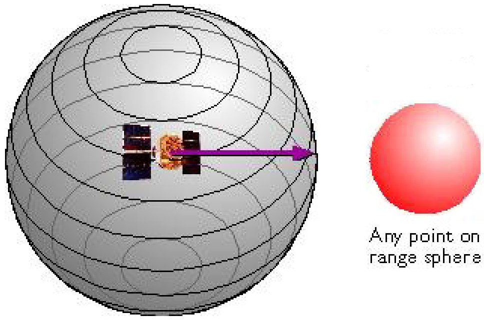


Fig. 2: First measurement puts the receiver somewhere on this sphere [8]

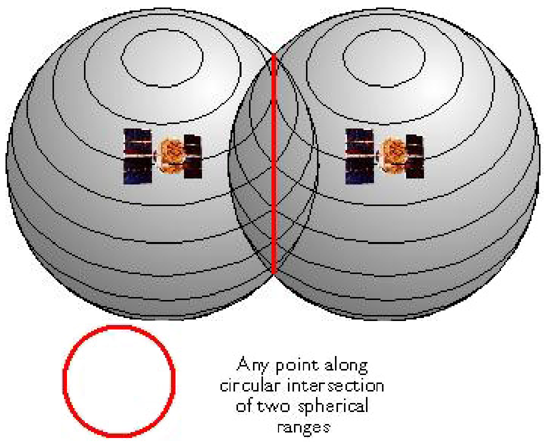


Fig. 3: Second measurement from a second satellite provides that the receiver is somewhere on this circle [8]

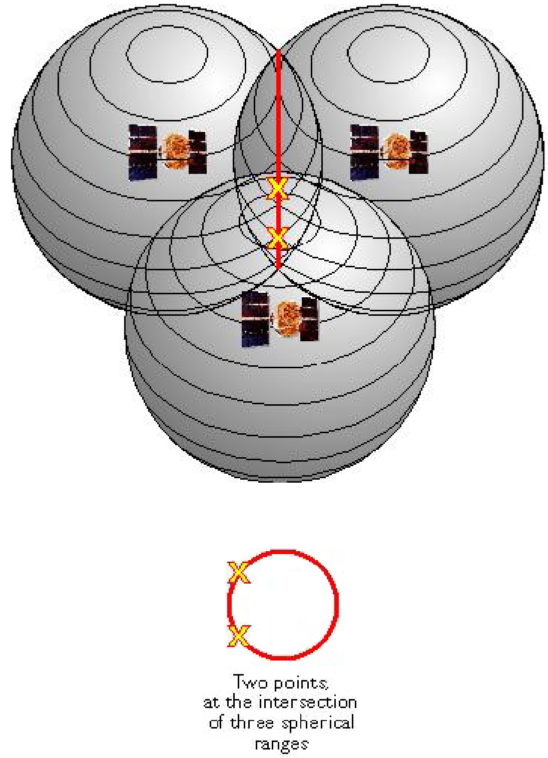


Fig. 4: Third measurement from another satellite puts the receiver at one of two points where all three spheres intersects [8]

B. GPS System Segments

As illustrated in Fig.1, The GPS system is composed of three main parts, namely the user segment, the space segment and the control segment [4].

The space segment is comprised of all the GPS satellites divided into six orbits. In general, a GPS receiver has a line of sight and thereby receives signals from 4 to 11 satellites [7].

The user segment can be regarded as the set of all military and civilian GPS user receivers. With a GPS receiver, a user can identify their position anywhere in the earth.

The control segment is composed of five control stations, one of which is the master, located at Falcon Air Force Base, Colorado Springs, CO. The GPS control stations are aligned far apart from each other around the world so as to monitor the performances of all of GPS satellites and collect sufficient data [7]. All the acquired data by the control stations are sent to the master control station so as for them to be processed. The master control station is responsible for determining the deviations in the system such as deviation in satellite locations, or deviation in satellite atomic clocks. All the computed corrections are uploaded into the GPS satellites [4][7].

C. GPS Counterparts

The Russian equivalent GNSS system to GPS is the GLONASS (Global Navigation Satellite System) and it is also in full operation as GPS [6]. Galileo, the European counterpart and BDS (Beidou Navigation Satellite System) also known COMPASS or Beidou-2, the Chinese counterpart to GPS, is currently under development [1] [9]. The equivalent GNSS systems are dissimilar to each other in terms of the signal structure, the control segment and the space segment [9]. Details of the distinctions are out of the scope of this study.

II. WORKING PRINCIPLES OF GPS SYSTEM

A. Trilateration

In any range measurement, the receiver is located somewhere on a spherical shell, in the center of which the broadcasting satellite is located [1]. Range measurement from several satellites leads all the spherical shells to meet in a particular region and the increase in the number of observable satellites minimizes this region, and so the position error [1]. If a receiver can acquire GPS signal from one satellite only, as shown in Fig.2, the set of possible locations of the receiver would be the whole spherical shell, in the center of which the broadcasting satellite is located and whose radius is the measured distance. In other words, the receiver is somewhere on this sphere surface. If a receiver can acquire GPS signals from two satellites, as displayed in Fig.3, the receiver is somewhere on the intersection, i.e. a circle, of two spherical shells. If a receiver can acquire GPS signals from three satellites, illustrated in Fig.4, the receiver's location is one of

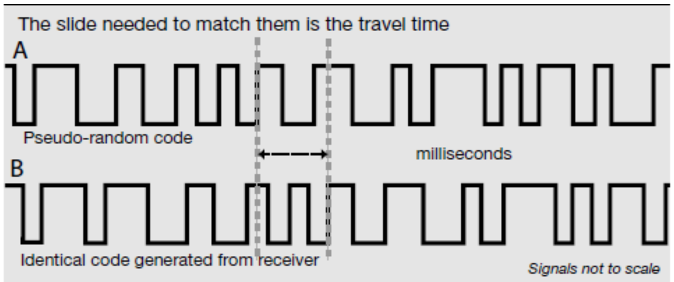
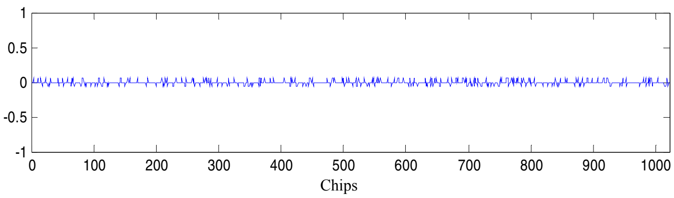
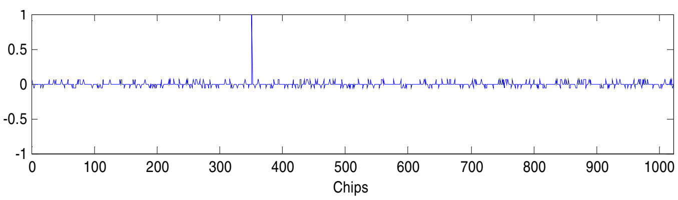


Fig. 5: Pseudo Random Code [10]



PRN1 is uncorrelated with PRN2



PRN1 is correlated with PRN2

Fig. 6:(a) Erroneous GPS Satellite (Upper), (b) True GPS Satellite Match ((Lower) -PRN1 is shifted 350 bits) [11]

the two intersection points of the three spherical shells. The closest point to the earth's surface is the receiver's position. Whilst 3 satellites are enough to locate one's location, a fourth one at least is required for a reliable position estimation [8].

B. True Satellite Match - Cross vs. Auto Correlation

As shown in Fig.5, each satellite in GPS system generates an entirely unique 1023-bits long PRN code and the identical code for each satellite is produced also by GPS receivers. Each code is pseudorandom and cross-correlation of any code with respect to any other is very low as displayed in Fig. 6(a). A receiver contains all of the codes belonging to any satellite and by means of cross correlation it determines from which satellite the signal is transmitted. A peak cross correlation-coefficient is obtained only with matching satellite code. Fig. 6(b) provides an exemplary PRN Code match, where the peak correlation coefficient is obtained.

C. Converting Coordinate System & Calculating a Position

The nonlinear equations built for position estimation are not straightforward to solve directly. Linearization and iteration methods are required to use in order to solve them. Moreover, as it is in Cartesian coordinate system, the result is required to be transformed into a spherical coordinate system [7]. Nevertheless, as the shape of the earth is not a perfect sphere but a geoid, the estimated position is converted into the earth-based coordinate system [7]. For computations of GPS coordinate conversions, [10] could be referred.

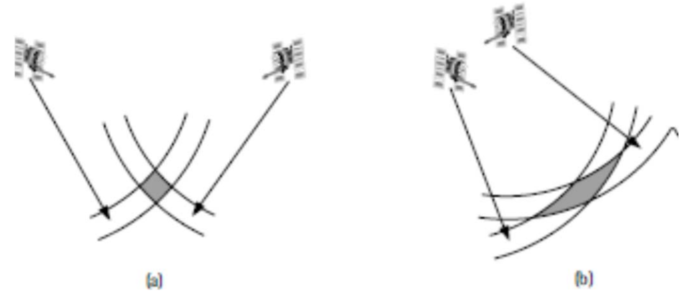


Fig. 7: (a) Good Satellite Geometry; and (b) Bad Satellite Geometry [4]

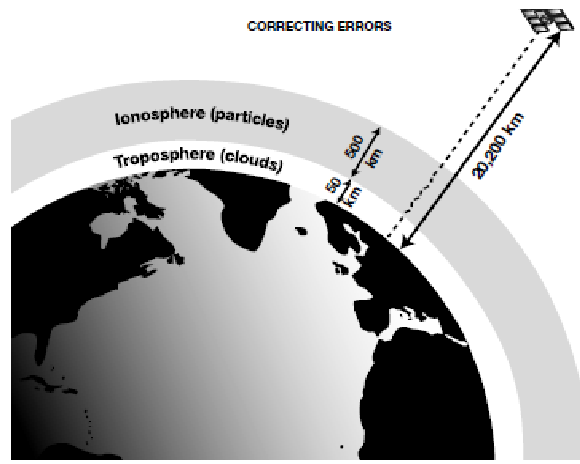


Fig. 8: Atmospheric Effects in the Troposphere and Ionosphere [2]

III. Sources of GPS Position Estimation Error

A. Satellite and Receiver Clock Error

Although the atomic clocks used by GPS satellites are very accurate, they are not impeccable. The satellite clock error varies between 8.64 ns to 17.28 ns per day which corresponds to an error range roughly between 2.59 m to 5.18 m as a result of a straightforward multiplication with speed of light [4]. It is notable that cesium clocks are inclined to perform better over a long time span in comparison to rubidium clocks.

The satellite clock performances are watched by ground control segment. The time deviation on each satellite clock is computed and passed on the corresponding satellite so as for them to adjust their own clocks [4].

In a receiver, a crystal clock whose accuracy is relatively low is broadly used to keep the size, cost and complexity low.

B. Electronic Noise in the Signal and in the Receiver

The design quality of the receiver, temperature and interference caused by other radio signal sources result in error in position computation [12].

C. Uncertainty in the Position of the Satellites (Ephemeris)

Although satellite position correction signals are transmitted by master control station, there is still uncertainty in satellite position accuracy. This uncertainty causes error in receiver position measurement [12].

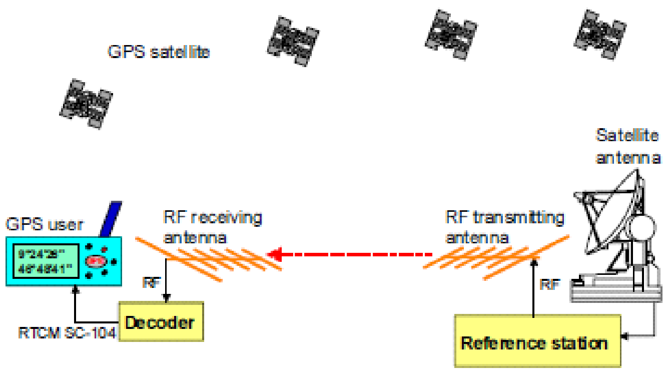


Fig. 9: [10] Differential GPS- Relaying the Position Correction Values

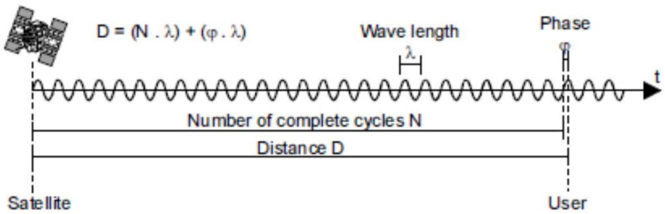


Fig. 10: The Principle of Phase Measurement [10]

D. *Intentional Degradation – Selective Availability*

Originally, So as to prevent enemy attacks, some position errors, within ± 100 m, are introduced intentionally to the GPS satellites by the US military. This intentional deterioration in position accuracy so called Selective Availability is abolished in 2000 [12].

E. *Multipath Error*

Multipath error is encountered when a satellite signal arrives at the receiver from multiple paths, one of which is directly and the others are reflected by structures. This error in GPS system can be diminished noticeably with the utilization of special antennas with concentric metallic rings around the antenna or with grounded metallic disk about 65 cm in diameter [12].

F. *Geometric Arrangement of the Satellites (Dilution of Precision (DOP))*

As in all ranging systems, estimated position accuracy in the GPS system is affected by receiver-transmitter geometry. Broadly, in the case satellites are spread farther apart from each other, the lower uncertainty in the receiver position is obtained, even though the measurement uncertainty is identical.

As demonstrated in Fig. 7, the shaded area represents receiver's position, when two satellites are aligned closer (b), the size of the uncertainty area grows up, causing a worse accurate position estimation. In contrast, when satellites are aligned farther apart from each other (a), position uncertainty region reduces, consequently leading more accurate position estimation. [13].

G. *Atmospheric Effects in the Troposphere and Ionosphere*

As demonstrated in Fig.8, Troposphere and Ionosphere layers of the earth's atmosphere span 50 km from the earth surface and 500 km from the Troposphere upper limit, respectively.

When the light passes through the troposphere and ionosphere, the speed of it drops, resulting in the measured range to the satellite is longer than the true distance. The speed reduction in the ionosphere varies depending on the electrons density along the signal path. The electrons density along the path is highly reliant on the time of the day, the geomagnetic latitude of the receiver and the height of the satellite. Troposphere effect on speed of the light is relatively small compared to that of the ionosphere [12].

H. *Effect of Radio Frequency Interference on GPS Signals*

Accuracy in GPS position estimation could be shrunk significantly by RFI (Radio Frequency Interference). Single and dual-frequency GPS receivers are influenced differently from an external RF interference [14]. A single frequency receiver undergoes the interference sooner in comparison to a dual-frequency receiver. According to outcomes of [14], The RFI impact could be diminished considerably by computing the difference in L1 and L2 phases. As a result, RF interference together with other signal interferences could be removed remarkably. This makes dual-frequency receivers more capable of restraining the influence of RFI, compared to single frequency receivers.

IV. IMPROVING GPS POSITION ACCURACY

In this section, most powerful GPS position enhancement techniques are evaluated

A. *PRN Code based Differential GPS (DGPS)*

The DGPS (Differential GPS) method requires at least two GPS receivers having line of sight to the same satellites and the main concept is that any receivers that are close to each other encounters alike atmospheric errors. As illustrated in Fig. 9, one receiver, so called reference or base station, is located at a fixed and accurately known position and computes its "position" according to the GPS signals received. It calculates the difference between the measured position and the actual position and transmits the correction data to the nearby DGPS receiver. This system provides an accuracy within a meter [12]. It is notable that a DGPS receiver requires an extra antenna, apart from that used for GPS signal receipts.

B. *Carrier phase based DGPS*

So as to obtain a positioning accuracy within a few millimeters, the satellite carrier signal phase could be used. The distance to a satellite can be estimated with the computations in shown in Fig. 10.

By constantly comparing the reference receiver with the user receiver at different times and solving innumerable sets of equations, a highly accurate position, within a few millimeters, can be estimated [10]. Real Time Kinematic (RTK) is a variation of differential GNSS method offering a noticeably enhanced accuracy.

C. Code Pseudo Ranges vs. Phase Pseudo Ranges

Although the position accuracy with the use of PRN code is at the meter range, it is in the millimeter level when the carrier phase technique is used. [9]

Both the L1 and L2 carrier frequencies are employed with carrier phase method. When this technique is used, the resolution increases remarkably as carrier frequency is 1000 times greater than that of the C/A code. Nevertheless, it requires modelling the ionosphere and troposphere and involves high load of corrections to the computations with the employment of orbital data [15]. That is to say, the carrier-phase method requires substantial post-processing. Thus, it is impractical when immediate position information is needed. It is most suitable for geodetic and surveying applications.

D. GNSS Interoperability – Hybrid GNSS

The cooperation of multiple GNSS systems leads augmentation of the position estimation accuracy as growing number of observations consequently results in the DOP (Dilution of Precision) values generally to reduce [9]. Such a cooperation of GNSS systems requires interoperability and compatibility. For interoperability, it is needed for GPS receivers to be equipped in a way that they are capable of acquiring and processing the signals from each system. For compatibility, all the systems require to work simultaneously, but autonomously without worsening each other's standalone performance. [16]

V. FUTURE EXPECTATIONS

For the time being, BeiDou supplies regional navigation and positioning and is expected to supply service globally by 2020 [17]. In a multi-constellation GNSS consisting of BeiDou, Galileo, GLONASS and GPS, there are more than 70 satellites currently available and around 120 satellites will be in use once BeiDou and Galileo are in full operation as GPS and GLONASS in the forthcoming years [18]. Since Galileo currently have a small number of satellites in orbits, the contribution of it to the quad-constellation GNSS in positioning performance accuracy enhancement and in convergence time improvement is lesser than that of the other three. There are also Indian Regional Navigation Satellite System (IRNSS) and Japan Quasi-Zenith Satellite System (QZSS) that are in their infant stages [19]. After completion of the launch of the intended number of satellites and of the all augmentations in the each system, a six-constellation-GNSS would boost the positioning performance in a significant degree.

Increased number of satellites generally provides more accurate positioning. Nevertheless, weather conditions have a noticeable impact on the accuracy. According to [20] , A-quad constellation GNSS, including GPS, BeiDou, GLONASS and Galileo enables noticeably more accurate positioning in poor sky visibility compared to that in clear weather conditions. In particular, this fact is observed in the Asia-Pacific region where BeiDou satellites are available. This findings reveal the proposal that there is no need to have large number of satellites in direct line of sight in the regions where generally good sky visibility prevail; conversely, it is good to have a plentiful number of satellites available in the regions mostly in poor weather conditions. It can be reached a conclusive point that all the satellites in multi-constellation GNSS system can be formed in consideration and in computation of general sky view of distinct regions [20].

Until very recently, for PPP (Precise Point Positioning), one reference station solely was utilized in the systems utilizing differential GNSS techniques, DGPS and RTK (Real Time Kinematics), so as for transmission of correction signals. With the launch of a Continuously Operating Reference Station (CORS) network, more than one reference station is used for correcting positioning [21] [22]. It is well known that having a large data set and averaging them reduces the noise. Considering this concept, it may be a viable enhancement to increase reference stations broadcasting error correction signals in the vicinity, about 20 km, of the user GPS receiver, i.e. mobile or stationary units in interest. In other words, if it may be feasible to construct and use several base stations, i.e. reference stations that broadcast correction singles, and averaging these correction signals may have a remarkable contribution on precise position estimation.

The Galileo satellites have an exclusive feature that they carry passive hydrogen MASER (PHM) atomic clocks in addition to rubidium atomic clocks [19] [23]. Passive hydrogen masers provide an outstanding clock stability with better than 0.00000036 seconds, i.e. it could lose 1 second only every 3 million years. At first glance, such an exceptional stability could appear to be meaningless. Nevertheless, if speed of light is recalled, an error of only a few nanoseconds would cause a positioning error within meters, which is quite unwanted. A multi-constellation GNSS, all equipped with PHM atomic clocks would lead a highly demanding PPM (precise point positioning).

VI. CONCLUSION

The GPS is used in a variety of applications including personal navigation, mobile phone applications (position information is used), aviation navigation, vehicle navigation, marine navigation, mapping, survey and infrastructure.

With the use of differential GPS, positioning accuracy can be increased noticeably. In particular, Carrier phase-based differential GPS techniques, DGPS and RTK present remarkably high accuracy in navigation, surveying and geodesy. A-multi-constellation GNSS system using differential GNSS techniques would provide precise point positioning (PPP) in high accuracy. GPS counterparts Galileo, COMPASS (BeiDou), IRNSS and QZSS are still under construction. A hybrid receiver enhances multipath performance by choosing only most meaningful and useful signals amongst the observable satellites and decreases dilution of precision. In particular, it offers considerable enhancement in the areas where satellites signals are highly obstructed by structures.

According to the our arguments in this paper; excellent global positioning data, i.e. an outstanding GPS positioning accuracy will be available for humanity when all the GNSS systems become in full operational mode and if the following conditions would be met:

- A hybrid model of all the six GNSS systems can be created.
- Constellation of all the satellites are succeeded based on the regional sky visibility.
- Passive hydrogen maser atomic clocks are used in each satellite.

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