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Introduction to Global Navigation Satellite Systems and Its Errors

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Abstract

Global Navigation Satellite Systems (GNSS) include different parts such as control and monitoring stations for the Earth and space settings. Timing, positioning, and control of navigation methods are the main outputs of GNSS. Based on Approach Procedure with Vertical guidance (APV), local and global satellite navigation systems used for positioning and precision approach in aviation instead of present systems like Instrumental Landing Systems (ILS) and its future predict of ICAO. According to ASBU, development of present systems in new flight instructions must include GNSS because flight capacity increase significantly through it. But these systems have errors in positioning and velocity measurement segments. Different methods exist in view point of installing earth antennas and satellite position to reduce estimation errors. In this paper two methods was studied.

Keywords: GNSS, Satellite, Navigation

Introduction

The Global Navigation Satellite Systems (GNSS), including the US's Global Positioning System (GPS), Russia's GLONASS, EU's Galileo and China Beidou (also called COMPASS) as well as several regional navigation satellite systems, can be characterized as a highly precise, continuous, all-weather and near-real-time microwave (L-band) technique with signals through the Earth's atmosphere. These characteristics of GNSS imply more and wider applications and potentials. Each GNSS satellite continuously broadcasts radio signals in two or more frequencies in L-band (1–2 GHz) with wavelength around 20 cm, the direct signals are be used for navigation, positioning and timing. The refracted signals from GNSS Radio Occultation satellites together with ground GNSS observations can provide the high-resolution tropospheric water vapor, temperature and pressure, tropopause parameters and ionospheric total electron content (TEC) and electron density profile as well. The GNSS reflected signals from the ocean and land surface could determine the ocean height, wind speed and wind direction of ocean surface, oil moisture, ice and snow thickness. Therefore, the refracted and reflected GPS signals can image the Earth's surface environments as a new, highly precise, continuous, all-weather and near-real-time remote sensing tool, which will play a key role in various atmospheric sounding, ocean remote sensing and land/hydrology mapping. In the following sections, the GNSS history, system, signals, theory and applications are introduced (Fig. 1).

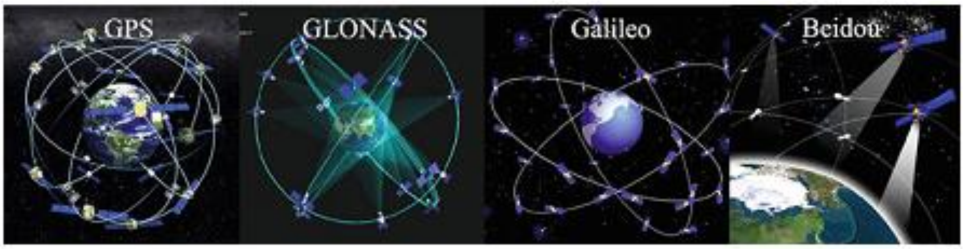

Fig.1. Global Navigation Satellite Systems (GNSS).

GNSS Signals and Systems

GNSS Segments

GNSS is consisting of a space segment having a constellation of satellites in Medium Earth Orbit (MEO) at the height of nearly 20,000 km and above, *control segment* having monitoring and control stations to monitor/control/update the constellation of satellites and the *user segment*; consisting of receivers to give position, velocity and time (PVT) of the static and mobile user all over the globe at all times using at least four satellites of the constellation in view.

The Global Navigation Satellite System (GNSS) has a well-defined structure, initially designed by US and USSR and then is being followed by the systems like Galileo and Beidou. The basic segments like space, control, user and augmentation are discussed in next lines. The reference architecture is about the GPS as it is only the fully operational at this moment with maximum information too. The signal structure is also discussed briefly to understand the basic principle of navigation and finding the position and time information.

Space Segment

It consists of constellation of satellites equipped with navigational payload, precise atomic clocks, navigational antennas and other subsystems like thermal, propulsion, attitude and orbit determination and control (AODC), Tracking, Telemetry and Command (TT&C) and power subsystems. The constellation is designed considering the availability of at least four satellites at all times across the globe. The satellites are arranged in different planes to provide the best geometric dilution of precision (GDOP), a parameter of satellite geometry. Medium Earth Orbits (MEO), 20,000–30,000 km, are chosen for the constellation of satellites due to considerable launch cost and global coverage.

Control Segment

It consists of master control centre along with some monitoring stations and telemetry telecommand antennas spread all over the globe to perform the following main tasks.

- Measures the position of each satellite and controls its attitude and orbit;
- Monitors the signals broadcast by satellites
- Sends information to satellites for a proper clock alignment
- Sends information to satellites for the navigation message

User Segment

User segment consists of mainly the GNSS receivers to process the signals received from the satellites and estimates the user's position. The functionalities common to any kind of receiver can be summarized as identification of the satellites in view, estimation of the user-satellite distance and Triangulation.

Augmentation Segment

It includes additional equipment like local elements, pseudolites or Geo-Satellites allowing new services or improved performance. Differential GPS (DGPS), Local area GPS (LGPS), Wide Area GPS (WGPS), WAAS (Wide Area Augmentation System), GDGPS (Global Differential GPS) by NASA, MSAS (Multifunction Satellite Augmentation System) by Japan and EGNOS (European Global Navigation Overlay System) by European Union are the few examples.

GNSS Signals

GNSS signals are summarized in Table 1 (Hofmann-Wellenhof et al. 2008). For example, GPS satellites continuously broadcast right-hand circularly polarized signals with both the navigation message and ranging codes modulated on two L-band microwave carrier frequencies, i.e., the L1 (f_1=1.57542 GHz, λ_1≈19.0 cm) and L2 (f_2=1.2276 GHz, λ_2≈24.4 cm). Starting from 2006, as part of GPS modernization effort, two new civilian-use signals L2C (L2 frequency, *C* denoting civilian) and L5 (f_{L5}=1.17645 GHz, λ_{L5}≈25.5 cm) were broadcasting on the new generation GPS satellites. Also another civilian-use frequency L1C is down the road in the near future. The navigation message includes the *ephemeris* data, used to calculate the position of the individual GPS satellite in orbit at the time of signal transmission, and the *almanac* data with the information about the time and status of the entire satellite constellation.

On the other hand, the ranging code enables the user's receiver to determine the transit (or propagation) time of the signal and thereby determine the satellite-to-user range. The satellite network uses a CDMA (code division multiple access) spread-spectrum technique where the low-bit-rate message data is encoded with a high-rate "pseudo-random noise" (PRN) sequence that is unique for each GPS satellite. The PRN is a binary signal with random noise-like properties, which is generated by mathematical algorithm or "code", and consists of repeated pattern of 1's and 0's.

Both L1 and L2 signals are modulated by a pseudo-random precision ranging code (P code). The L1 carrier signal is also modulated with coarse/acquisition (C/A) ranging code for civilian use. The P code can be encrypted as a so-called P(Y) which is only available to military equipment with a proper decryption key. The L1 and L2 signals received from each GPS satellite can be expressed as follows (Spilker 1980):

$$S_{L1}(t) = \sqrt{2C_{C/A}}D(t)X(t)\sin(2\pi f_1 t + \theta_1) + \sqrt{2C_{P1}}D(t)P(t)\cos(2\pi f_1 t + \theta_1) \quad (1)$$

$$S_{L2}(t) = \sqrt{2C_{P2}}D(t)P(t)\cos(2\pi f_2 t + \theta_2) \quad (2)$$

where $C_{C/A}$ and C_{P1} are the received powers of the in-phase and quadrature components of the L1 signal, respectively, C_{P2} is the received power of L2, $D(t)$ is an amplitude modulation for L1 and L2 containing navigation data, $X(t)$ is a pseudorandom sequence of ±1, known as clear acquisition or C/A code-modulating the in-phase component of L1 at a rate of 1.023 MHz, and $P(t)$ is a pseudorandom sequence of ±1, known as P-code-modulating the quadrature component of L1 and L2 at a rate of 10.23 MHz. The C/A-Code and the P-Code are examples of PRN codes. Each satellite transmits a unique C/A-Code and P-Code sequence (on the same L1 and L2 frequencies), and hence a satellite may be identified according to its "PRN number", e.g. PRN2 or PRN14 are particular GPS satellites.

The CDMA technique allows the receiver to recognize multiple satellites on the same frequency with different PRNs. A GPS receiver will detect amplitude, pseudo-range and phase measurements for each C/A, L1 P-code (P1) and L2 P-code (P2) signals. The C/A and P1 contained identical information, however, the C/A is preferred over P1 due to its stronger power and not being encrypted. Note that the pseudo-range is an absolute measurement of differential group delay between time of transmission and reception. It is the sum of the actual range between the transmitter and the receiver, atmospheric and ionospheric delays and transmitter and receiver clocks offsets. Note that the early GPS included a feature called Selective Availability (SA) that adds intentional, time varying errors of up to 100 m (328 ft) to the publicly available navigation signals. This was intended to deny an unauthorized use of GPS signals. The SA service was eventually terminated in year 2000.

Table1. GNSS Signals

System	Carrier	Modulation	Multiple Address
GPS	L1/L2/L5 L1C/L2C	BPSK/BOC/MBOC/QPSK	CDMA
Galileo	E1/E5/E6 E5a/E5b	BOCc/CBOC Alt BOC BPSK	CDMA
GLONASS	L1/L2/L3	BPSK/QPSK	FDMA/CDMA
Beidou	B1/B2/B3	MBOC/BOC Alt BOC QPSK	CDMA

GNSS Error Sources

GNSS User Equivalent Errors (USER) is defined as the errors in PVT computation due to three segments of GNSS architecture. In space segment, the source of error can be satellite clock stability, satellite perturbations or selective availability (turned off in May 2001). The control segment causes the errors like ephemeris prediction and the user segment contributes the major part due to Ionospheric delay, Tropospheric delay, receiver noise, multi-path, indoor positioning or due to urban canyons.

- Satellite and receiver clock errors
- Satellite orbit errors
- Atmospheric effects (ionosphere, troposphere)
- Multipath: signal reflected from surfaces near the receiver
- Antenna phase centre
- Solar radiation pressure
- Satellite Geometry
- Relativistic Effects
- Receiver noise
- Signal Obstruction

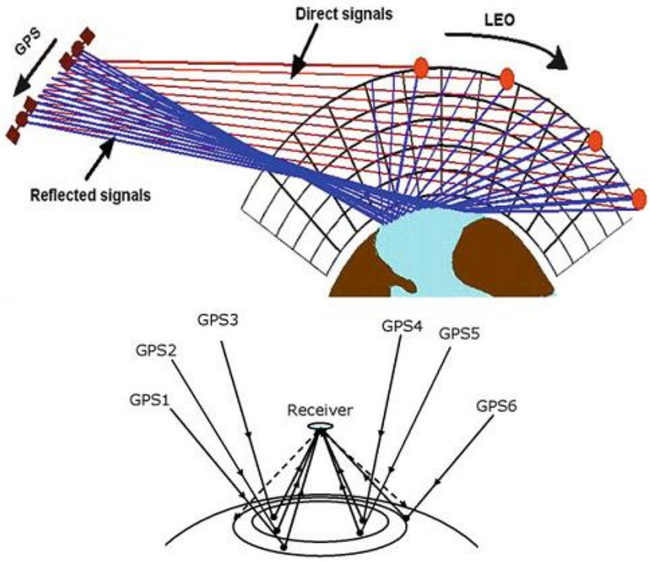

Fig.2- GNSS Refracted and reflected signals and geometry

GNSS Errors

GNSS Constellation Satellite Error

GNSS constellation satellite error mainly includes inherent orbital position error of the satellite and clock error. The former is mainly caused by influences of various perturbative forces, number of monitoring station and spatial distribution, number and precision of orbital parameters, and non-real-time property of ephemeris, and the range error caused thereby is approximately within 1.5 m–7.0 m; influences on range error are tried to be weakened generally through simultaneous observation to work out the difference or method of orbit improvement to limit it within the error scope of 1 m. The latter refers to the nonsynchronous deviation between satellite clock and GNSS standard time due to frequency offset and frequency drift between clock of GNSS constellation satellite and GNSS standard time; total quantity of such deviation may reach 1 ms, and equivalent range error caused thereby may reach 300 km; the deviation may correct the clock error model through continuous measurement of the ground station to limit the equivalent range error within 6 m; if residual error of GNSS constellation satellite clock is further weakened, it may be realized through differential technology.

GNSS Signal Propagation Error

GNSS signal propagation error mainly includes ionospheric refraction, tropospheric refraction, multipath error, etc. Ionospheric refraction error: Ionospheric refraction error is in direct proportion to atmospheric electron density and inversely proportional to the penetrated electromagnetic wave frequency. Atmospheric electron density varies with radiation intensity of the Sun and other celestial bodies, season, time, geographic position, etc. For GNSS constellation satellite signal, randomness of solar activity is large, so the difference of impact of ionospheric refraction on GNSS navigation and positioning error is large, and it is impossible to establish precise mathematical model for it. During GNSS navigation and positioning, methods may be generally adopted to weaken the impact of ionosphere on the precision of GNSS navigation and positioning include: (1) correction through double frequency observation; (2) correction through simultaneous observation value to work out the difference, i.e., relative positioning method.

Tropospheric refraction error: Tropospheric refractive index is irrelevant to frequency or wave length of electromagnetic wave, and reduces gradually with increase of altitude; it is also closely related to atmospheric pressure, humidity, and temperature. Since atmospheric convection is intensive and changes of pressure, humidity, and temperature are complicated, it is difficult for precise modeling, and range error generally caused thereby may reach nanometer.

An effective method to reduce influence of tropospheric refraction on navigation and positioning error is to estimate the propagation delay of electromagnetic wave in the troposphere. Measures commonly taken at present mainly include: (1) working out the difference through simultaneous observation to effectively reduce or even eliminate influences on delay of troposphere; (2) improving atmospheric model of troposphere through measured data nearby the monitoring station.

Multipath error; Besides directly receiving signals sent by GNSS constellation satellite, GNSS receiver also receives GNSS constellation satellite signals sent for once or many times by buildings surrounding the receiver antenna, i.e., during actual measurement, signals received by GNSS antenna are signals superimposed by direct and reflected wave. Phase delay may exist between reflected and direct wave since the length of path passed by the two signals is different, and multipath error is thereby caused. It is difficult to establish accurate error model due to the uncertainty of reflection coefficient of reflector and the distance between it and the receiver antenna. Measures may be taken to reduce multipath error at present mainly include: (1) trying to make GNSS receiver antenna avoid object surface with large reflection coefficient; (2) using GNSS receiver antenna with good directivity such as the choking coil antenna.

Signal Reception Error

Such errors mainly include GNSS receiver measurement error, GNSS receiver clock error, antenna phase centre error, etc. Among them, besides related to measurement resolution of software and hardware of GNSS receiver for constellation satellite signals, GNSS receiver measurement error is also related to installation precision of GNSS receiver antenna. GNSS receiver clock error is related to the receiver, so the clock error may be taken as an unknown parameter to estimate such error by working out the pseudo-range equation; influences of such error may also be eliminated by working out the differential treatment through observation quantity. Antenna phase centre error is caused by different incident angles, and equivalent range error may reach a few millimeters or even a few centimeters according to conditions of antenna performance.

Methods of Reducing Errors

Centralized Filtering Mode of SINS/CNS/GNSS Integrated Navigation System

The centralized filtering is to use an information fusion filter for centralized reception and processing of information from each navigation sensor, and feed the result of fusion processing back to the main navigation system. The SINS (Satellite Inertial Navigation Systems) among the SINS/CNS/GNSS integrated navigation system is set as the main navigation system of centralized filter. The state equation of centralized filter consists of error equation of the SINS and error equation of inertial components, the GNSS provides position and velocity measurement quantities of the carrier, and the CNS (Celestial Navigation System) provides attitude measurement quantities of the carrier. Typical structure for

centralized filter of the SINS/CNS/GNSS integrated navigation system is as shown in Fig.3. The system measurement quantity consists of two parts: attitude difference between the SINS and CNS; position difference and velocity difference between the SINS and GNSS.
The centralized filtering mode of the SINS/CNS/GNSS integrated navigation system may give optimal estimation of error state theoretically, but there are shortcomings such as high state dimension, heavy computation burden, poor fault-tolerance performance, and adverse to fault diagnosis, etc.

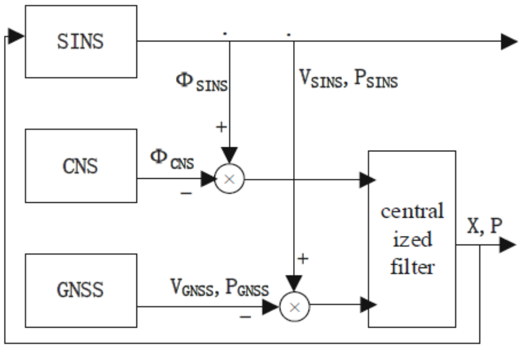

Fig 3. Structure of Centralized Filter

Each local filter of the federated filter uses observation value of corresponding subsystem to obtain optimal estimation of local state, and then inputs local estimation into the main filter for information fusion to obtain global estimation. The federated filtering adopts the structure of parallel processing by multiprocessor, and it is easy to realize multilevel fault detection and diagnosis of the system due to its flexible design, relative less calculation, good fault tolerance, and high reliability. Therefore, it is deemed to be a new filtering structure and algorithm independent of decentralized filtering.

Federated Filtering Mode

The federated filter has two-level filtering structure as shown in Fig.4. Specific to the SINS/CNS/GNSS integrated navigation system, since there are only two aided navigation subsystems namely CNS and GNSS, only subsystem 1 and subsystem 2 are drawn up in the figure. Common reference system in the figure is SINS subsystem, output X_k of which is provided for the main filter on the one hand, and for each sub-filter (local filter) on the other hand. Output of each subsystem is only passed on to the corresponding sub-filter. Local estimation value ˆXi and its covariance matrix Pi of each sub-filter are sent to the main filter, and then it is fused with the estimation value of the main filter to obtain global optimal estimation. If there are N local state estimations $\hat{X}_1$, $\hat{X}_2$, · · ·, $\hat{X}_N$ and corresponding estimation covariance matrixes P_{11}, P_{22}, · · ·, P_{NN}, and each local estimation is irrelevant, i. e., Pij = 0 (i = j).
Multiple federated filtering structures appear based on whether the estimated mean square error matrix and state quantity of the sub-filter are reset and different distribution modes of information factor. Among them, a common method is the estimation method of feeding back to the sub-filter after magnifying the global estimation value X_g and the corresponding covariance matrix P_g composed by the sub-filter and main filter to reset the sub-filter, i.e:

$$\hat{X}_g = P_g \sum_{i=1}^{N} P_{ii}^{-1} \hat{X}_i, \quad (3)$$

$$P_g = \left(\sum_{i=1}^{N} P_{ii}^{-1} \right)^{-1}. \quad (4)$$

Federated filtering algorithm based on different local models. At present, federated filtering algorithm based on information distribution principle has become the most common information fusion method of integrated navigation field due to its flexible design and good fault-tolerance performance, etc. However, it requires the local filter to have the same state variable, and the state variable of each local filter must be synthesized when the state variables of local model are inconsistent, i. e., the state variable of the main filter shall be combination of the state variable of each local filter; two outstanding problems are bound to be caused thereby: one is the increased amount of computation, and the other is decline of algorithm universality. In addition, the traditional information fusion method is inapplicable since the state variables of each sub-filter are inconsistent. Specific to federated filtering with different local models, different information fusion methods shall be adopted.

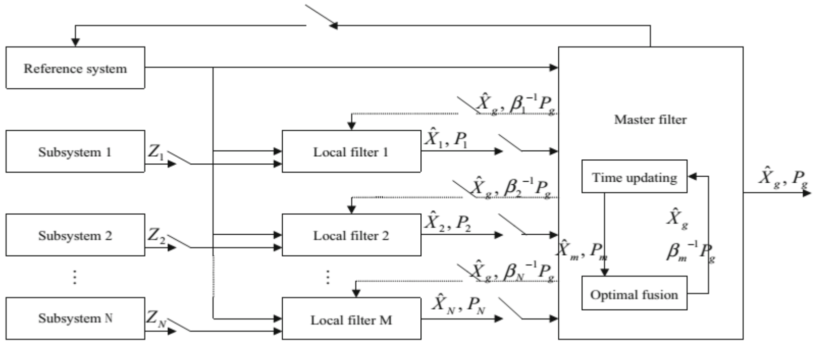

Fig 4. General Structure of Federated Filter.

Conclusion

According to error inspection of GNSS and proposed methods for reducing them, federated estimator (filter) addition to reduced computation, has better results for reducing deviations, reliability and simple design. These advantages come from parallel and multi-processing operation. Accuracy of pseudo-range method is more than “carrier phase observable” method which can reach millimeter precision, because the phase when tracking is started can only be known with an ambiguity of an unknown number of times the carrier wavelength.

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