

Proceedings

Terrestrial and Satellite-Based Positioning and Navigation Systems—A Review with a Regional and Global Perspective [†]

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Abstract: Satellite-based navigation techniques have revolutionized the modern-day surveying with unprecedented accuracies along with the traditional and terrestrial-based navigation techniques. However, the satellite-based techniques gain popularity due to its ease and availability. The position and attitude sensors mounted on satellites, aerial, and ground-based platforms as well as different types of equipment play a vital role in remote sensing providing navigation and data. The presented review in this paper describes the terrestrial (LORAN-C, Omega, Alpha, Chayka) and satellite-based systems with their major features and peculiar applications. The regional and global navigation satellite systems (GNSS) can provide the position of a static object or a moving object i.e., in Kinematic mode. The GNSS systems include NAVigation Satellite Timing And Ranging Global Positioning System (NAVSTAR GPS), of United States of America (USA); Globalnaya navigatsionnaya sputnikovaya sistema (GLObal NAVigation Satellite System, GLONASS), of RUSSIA; BEIDOU, of China; and GALILEO, of the European Union (EU). Among the initial satellite-based regional navigation systems included the TRANSIT of the US and TSYKLON of the USSR which became operational in the 1960s. Regional systems developed in the last decade include the Quasi-Zenith Satellite System (QZSS) and the Indian Regional Navigation Satellite System (IRNSS). Currently, these global and regional satellite-based systems provide their services with accuracies of the order of 10–20 m using the trilateration method of surveying for civil use. The terrestrial and satellite-based augmented systems (SBAS) were further developed along with different surveying techniques to improve the accuracies up to centimeters or millimeter levels for precise applications.

Keywords: GNSS; SBAS; NAVSTAR GPS; GLONASS; BEIDOU; GALILEO; IRNSS; QZSS; Omega; Alpha

1. Introduction

Terrestrial and Satellite-based navigation techniques have fulfilled one of the major needs of human beings, i.e., navigation. With the emergence of sensor-based techniques, many methods have evolved for terrestrial-based location finding as well as navigation using a set of sensors such as radio-frequency identification (RFID), wireless sensor networks, cellular networks, wireless local area networks (LANs), and many others. Similarly, the world witnessed the launch of Sputnik and Explorer series of satellites in the late 1950s by the USSR and the USA respectively. The space endeavor leads to the conceptualization and completion of TRANSIT and TSYKLON regional satellite-based navigation systems primarily meeting the requirements of that era, for the USA and USSR respectively. Today there are three completely operational satellite-based navigation systems and few regional navigations systems such as IRNSS (operationally known as “NavIC”: Navigation

with Indian Constellation) and QZSS. Initially, the two methods of navigation i.e., terrestrial and satellite-based navigation systems have been treated separately. However, in the last 3 decades and especially in recent times due to development in electronics and computers, the two techniques are coming together for providing the solution for positioning, navigation, and timing (PNT). Here in this review the terrestrial techniques, which can be operated over large ranges besides the traditional techniques, are considered, and which are under implementation and testing for joint utilization along with satellite-based navigation techniques. Some of the other traditional techniques for navigational requirements through mapping primarily include various traversing techniques utilizing instruments like a plane table, compass, sextant, theodolite, tacheometer, or the total station used in surveying; RFID and cellular tower methods.

Spencer et al. (2003) discuss the features and operational requirements of GPS in a detailed manner [1]. Whereas, the positioning systems in wireless sensor networks, and cellular networks, wireless LANs are discussed by Dardari et al. [2]. LORAN-C and Chayka are the terrestrial-based navigation systems developed by the USSR and the USA respectively [3,4]. The University of Rostock has started early experimentations for increasing the accuracy, availability, and reliability using integrated solutions with (D)GPS/(D)GLONASS or their combination with LORAN-C for identification of dynamics of ships. Support using LORAN-C or Chayka appeared to be correct regarding the uncertainties of GNSS against jamming in the study [5]. The presented review paper assesses the utility of these systems for the users with special preference to navigation, and remote sensing and geographical information systems (RS&GIS) based applications.

2. Materials and Methods

An extensive literature review was conducted on the important topic of navigation. Majorly the terrestrial and satellite-based navigation techniques have been investigated operating over continental scales, local-level and are especially useful in the area of navigation, RS&GIS, or web-based applications. A large number of published papers, reports, standard books, and authentic web-content were utilized in the study besides the experience in the area of GNSS specifically. The key systems and methods are then presented in the following sections along with the challenges in combining the two technologies with the available solution currently for the user. Figure 1 shows the basic design of NAVSTAR GPS describing the carrier waves (L1, L2, L5), codes (C/A, P(Y), L1C, L2C, M, I5, Q5) and satellite messages having information of Almanac as well as ephemeris used for PNT services. These codes and carrier waves are used for the computation of pseudoranges and fixing the location of the receiver.

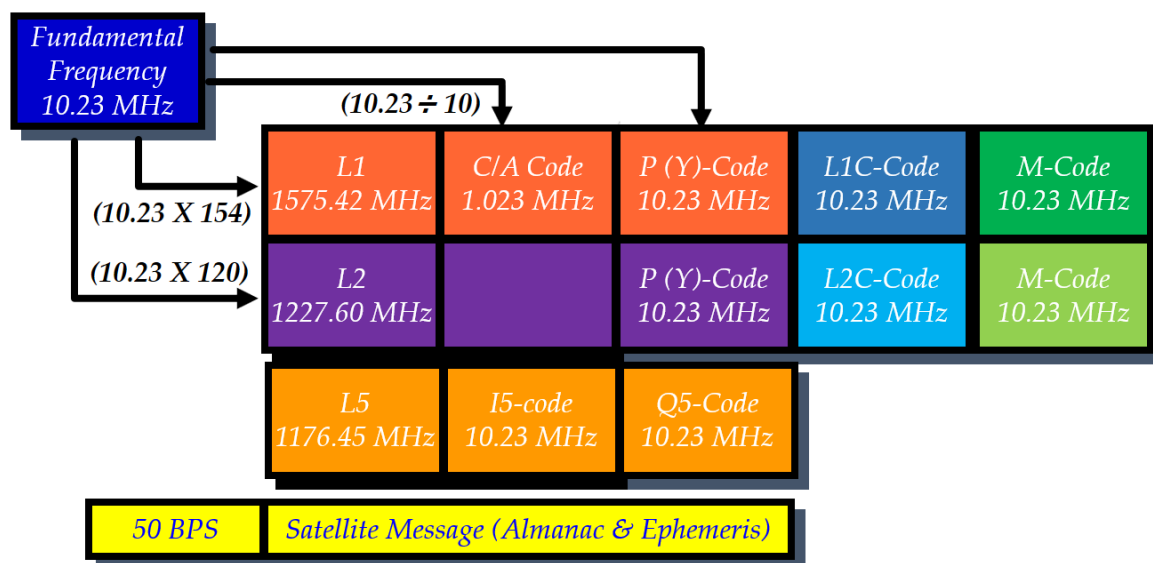


Figure 1. The basic design of NAVSTAR GPS describing the carrier waves and codes used for PNT.

3. Satellite Navigation Systems

Currently, three global satellite-based navigation systems namely, NAVSTAR GPS of the USA, GLONASS of Russia, and BEIDOU of China, are providing PNT services with full functionality. The fourth system GALILEO is being developed by the EU and is expected for completion by 2020 [6]. These systems use geostationary orbits (GSO), inclined Geosynchronous orbits (IGSO), and Medium earth orbits (MEO) for the satellites in the constellations (Table 1).

3.1. Global Satellite-Based Navigation Systems

Table 1 provides the details of the major characteristics and features of the four GNSS systems. These satellite-based navigation systems are mainly working on one-way ranging principles. These systems use the trilateration technique among methods of surveying to compute the location of the receiver using pseudo-range equations for a minimum of four number of satellites through a code or phase-based solution. Signals from more or redundant satellites enable in obtaining high accuracy by reducing the errors using the least square adjustment method in the computation of location coordinates. GNSS provides standard positioning services (SPS) and precise positioning services (PPS) or high precision services (HPS) through encryption for authorized users. Galileo has planned to provide more services on becoming fully operational, such as open services (OS), search and rescue (SAR), public regulated services (PRS), commercial services (CS), and Safety of Life (SoL) [7]. These systems are extensively useful in RS&GIS for mapping and resource management applications [8]–[11]. The Chinese Beidou system is the latest addition to GNSS and is also under extensive use now, as its constellation was recently completed in 2020. Beidou has formed an International GNSS Monitoring and Assessment Service (iGMAS) and provide code division multiple access (CDMA) signals for compatibility with existing systems of NAVSTAR GPS and GLONASS. A figure of merit called Geometric Dilution of Precision (GDOP) is utilized in GNSS to signify the quality of signals and associated uncertainty, which largely depends on the geometry of the available satellites from which the receiver is receiving the signals.

Table 1. Characteristics and features of GNSS constellations.

GNSS:	NAVSTAR GPS	GLONASS	BEIDOU	GALILEO
Master Control	1	1	1	2
Surveillance	11	7	30 (iGMAS)	30–40
Satellites	30	24	35 (GEO-5, IGSO-3, MEO-27)	30
Orbital plane	6	3	7 (3 IGSO + 3 MEO + GEO)	3
Inclination	55°	64.8°	55°	56°
Altitude (Km)	20,180–25,820	19,100–24,680	GEO, IGSO, MEO:21528	23,222–28,920
Ground track repetition	1 day	7 d 23 h 27 m	1/7/10–day(s)	10 days
Revolution time	11 h 57 m 58 s	11 h 15 m 44 s	12 h 53 min 24 s (MEO); 24 h (GEO/IGSO)	14 h 4 min
Services	SPS, PPS	SPS, HPS	OS, Authorized Service	OS, SoL, CS, PRS, SAR
Frequency bands	L1, L2, L3, L4, L5	L1, L2, L3	B1I, B2I, B3I*, B1C, B2a	L1, E5a, E5b, E6, L6

3.2. Regional Satellite-Based Navigation Systems

IRNSS and QZSS are the two regional operational satellite-based navigation systems belonging to India and Japan, respectively. IRNSS/NavIC provides precise and accurate PNT services over the Indian region and upto 1500 km beyond the Indian boundaries. Regional systems also provide standard positioning services (SPS) and precise positioning services (PPS) through Restricted services (RS) for authorized users which are encrypted [12]. Regional satellite-based navigation systems are also extremely useful in RS&GIS applications [13,14]. In a study by Dey et al. (2020) on IRNSS signals,

the diurnal variation of the position error indicated a maximum at afternoon hours, coinciding with the time of maximum total electron content (TEC) over the equatorial ionization anomaly (EIA) crest region [15].

4. Terrestrial Navigation Systems

Global and regional terrestrial (tower)–based navigation techniques were developed initially, by various agencies of developed countries. These radio navigation systems require technically complex design of a large set of tall antennas and costly infrastructure for continental or global-scale solutions for the shipping industry especially. All radio navigation systems, depend on measuring or inferring by some means the distance from a known location to the craft's (or receiver's) current position [16].

4.1. Global Terrestrial-Based Navigation Systems

The global terrestrial (tower)–based navigation techniques include Alpha developed by USSR [17] and Omega developed by the USA [18]. Alpha is also known as RSDN-20 in the Russian language and on translation in English, it means “radio-technical long-distance navigation system”. These systems operate at very low frequency (VLF) ranges as per the International Telecommunication Union (ITU) designation for radio frequencies (RF) and provide PNT solutions to respective users with almost global coverage. Omega uses the intersection of Line of Positions (LOPs) using range-range (or rho-rho) or range-range-range measurements to determine the position of the receiver. Preferably a minimum of three or more independent range measurements and LOPs can be used (referred to as a multilateration or multiranging navigation) for providing higher accuracy using basic principles of surveying. In general, the requirement is to measure the time it takes for a radio signal to propagate over the desired distance to infer the distances with the signal phase as the fundamental measurement necessitating the corrections for phase during the travel between the transmitter(s) and receiver(s). A figure of merit called Geometric Dilution of Precision (GDOP), is computed as the ratio of position error divided by range measurement error, to give a measure for quality of solution [16].

4.2. Regional Terrestrial-Based Navigation Systems

Long-range navigation system, also known as Loran-A (or “Standard LORAN”) is a hyperbolic radio navigation system developed in the United States and used extensively for the navigation of ships as well as aircraft. United Kingdom (UK) also has a Gee system, which is operated at lower frequencies to provide an improved range up to 1500 miles. LORAN used multilateration principle to determine position using a receiver by computations based on the time difference of arrival (TDOA) difference in the signals from the master and slave(s) stations.

Similarly, U.S. developed Loran-B, which offered accuracy on the order of a few tens of feet [3]. Loran-C has been a more successful system and is attempted for integration in the solution of PNT services along with satellite-based navigation systems. Loran transmitter antennas are vertical towers approximately 200 m high to provide vertical polarization. The phase center of antennas is maintained within about 1 m from the published positions. The excellent stability of the enhanced Loran (eLoran) system yields repeatable accuracies of 20–50 m [19]. Whereas, the enhanced Differential Loran (eDLoran) is providing an accuracy improved to an order of 10 m [4,19–21]. Locata is another terrestrial PNT technology providing PNT services at the local service level using a constellation of master and slave sets of LocataLite setup [22].

5. Eurofix: Combined Use of Terrestrial and Satellite-Based Navigation Techniques

Delft University initially proposed the Eurofix concept in 1989 for a PNT solution by combining GNSS and LORAN/Chayka [23]. Eurofix has a large potential in improving the PNT solution over continental areas and can become an alternative ground-based solution to the satellite-based augmentation systems (SBAS) such as Wide Area Augmentation System (WAAS) in the USA or the

European Global Navigation Overlay System (EGNOS) in the EU [24]. Reelektronika has developed a powerful alternative PNT solution for Integrated GNSS eLoran/Chayka called the Loradd++, providing with very small size chip ($60 \times 30 \times 8$ mm) having Dual-channel receiver and Low power < 500 mW (3.3 V) requirements.

6. Major Challenges in the Existing Methods

The terrestrial and satellite-based navigation techniques have their own set of advantages and disadvantages. The terrestrial based navigation techniques largely depend on the ground network of towers for communications, wherein the line of sight, distribution, as well as density of towers along with factors influencing the attenuation of signals, are some of the major constraints with heavy-tall as well as costly infrastructure. Whereas in the case of satellite-based navigation techniques the major constraint is in the covered areas such as dense forest canopy regions, and tunnels, or underground regions, where local solutions can be better such as LAN or RFID providing indoor location tracking systems [25]. Thus, it is required to combine the two techniques and provide a more robust system overcoming the constraints of the existing terrestrial and satellite-based navigation systems.

7. Conclusion

Civilian and authorized users are using terrestrial and Satellite-based navigation techniques extensively. The number of applications built on the navigations services is increasing perpetually due to the technological advances and easy availability of the internet with internet-based mobile platforms having various domain-specific (land/ocean/air/space) applications. The literature review shows that the regional satellite-based navigation systems like IRNSS and QZSS provide accuracies comparable to GNSS in their primary service region. The study shows that there is a large potential for the combined navigation solutions from terrestrial and Satellite-based navigation systems. Further integration of these systems with local solutions like RFID or LAN will assist in uninterrupted PNT services in indoor as well as open environments.

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