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

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† Presented at the 7th Electronic Conference on Sensors and Applications, 15–30 November 2020; Available online: https://ecsa-7.sciforum.net/.

Published: 14 November 2020

Abstract: Satellite-based navigation techniques have revolutionized modern-day surveying with unprecedented accuracies along with the traditional and terrestrial-based navigation techniques. However, the satellite-based techniques gain popularity due to their 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 the NAVigation Satellite Timing And Ranging Global Positioning System (NAVSTAR GPS), of the United States of America (USA); the 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 are the TRANSIT of the US and TSYKLON of what was then 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

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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 led 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 Indian Regional Navigation Satellite System (IRNSS) (operationally known as "NavIC": Navigation with Indian Constellation) and Quasi-Zenith Satellite System (QZSS). Initially, the two methods of navigation i.e., terrestrial and satellite-based navigation systems have been treated separately. However, in the last three decades and especially in recent times due to development in electronics and computers, the two techniques are coming together to provide the solution for positioning, navigation, and timing (PNT). Here in this review the terrestrial techniques, which can be operated over large ranges alongside the traditional techniques, are considered, and those that are under implementation and testing for joint utilization along with satellite-based navigation techniques reported. 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]. In addition, 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 which were developed by the USA and the USSR, respectively [3,4]. The University of Rostock has started early experimentations for increasing their accuracy, availability, and reliability using integrated solutions with (D)GPS/(D) Globalnaya navigatsionnaya sputnikovaya sistema (GLObal NAvigation Satellite System (GLONASS) or their combination with LORAN-C for identification of the dynamics of ships. Support using LORAN-C or Chayka appeared to be correct regarding the uncertainties of global navigation satellite systems (GNSS) against jamming in the study [5]. The presented review paper assesses the utility of these systems for users with a special preference for 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. Mostly terrestrial and satellite-based navigation techniques have been investigated operating over continental scales and at 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 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 NAVigation Satellite Timing And Ranging Global Positioning System (NAVSTAR GPS) describing the carrier waves (L1, L2, L5), codes (C/A, P(Y), L1C, L2C, M, I5, Q5) and satellite messages with Almanac information 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.

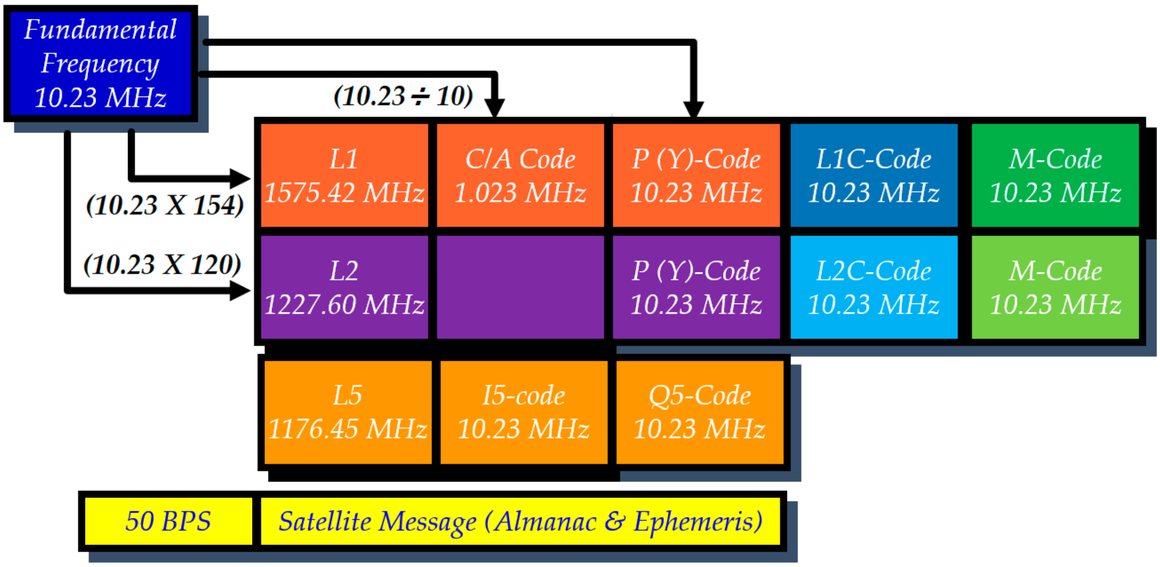

Figure 1. The basic design of NAVigation Satellite Timing And Ranging Global Positioning System (NAVSTAR GPS) describing the carrier waves and codes used for positioning, navigation, and timing (PNT).

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 to be completed 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).

Table 1. Characteristics and features of global navigation satellite systems (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

3.1. 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 of satellites through a code or phase-based solution. Signals from more or redundant satellites enable the attainment of 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 is 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 provides code division multiple access (CDMA) signals for compatibility with existing the 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.

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 up to 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 during 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 a 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 the USSR [17] and Omega developed by the USA [18]. Alpha is also known as RSDN-20 in the Russian language and after 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

A 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. The United Kingdon (UK) also has a Gee system, which is operated at lower frequencies to provide an improved range up to 1500 miles. LORAN used the 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 stations.

Similarly, USA developed Loran-B, which offered accuracy of the order of a few tens of feet [3]. Loran-C has been a more successful system and integration is being attempted into 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 the 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]. Furthermore, the enhanced Differential Loran (eDLoran) provides 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 a 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 for improving the PNT solution over continental areas and can become an alternative ground-based solution to the satellite-based augmentation systems (SBAS) such as the 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 an Integrated GNSS eLoran/Chayka called the Loradd++, providing it with very a small size chip (60 × 30 × 8 mm) with a 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. In the case of satellite-based navigation techniques the major constraint is in 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. Conclusions

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 with 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.

Funding: This research received no external funding.

Acknowledgments: The author would like to send words of appreciation to the international and national space agencies as well as telecommunication agencies like International Telecommunication Union (ITU), Indian Space Research Organisation (ISRO), Japan Aerospace Exploration Agency (JAXA), National Aeronautics and Space Administration (NASA), Russian Federal Space Agency (Roscosmos), European Space Agency (ESA), China National Space Administration (CNSA) along with their collaborators for their insights and support to the GNSS or terrestrial navigation systems or both. Their support is highly valuable for users and in the presented study, helping the entire scientific fraternity at large as well as the commercial consumers or authorized users. The author is highly indebted to the Director of the IIRS for the continual support and encouragement for conducting the research activities.

Conflicts of Interest: The author declares no conflict of interest.

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