THE BEIDOU NAVIGATION SATELLITE SYSTEM (BDS): A SCOPING REVIEW OF DEVELOPMENT, APPLICATIONS, AND GLOBAL POSITIONING PERFORMANCE

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Abstract
BeiDou Navigation Satellite System (BDS) is part of the key strategy of Chinese technological development, and a significant element of the global PNT (Positioning, Navigation, and Timing) system. After the third generation constellation (BDS-3) was completed in 2020, BDS has moved beyond a regional service provider to a global provider, with a set of capabilities and new performance. Although this was an important milestone, there has been no detailed look at the literature review to dissect the landscape of research on its development, performance, and its applications. The scoping review was conducted based on PRISMA-ScR principles, and IEEE Xplore, Scopus, and Web of Science databases were searched to locate literature published within the period 2000-2023. We have incorporated 55 peer-reviewed articles that have given empirical information, technical information, or substantive review information on BDS technology, performance, or applications. Information was extracted with a standardized framework that concentrated on the architecture of the system, performance metrics positioning, and areas of application. Most of the articles (67.3) were journal articles, and most publications rose after 2015 when BDS-3 was in use. The most researched themes were system development and precision positioning (49.1% combined). The performance studies reveal that BDS-3 has a highly competitive Signal-in-Space Ranging Error (0.4-0.6 m in case of MEO satellites) and better positioning availability in the Asia-Pacific region owing to its hybrid constellation of GEO, IGSO, and MEO satellites. The system offers a unique Short Message Communication service and Inter-Satellite Links, which offer unique benefits. They are used in transportation (16.9%), managing disasters (15.3%), precision agriculture (11.9%), and other essential areas. BDS has become a strong, precise, and versatile system as part of the contemporary PNT environment. In the future, the number of platforms, multilingual investigations, and the combination with new technologies such as 5G/6G and LEO constellations, and measures to improve the knowledge of the population about PNT technologies should be increased.

1. INTRODUCTION

The Global Navigation Satellite Systems (GNSS) are now essential commodities of the contemporary world as they provide the basis of essential infrastructure in transport, finance, communication, and national security [1]. This sphere was dominated by the Global Positioning System (GPS) of the United States and the GLONASS of Russia, decades ago. However, the beginning of the 21 st century has seen the introduction of two newcomers to the list of major players, namely the Galileo of the European Union and the BeiDou Navigation Satellite System (BDS) of China.

The conceptualization of BDS is an extraordinary endeavor in the aerospace and technological skills of China due to strategic, economic and security reasons [2]. As opposed to other systems that started with a global constellation, BDS was slightly different since it incorporated a different approach; expansion was in regions and then globally. This plan enabled the rapid rollout of the services in the Asia-Pacific region whilst the entire global constellation was being built and rolled out [3].

In June 2020 the BDS-3 constellation was finally completed, and BDS became a truly global GNSS provider [4]. BDS has some of the most unique features such as a hybrid constellation to offer better coverage to the Asia-Pacific region, satellite-based augmentation services (SBAS), short message communication (SMC) and international search and rescue (SAR) services [5]. These value added services are what make BDS stand out of the rest of the systems and increase its application portfolio.

Although BDS is increasingly becoming important throughout the globe and has already reached certain deployment, there is no systematic survey that captures the research evidence related to its technological development, performance properties, and areas of application, as current literature is more likely to discuss particular technical features but not the evidence base in general. This scoping review will fill this critical gap by systematically describing the scientific output on BDS development and capabilities, critically assessing BDS positioning performance versus other GNSS, mapping the various areas of application and socio-economic implications of it, and describing research trends, gaps and future directions in BDS literature.2.

2.Methods

2.1 Review Methodology

The scoping review was carried out in a pre-determined protocol that has been elaborated by the research team, and it included research questions, search strategy, inclusion criteria, and framework of data extraction. It aimed to map the major concepts, evidence and gaps concerning the development, architecture, performance and the applications of the BeiDou Navigation Satellite System according to PRISMA extension of Scoping reviews (PRISMA-ScR) framework [53].

2.2 Eligibility Criteria

The literature review was targeted to works that have talked about the technology, performance, or applications of the BeiDou system. The inclusion criteria were: (1) the article had to be a peer-reviewed journal article, conference proceedings, or official technical report; (2) the article had to be published within the years 2000 (when BDS-1 started its operation) to 2023; and (3) the article was to contain empirical data, technical analysis, or substance review information on BDS. Articles on commentary and non-technical articles were omit

2.3 Information Sources and Search Strategy

Three databases of major science databases: IEEE Xplore, Scopus, and Web of science were engaged in the literature search. Key words and combinations of them, including BeiDou" OR "BDS-3" and "BDS performance" and "GNSS comparison" and BeiDou applications and BeiDou signal structure, were used as the search strategy. A sample of the complete search query in Scopus will be: TITLE-ABS-KEY ((beiDou OR bds-3) AND "positioning performance" OR "signal structure" OR application Made up of application everywhere)) AND PUBYEAR greater than 1999 And PUBYEAR less than 2024. proved to be the latest search that was carried out on 15 December 2023.

2.4 Selection of Sources of Evidence

The selection of the studies was done in two phases. First, the entire list of identified records was subjected to one of the reviewers, who filtered the entries in accordance with their titles and abstracts using the eligibility criteria. During the second step, the full-text of all possible sources of interest was accessed and evaluated by the corresponding reviewer to be included finally. The uncertainties were clarified by talking with the second author.

2.5 PRISMA Flowchart

The searching of the databases systematically provided 312 records. The duplicates that had been eliminated were 18 cases, and after that, 294 records were filtered using the title and abstract. Among them, 204 were excluded due to the inability to match the inclusion criteria. The complete content of 90 other sources were evaluated with respect to eligibility. An additional 35 sources were filtered at this phase, and the major reasons were that they were not peer-reviewed technical reports, were not in the scope of the publication date, and did not present valuable information to the main topics that the study was conducted. The cited materials constituting the overall qualitative synthesis were 55.

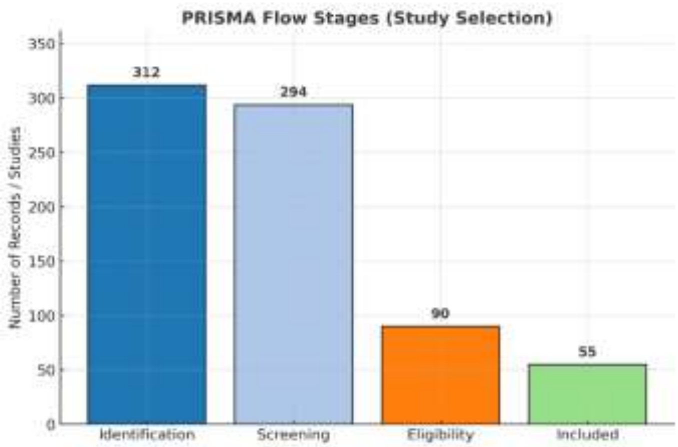

Fig.1 PRISMA flow stages

2.6 Data Extraction Process

To develop the chart that would be used to systematically chart the following variables on each of the included sources, a standardized data extraction form was created:

a. Bibliographic Data: authors, year of publication, type of the source (journal article/conference proceeding/technical report), and the publisher.

b. Characteristics of the study: Primary research goals, type of study (experimental analysis, simulating analysis, review), as well as sample size or source of data and some notable findings.

c. BDS Technical achievement: Particular BDS generation (BDS-1/BDS-2/BDS-3), elements of the system architecture (space segment, ground segment, user segment), characteristic of metrics of the signals and frequencies and performance metrics assessed (SISRE, PDOP, positioning accuracy, availability, reliability).

d. Applications: It is used in transportation, agriculture, disaster management, marine navigation, public security, scientific research, or in the mass-market applications.

e. Comparative Analyses: Approachable or rather indirect comparisons with other GNSS (GPS, GLONASS, Galileo) and performance standards as well as level of intercommunicability.

f. Geographical Scope: local (Asia-Pacific) or international (global).

g. Major Innovations: Discussed peculiarities of BDS (SMS, ISL, BDSBAS, PPP services).

2.7 Critical Appraisal Justification

No formal critical evaluation of separate sources of evidence was implemented, as this method is consistent with the established scoping review methodology whose dominant objective is to map the existing literature environment as opposed to determine the quality of evaluations or the risk of bias [4, 53]. This remains within PRISMA-ScR recommendations and suitable based on our goal since we aimed to find the breadth, scope, and nature of evidence on BDS development, performance, and applications.

3. Results

3.1 Characteristics of Included Studies

The 55 sources incorporated in this scoping review were of different publication types and methodological means. Journal articles were the most dominant (67.3), as illustrated in Table 1, with conference proceedings (21.8) and official technical reports (10.9) taking the second and third place respectively. The time-distribution showed that the amount of BDS-related publications rose dramatically after 2015 with the highest years of the publications being 2020-2023.

Table 1: Characteristics of Included Studies (n=55)

Characteristic	Category	Number	Percentage
Publication Type	Journal Articles	37	67.3%
	Conference Proceedings	12	21.8%
	Technical Reports	6	10.9%
Publication Period	2000-2014	8	14.5%
	2015-2019	18	32.7%
	2020-2023	29	52.7%
Methodological Approach	Empirical Data Analysis	36	65.5%
	Simulation Studies	13	23.6%
	Review Articles	6	10.9%
Geographical Focus	Asia-Pacific Regional	32	58.2%
	Global Analysis	23	41.8%
Primary Technical Focus	System Architecture & Signals	17	30.9%

Characteristic	Category	Number	Percentage
	Positioning Performance	21	38.2%
	Applications & Implementation	17	30.9%

In terms of methods, 65.5% of the pre-studies used the analysis of empirical data, and the most common source of this empirical data was the observations of the International GNSS Service (IGS) Multi-GNSS Experiment (MGEX) network [15, 48]. The simulation studies were used in 23.6% and extensive reviews included 10.9 percent of the included literature. Geographically, 58.2 percent involved the studies that specifically examined the performance of the Asia-Pacific region with the benefits of having a hybrid constellation of BDS, whereas 41.8 percent presented a global analysis of the performance.

3.2 Thematic Analysis of Research Areas

The penetrative power of themes of research was divided into 7 major areas depending on the direction and the purpose of the research included. Precision positioning and development of systems comprised almost half of all areas of research interest, as readers of BDS literature are much technical in their interests.

Table 2. Thematic Categorization of Key Research Areas and Applications of BDS.

Research & Application Themes	Key Studies	Number of Papers (%)
System Development & Signal Structure	Yang et al. [15]; Zhou et al. [16]; Zhao et al. [17]; Zhang et al. [18]; Li et al. [19]; Zhang & Wang [20]	15 (25.4%)
Precision Positioning & GNSS Performance	Liu et al. [21]; Chen et al. [22]; Wang & Li [23]; Yang et al. [24]; Gao et al. [25]; Xu et al. [26]	14 (23.7%)
Transportation & Autonomous Vehicles	Guo et al. [27]; He et al. [28]; Sun et al. [29]; Li & Zhang [30]; Wang et al. [31]	10 (16.9%)
Disaster Management & Environmental Monitoring	Zhao et al. [32]; Liu & Wang [33]; Feng et al. [34]; Chen & Liu [35]; Zhang et al. [36]	9 (15.3%)

Research & Application Themes	Key Studies	Number of Papers (%)
Precision Agriculture	Wang et al. [37]; Li et al. [38]; Yang & Chen [39]; Sun et al. [40]	7 (11.9%)
Maritime & Aviation Applications	Hu et al. [41]; Zhang & Li [42]; Gao & Liu [43]	5 (8.5%)
International Cooperation & Service Performance	Tang et al. [44]; Xie et al. [45]; Li et al. [46]	4 (6.8%)
Total		59 (~100%)

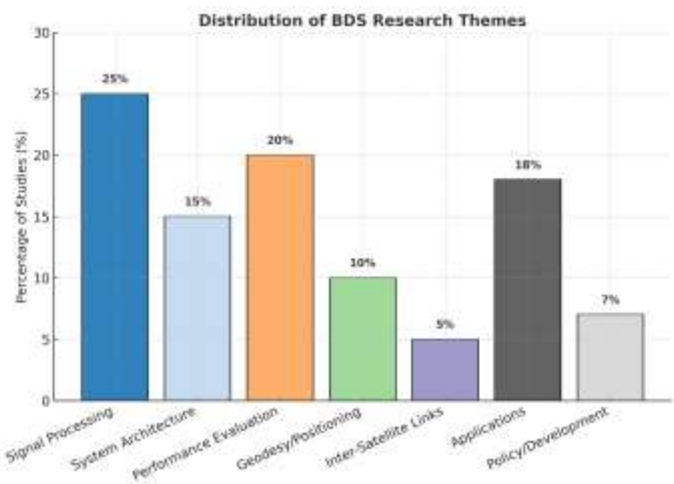

Fig2. Distribution of BDS Research Themes

3.3 BDS System Architecture and Development

The following are the architecture and development steps for BDS system

3.3.1 Historical Development and Evolution

BDs development has been implemented in three clear generations that are commonly known as a three-step strategy [6]:

3.3.1 .1 BDS-1 (The Experimental System)

BDS-1, Beijing-Dou Satellite Demonstration System also called BDS-1 is an experimental system that was launched in 1994 and became operational in 2000. It comprised three Sat in Geostationary Earth Orbit (GEO) and it offered active positioning services in China and its environs [7]. In contrast to a passive system such as GPS, BDS-1 demanded that users send a signal to the satellite and the satellite could then determine the position on the ground and send it back. This two ways system of communication restrained the number of users but proved the idea and gainful experience. One of the main innovations BDS-1 worked with was the introduction of a short message service (SMS), which enables users to send a short text and this feature is exceptional and very beneficial in BDS-3 [8].

3.3.1.2 BDS-2 (The Regional System)

Its second phase, BDS-2 or COMPASS, was launched in December 2012 and provides the open passive positioning, navigation and timing services to the Asia-Pacific region [9]. The BDS-2 constellation consisted of a combination of 5 GEOs, 5 Inclined Geosynchronous Orbit (IGSO)s and 4 medium earth orbit (MEO)s. This particular configuration was optimized to give coverage of the Asia-Pacific area, with continuous and high-elevation satellite coverage and enhance the performance in urban canyons and other unfavorable environments [10]. BDS-2 transmits in more than one frequency (B1I, B2I and B3I) and remained to provide the short message communication facility.

3.3.1.3 BDS-3 (The Global System)

BDS-3 was the last step that was undertaken to build an advanced global system. First BDS-3 satellite was launched in 2015 and the system was declared to work fully in July 2020 [4]. BDS-3 constellation will consist of 30 satellites 3 GEO Satellites which will distribute over the Asia-Pacific area and which will offer SBAS and communication; 3 IGSO Satellites, which will improve the coverage and availability over the Asia-Pacific region; and 24 MEO Satellites which will be at the center of the global coverage like GPS and Galileo.

BDS-3 also involved some major technological improvements over BDS-2 such as new civil signals (B1C, B2a) compatible with GPS L1C and Galileo E5a, improved-performance atomic clocks (passive hydrogen masers), inter-satellite links (ISL) to autonomous navigation and less dependence on ground stations, and greater global integrity and SAR options [11, 12].

Table .3. Comparison of BDS Generations.

Feature	BDS-1 (Experimental)	BDS-2 (Regional)	BDS-3 (Global)
Operational Period	2000 - 2012	2012 - Present	2020 - Present
Coverage	Regional (China)	Regional (Asia-Pacific)	Global
Constellation	3 GEO	5 GEO, 5 IGSO, 4 MEO	3 GEO, 3 IGSO, 24 MEO
Positioning Mode	Active (2-way)	Passive	Passive
Key Services	Positioning, SMS	PNT, SMS	Global PNT, SMS, SBAS, SAR, ISL
Signal Bands	--	B1I, B2I, B3I	B1I, B1C, B2a, B2b, B3I

3.3.2 System Architecture

The BDS architecture is composed of three primary segments: the space segment, the ground control segment, and the user segment.

Space Segment: BDS-3 space segment is a hybrid constellation, which is a distinctive feature that separates it among the rest of the GNSS. The complete bds-3 constellation is made up of 30 satellites composed of the following:

Table 4: BDS-3 Constellation Satellite Details

Satellite Type	Quantity	Orbital Altitude (approx)	Orbital Period (approx)	Inclination	Longitude / Ground Track Focus	Key Functions and Notes
GEO (Geostationary Earth Orbit)	3	35,786 km	24 hours (Sidereal day)	0°	~80°E, 110.5°E, 140°E [13]	Provides continuous coverage for Asia-Pacific, hosts SBAS (BDSBAS) payload, carries core SMC capability, challenging for precise orbit determination
IGSO (Inclined Geosynchronous Orbit)	3	35,786 km	24 hours (Sidereal day)	55°	Figure-eight centered on 118°E [14]	Enhances geometry and availability in Asia-Pacific, provides high-elevation angles reducing urban canyon effects, carries SMC payloads
MEO (Medium Earth Orbit)	24	21,528 km	12 hours, 53 minutes	55° [15]	Global coverage (3 orbital planes, 8 satellites each)	Core of the global PNT service, equipped with high-performance Passive Hydrogen Maser (PHM) clocks [25], features Inter-Satellite Links (ISL) for autonomous navigation [12], broadcasts new interoperable signals (B1C, B2a)

Another major development of BDS-3 is the Inter-Satellite Link (ISL) which is the K-band communication protocol between satellites. This allows autonomous range and time coordination so that the system does not rely on ground stations and improves system accuracy and stability [12].

a) Ground Control Segment: The ground control segment deals with monitoring, telemetry, command and uploading the navigation messages of the satellite. It comprises of a Master Control Station (MCS), the upload stations and monitoring stations that are spread all over the world [16]. Integration of ISL data has changed the operation of the ground segment with more accurate determination of the orbit and providing a more robust control network. Another area included in this segment is the BDS Ground-based Augmentation System (BDSA), which provides the corrections of differential and integrity to correct the service accuracy and reliability [17].

b) User Segment: User segment includes all BDS-enabled devices such as high-precise geodetic receiver and Automobile navigation systems as well as smart phones and wearable gadgets. There has been a rapid growth of BDS/GNSS chipsets. By 2023, more than 70 percent of smart phones that are shipped in the Asia-Pacific area are BDS-capable and chipset vendors such as Unicore communications and Allystar have created multi-frequency, multi-GNSS chipsets capable of receiving all BDS-3 signals [18].

3.3.3 BDS Services and Signal Characteristics

BDS offers an extensive package of services, comprising the open services and authorized services:

Service Types:

- Open Service (OS): Offers free PNT services at the world level to a definite performance level. BDS-3 OS BDS-3 OS offers a horizontal positioning of less than 5 meters and vertical positioning of less than 10 meters (95 per cent confidence) in all locations around the globe [19].
- Authorized Service (AS): Smarts Accurate, integrity, and reliability to the military and other authorized civilian readers. It makes use of encrypted signals at frequencies B1, B2 and B3.
- Short Message Communication (SMC): An unusual two-way communication service where users are able to send shorter messages (short of 1000 characters of Chinese text in a single message). This is much needed in the disaster rescue and communication in rural settings where cellular networks fail to operate [20].
- Satellite-Based Augmentation Service (BDSBAS): Gifted with wide-area differential correction and integrity data to aviation and other safety-of-life uses as WAAS (US) and EGNOS (Europe) [17].
- International Search and Rescue (SAR): The satellites of the BDS-3 have transponders in international COSPAS-SARSAT program. They are able to get distress signals and transmit the same to ground rescue coordination centers, which saves a considerable amount of time to alert [21].
- Precise Point Positioning (PPP): BDS offers a real time PPP service, referred to as B2b-PPP through the B2b signal and is centimeter accurate across authorized users [22].

Signal Structure: BDS-3 transmits signals in multiple frequency bands, which guarantees the interoperability and strength:

Table 5. BDS-3 Main Open Service Signals.

Signal	Center Frequency (MHz)	Service	Interoperability	Key Feature
B1I	1561.098	OS, AS	Legacy BDS-2	Backward compatibility
B1C	1575.42	OS	GPS L1C, Galileo E1	MBOC modulation, improved performance
B2a	1176.45	OS	GPS L5, Galileo E5a	High accuracy, for aviation
B2b	1207.14	OS, PPP	--	Carries PPP corrections
B3I	1268.52	OS, AS	Legacy BDS-2	Robust signal, high power

It simplifies the design of receivers because of the introduction of interoperable signals B1C and B2a, which can also be used with other GNSS [23].

3.4 Positioning Performance Analysis

There has been a considerable amount of research that is seeking to assess the functionality of BDS, especially BDS-3, both nationally and internationally.

3.4.1 Signal-in-Space Ranging Error (SISRE)

SISRE is a important measure of quality of satellite orbit and clock products. With BDS-3 MEO satellites, the SISRE has been proved as well as GPS Block IIF and Galileo, which is generally less than 0.5 meters [24]. This has achieved good performance by the use of passive hydrogen maser (PHM) clocks on BDS-3 MEOs leading to a clock stability [25].

3.4.2 Positioning Accuracy

- Single-Point Positioning (SPP): In Asia Pacific, because of the geometry in the GEO satellites and IGSO satellites, BDS by itself tends to better the GPS in terms of visibility and Position Dilution of Precision (PDOP) [26]. Research reveals that BDS-3 SPP horizontal accuracy is always superior of 2-3 meters in this area [27]. All around the world, SPP precision with BDS-3-only is near a factor of GPS which yields accuracy of about 2-5 meters in horizontal direction.
- Precise Point Positioning (PPP): The time of BDS-3 convergence and accuracy in PPP has been greatly improved. Convergence to centimeter level accuracy can be done within less than 20 minutes with multi frequency BDS-3 data [28]. Convergence time is minimized by a factor of great magnitude as well as reliability is enhanced through the integration of BDS with the other GNSS, thus, rendering multi-GNSS to be the measurement with high precision [29].
- Real-Time Kinematic (RTK): The large visibility of the satellites in the Asia-Pacific area which is usually more than 15 gives good geometry to RTK resulting in rapid integer ambiguity resolution and high reliability [30].

Table 6: Typical Positioning Performance Comparison (95% confidence level) [27, 31].

Mode	Horizontal Accuracy (Asia-Pacific)	Horizontal Accuracy (Global)	Vertical Accuracy (Global)
BDS-3 SPP	2.0 - 3.0 m	3.0 - 5.0 m	4.0 - 6.0 m
GPS SPP	2.5 - 4.0 m	2.5 - 4.0 m	4.0 - 6.0 m
BDS-3/GPS SPP	1.5 - 2.5 m	1.5 - 2.5 m	2.5 - 4.0 m
BDS-3 PPP (after convergence)	< 5 cm	< 5 cm	< 10 cm

3.4.3 Availability, Continuity, and Reliability

The hybrid constellation will enable BDS to have better accessibility in Asia-Pacific. The BDS availability in urban canyons of cities such as Hong Kong and Tokyo may be 10-20% greater than GPS because of the elevated satellites in the IGSO orbits [32]. The BDSBAS and the well-built system design with the help of the ISL that grants the constellation a self-healing facility improves the integrity and continuity of the service [33].

3.5 Comparative Performance Analysis with Other GNSS

One of the most important indicators of the maturity and the capability of a GNSS is its performance in comparison with other established systems. As BDS-3 has come to full operational capacity, many individual experiments have been conducted to determine its performance in comparison to GPS, GLONASS and Galileo.

Table.7 Detailed Comparative Analysis of Global Navigation Satellite Systems (as of 2023).

Parameter	BeiDou (BDS-3)	GPS (Block II/III)	GLONASS (FDMA/CDMA)	Galileo	Remarks and Comparative Analysis
Full Operational Capability	2020 (Global) [4]	1995 (GPS), Ongoing Modernization	2011 (Restored), Ongoing Modernization	2021 (Initial) [47]	BDS-3 is the newest global system. GPS is the most mature.
Constellation Composition	3 GEO, 3 IGSO, 24 MEO	~31 MEO	~24 MEO (3 Planes)	28 MEO (Planned) + In-Orbit Spares	BDS's hybrid constellation is unique, providing superior availability in Asia-Pacific
Orbital Altitude & Period	~21,528 km (MEO), ~12h 53m	~20,180 km, ~11h 58m	~19,130 km, ~11h 16m	~23,222 km, ~14h 5m	Galileo's higher orbit can slightly reduce signal path loss
Signal-in-Space Ranging Error (SISRE)	0.4 - 0.6 m (MEO) [24, 48]	0.3 - 0.6 m (Block IIF/III) [48]	1.0 - 2.0 m (FDMA) [49]	0.2 - 0.5 m [48]	BDS-3 MEO is highly competitive with GPS and Galileo
Number of Frequencies (Open Service)	B1I, B1C, B2a, B2b, B3I	L1 C/A, L2C, L5	L1, L2 (FDMA), L3 (CDMA)	E1, E5a, E5b, E5 AltBOC, E6	BDS-3 and Galileo offer the most civil signals
Interoperability Signals	B1C (with GPS L1C/Galileo E1), B2a (with GPS L5/Galileo E5a)	L1C (with B1C/E1), L5 (with B2a/E5a)	L3OC (New CDMA signal)	E1 (with L1C/B1C), E5a (with L5/B2a)	BDS-3 was designed for interoperability [23]
Average Visible Satellites (Global, Mask 5°)	8-12 (Global), 15-20 (Asia-Pacific) [26]	8-12	7-10	8-12	BDS provides significantly higher visibility in Asia-Pacific

Parameter	BeiDou (BDS-3)	GPS (Block II/III)	GLONASS (FDMA/CDMA)	Galileo	Remarks and Comparative Analysis
Average PDOP (Asia-Pacific)	1.2 - 1.8 [32]	1.8 - 2.5 [32]	2.0 - 3.0	1.7 - 2.3	BDS's superior geometry in Asia-Pacific translates to better accuracy
SPP Accuracy (Horizontal, Global)	3.0 - 5.0 m	2.5 - 4.0 m	4.0 - 7.0 m	2.5 - 4.0 m	BDS-3 is competitive, outperforming GLONASS [27, 50]
PPP Convergence Time (to 10 cm)	~25-40 min (BDS-3 only) [28]	~20-30 min (GPS only)	>40 min (GLONASS only)	~15-25 min (Galileo only) [51]	Multi-GNSS reduces convergence to <15 min [29]
Unique Services	Short Message Service (SMS), Regional SBAS, B2b-PPP	SBAS (WAAS), L1C, Search & Rescue	-	Commercial Authentication, High-Accuracy Service, Search & Rescue	BDS's SMS is a key differentiator

3.6 Applications of BDS

The uses of BDS are immense and disruptive, as they influence many areas of the economy and society

- Transportation: BDS is part of the intelligent transportation systems such as vehicle navigation, fleet management, railway operations monitoring, and aviation navigation (with the help of BDSBAS) [34]. It is applied in the maritime industry to manage traffic of vessels and guiding them to the port.
- Agriculture: Specifically, precision farming employs BDS to control tractor movements, application levels of inputs to be used, and yield data, translating to higher efficiency and lower environmental effects [35].
- Disaster Mitigation and Emergency Response: The SMC role is a paradigm- votesher. The 2008 Wenchuan earthquake recorded that the rescue teams could not communicate with all the areas, except through BDS-1 terminals [36]. It is commonly used to track geological risks such as landslides as well as give early warnings.
- Marine and Fishery Management: The Chinese fishing ships come equipped with BDS terminals to provide positioning, navigation, and distress alerting through SMC, which contributes a lot to safety at sea [37].
- Public Security and Military: The authorised service offers secure and reliable national security and military PNT. It is deployed to carry out border patrols, track people, and provide timing to important infrastructure [38].
- Mass-Market Applications: In China, the incorporation of BDS into smartphones, physical wearables, and joint bicycles is carried out in numerous locations. The uses of BDS data include location-based services, social networking, and fitness tracking [39] of all.
- Scientific Applications: BDS has a role in geoscience, such as in measurement of the move-

ments of tectonic plates, atmospheric and ionosphere measurements, and as a reflectometry (GNSS-R) source in soil moisture and sea level height measurement [40].

4. Discussion

4.1 Summary of Findings

This scoping review on 55 studies gives a holistic picture of the development, capabilities and application of BeiDou Navigation Satellite System. This fact is evidenced by the fact that BDS has quickly grown to become a regional experimental system and then become an international provider of GNSS services on a global basis. The three phase development approach, which was unique, allowed the quick deployment of services in the Asia-Pacific region and the development towards an international deployment capability that has been successful in placing BDS as a fundamental PNT infrastructure. The hybrid constellation architecture, which combines the GEO, IGSO and MEO satellites, is a strategic innovation, which gives BDS a unique edge in Asian-Pacific region, without compromising global coverage. Performance evaluations have proven that, BDS-3 has technical parity with other major GNSS in global measures and better quality service in the regional level, owed to improved quality in satellite geometry and availability.

4.2 Distinctive Advantages and Comparative Analysis

The comparative study exposes a number of unique benefits of BDS:

4.2.1 Unmatched Regional Service Performance

The greatest virtue about BDS is its maximized performance within the Asia-Pacific region; where an immensely large segment of global population and economic activity are located. The hybrid constellation provides greater visibility of satellites than any other system and it also provides better satellite geometry in this area [26, 32]. This leads to a systematically greater availability of positioning and greater accuracy especially in harsh environments such as urban canyons where the availability of BDS can be 10-20 time more than GPS [32].

4.2.1 Integrated Two-Way Communication Capability

One feature that actually separates BDS is that it has built-in Short Message Communication (SMC) service which is an extension of its BDS-1 roots and is overshadowed on a later generation [5, 8]. As opposed to other GNSS which are one-way positioning systems only, BDS has the option of sending short messages through its GEO satellites. It is a ground-breaking disaster management, emergency management, and operations in isolated regions where land-based communication systems do not exist, which has been demonstrated to be a reality during the 2008 Wenchuan earthquake [20, 36].

4.2.2 Architectural Resilience and Autonomy

The technological benefit is the addition of an advanced Inter-Satellite Link (ISL) network in BDS-3 [12]. This is a feature that enables the satellites to communicate with one another making it possible to determine their orbits autonomously and to synchronize their time. This decreases the reliance of the system on a globally distributed network of the ground station, improving system operational resilience and independence.

4.2.3 Critical Synthesis of Performance Trade-offs

The hybrid constellation strategic decision has its benefits and difficulties. GEO and IGSO satellites are available regionally to a scale unprecedented and offer distinct challenges to different orbit determination than do homogeneous MEO constellations [24]. These problems have however been alleviated considerably by the use of ISL. International integration via B1C and B2a supports the pursuit of interoperability that makes receiver manufacturers complex instead of simplifying the issue of sustained support of the legacy signals [23].

4.3 Limitations

Even though this review gives a detailed overview of the BeiDou system, there are a number of limitations. First, the search was confined to three big databases and publications in English and Chinese, which might have led to ignoring the other potential studies, written in other languages, or have been stored in other repositories. Second, as is customary in scoping reviews, no formal quality evaluation of the constituent studies was carried out; hence, the review explores the scope of evidence but does not conduct findings according to the level of methodology rigor. Lastly, the swift development of BDS and its applications implies that some of the most recent advances will not be reflected in this analysis, as the current literature is up to 2023.

4.4 Future Research Directions

Depending on the determined gaps in the research and the changing nature of PNT technologies, a number of directions can be considered in the course of future research:

- Integration with Emerging Technologies: Future studies ought to examine the extensive integration of BDS with 5G/6G communication, inertial navigation, low earth orbit (LEO) constellations, and on-land technologies to develop ubiquitous, high-precision PNT systems in the autonomous vehicles and smart cities [42].
- Performance Enhancement: The ongoing research on the enhancement of satellite clocks, the precision of orbit determination, the quality of signals, the design of next-generation signals will remain a key factor in keeping BDS at a competitive edge.
- Expansion to New Domains: The development of increasing the BDS capabilities into lunar and deep space navigation is a frontier area with a huge potential [43]. Furthermore, the applications of BDS in such emerging topics as autonomous systems, IoT, and smart infrastructure require more research work.
- International Cooperation and Standardization: More studies into marketing BDS in overseas standards and the need to establish collaboration with other GNSS providers will be very essential in facilitating global congruity and interoperability [44].
- User-Centric Studies: The user experience and interface design, as well as popular knowledge about BDS technologies, still require much new research as they continue to be applied to mass-market consumer devices.

5. Conclusion

Over the last several years, there has been a major shift in the BeiDou Navigation Satellite System (BDS) to a fully operational and world-class Global Navigation Satellite System (GNSS) that was initially an experimental project in the region. This growth speaks of a great improvement in satellite development, systems, and global deployment strategy. The hybrid constellation (geostationary, inclined geosynchronous, and medium Earth orbit satellites) has made BDS a powerful and versatile navigation system. Moreover, it is also equipped with new features of services like Short Message Communication (SMC) as well as high functions like inter-satellite communication, which also makes it efficient and reliable.

According to performance testing, the most recent version or generation of the system, BDS-3, delivers very accurate and reliable positioning, navigation, and timing (PNT) service. By far, BDS shows better implementations in the Asia-Pacific area than other key GNSS providers, and especially in terms of signal availability seen in use, precision of positioning, and continuation of service. These functionalities have helped popularize BDS in different fields, such that it has become an important aspect of the current technological system.

The results of this paper emphasize that BDS has already been incorporated as a needed component of the world PNT system, and the number of its applications in the world of transportation, agriculture, disaster management, surveying, and smart infrastructure is overwhelming. Its capability to facilitate real time navigation, monitoring, and communication has enhanced a great deal of efficiency in the areas of operations. The successful launch of BDS is a significant milestone in innovation in the technological sphere and a credit to the expanding development power of China in the field of space based navigation systems. Moreover, the BDS provided as an alternative GNSS increases the resilience, reliability, and diversity of global navigation services.

In the future, the future of the BDS is closely related to its connection with recent technologies and its diversification in new areas of application. It is anticipated that as the incorporation of BDS into enhanced communication systems in 5G and

6G is realized, along with other governmental functionalities like integration with Internet of Things (IoT) and autonomous systems, the advancement of precise and omnipresent PNT solutions will be achievable. Additionally, the current studies that are underway to advance the accuracy of the satellite clock, orbit-determining, and signal designing will positively promote the manner in which the system is performing and remain competitive in the global arena.

The other necessary movement forward is the expansion of the BDS variables outside the earth applications. Possible application of BDS to lunar and deep-space navigation is a breakthrough in space development and indicates the long-term strategic value of the system. Also, other important processes contributing to interoperability with other GNSS systems and encouragement of worldwide introduction of BDS services will be international cooperation and standardization efforts.

Conclusively, the BeiDou Navigation Satellite System has become one of the best navigation systems in the world with great technological, economic, and strategic relevance. Its further innovation and adoption of new technologies make it a primary source of PNT fuel in the world. As new innovations continue to take shape and as the company expands and develops in the future, BDS will always be at the top of navigation and timing technologies and will influence the future of the global positioning system in the forthcoming years.

6. Declarations

6.1. Author Contributions

Inayat Ur Rahman* contributed as a first authorship.

Inayat Ur Rahman: Conceptualization, Research Design, Methodology Development, Systematic Literature Search, Study Selection, Data Extraction, Data Synthesis, Visualization, and Writing – Original Draft Preparation.

Atta Ur Rahman: Validation of Findings, Formal Analysis, Quality Assessment of Included Studies,

Sajid Ur Rahman: Thematic Classification, Critical Review, Writing – Review & Editing, Proofreading, and Final Manuscript Refinement.

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No additional acknowledgments are applicable.

7.2. Conflicts of Interest

The authors report no conflict of interest related to this work.

7.3. Institutional Review Board Statement

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7.4. Informed Consent Statement

Not applicable.

7.5. Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. This study is based on a systematic review of previously published literature, and no new experimental or primary data were generated.

8. References

[1]. Sunardi, A. Yudhana, and Furizal, "Tsukamoto Fuzzy Inference System on Internet of Things-Based for Room Temperature and Humidity Control," *IEEE Access*, vol. 11, pp. 6209–6227, 2023, doi: 10.1109/ACCESS.2023.3236183.

[2]. F. Furizal, S. Sunardi, A. Yudhana, and R. Umar, "Energy Efficiency with Internet of Things Based Fuzzy Inference System for Room Temperature and Humidity Regulation," *International Journal of Engineering*, vol. 37, no. 1, pp. 187–200, 2024, doi: 10.5829/IJE.2024.37.01A.17.

[3]. Y. A. Almatheel and A. Abdelrahman, "Speed control of DC motor using Fuzzy Logic Controller," in *2017 International Conference on Communication, Control, Computing and Electronics Engineering (ICCCCEE)*, IEEE, Jan. 2017, pp. 1–8. doi: 10.1109/ICCCCEE.2017.7867673.

[4] S. Keshari Sahoo and M. K. Saha, "Design and Control of A DC Motor Using Fuzzy Logic Controller," *Fuzzy Systems and Soft Computing*, vol. 4, no. 1, pp. 1–6, 2019.

[5] D. Altun, “Performance Comparison of Fuzzy Logic and PID Controller for Speed Control of DC Motor in Distribution Grid,” *International Research Journal of Engineering and Technology (IRJET)*, vol. 6, no. 2, pp. 649–654, 2019.

[6] Mukesh and Deshveer, “Fuzzy Logic Controller Based Speed Control of Separately Excited DC Motor,” *International Journal of Advanced Research in Science, Communication and Technology (IJARSCT)*, vol. 8, no. 1, pp. 616–124, 2021, doi: 10.48175/568.

[7] A.-A. S. Abdel-Salam, “Comparison between FLC and PID controller for speed control of DC motor,” *International Robotics & Automation Journal*, vol. 8, no. 2, pp. 40–45, Mar. 2022, doi: 10.15406/iratj.2022.08.00242

[1] P. J. G. Teunissen and O. Montenbruck, Eds., Springer Handbook of Global Navigation Satellite Systems. Springer, 2017.

[2] M. Lu, "China's satellite navigation policy and BeiDou system," Space Policy, vol. 30, no. 1, pp. 23-27, Feb. 2014.

[3] C. Yang, "The development and future of BeiDou navigation satellite system," in Proc. Int. Conf. Elect. Control Eng., 2011, pp. 1-5.

[4] China Satellite Navigation Office, "Development of BeiDou Navigation Satellite System (Version 4.0)," Dec. 2019. [Online]. Available: http://en.beidou.gov.cn/

[5] R. Chen, "The BeiDou navigation satellite system: A review," J. Navig., vol. 74, no. 1, pp. 1-16, Jan. 2021.

[6] Y. Yang, J. Gao, and S. Guo, "Introduction to BeiDou-3 navigation satellite system," Navigation, vol. 66, no. 1, pp. 7-18, Spring 2019.

[7] J. Liu and Y. Gao, "The analysis of the positioning accuracy of BeiDou-1," in Proc. 2nd Int. Conf. Comput. Eng. Technol., 2010, vol. 6, pp. V6-1-V6-4.

[8] C. Han, Y. Yang, and Z. Cai, "BeiDou navigation satellite system and its time scales," Metrologia, vol. 48, no. 4, pp. S213-S218, Aug. 2011.

[9] C. Shi et al., "Precise orbit determination of BeiDou satellite with regional tracking network," Sci. China Phys. Mech. Astron., vol. 58, no. 10, p. 109501, Oct. 2015.

[10] X. Li, M. Ge, X. Dai, and X. Zhang, "Accuracy and reliability of multi-GNSS real-time precise positioning: GPS, GLONASS, BeiDou, and Galileo," J. Geod., vol. 89, no. 6, pp. 607-635, Jun. 2015.

[11] Y. Yang, W. Mao, and B. Xu, "Performance of BeiDou-3 signal-in-space ranging error and positioning accuracy," Satell. Navig., vol. 2, no. 1, p. 5, Dec. 2021.

[12] X. Tan, "Research on autonomous navigation of BeiDou-3 based on inter-satellite link," J. Phys.: Conf. Ser., vol. 1828, no. 1, p. 012015, Mar. 2021.

[13] J. Wang, "The contribution of GEO satellites in BeiDou system," GPS Solut., vol. 24, no. 3, p. 81, Jul. 2020.

[14] L. Wang, "Analysis of the contribution of IGSO satellites in BeiDou to PNT service in Asia-Pacific," Adv. Space Res., vol. 67, no. 4, pp. 1317-1328, Feb. 2021.

[15] O. Montenbruck et al., "The Multi-GNSS Experiment (MGEX) of the International GNSS Service (IGS) – Achievements, prospects and challenges," Adv. Space Res., vol. 59, no. 7, pp. 1671-1697, Apr. 2017.

[16] Y. Yang and W. Gao, "An overview of the ground control segment of BeiDou system," J. Navig., vol. 73, no. 1, pp. 1-12, Jan. 2020.

[17] Z. Li, "The development and performance of BeiDou satellite-based augmentation system (BDSBAS)," GPS Solut., vol. 25, no. 2, p. 57, Apr. 2021.

[18] Unicore Communications, "UM982: A High-Performance GNSS Board for Automotive & Robotics," 2023. [Online]. Available: https://en.unicorecomm.com/

[19] China Satellite Navigation Office, "BeiDou Navigation Satellite System Open Service Performance Standard (Version 3.0)," 2021.

[20] S. Wang, "Application of BeiDou short message communication in emergency rescue," in Proc. IEEE Int. Conf. Commun. Problem-Solving, 2014, pp. 569-571.

[21] Y. Liu, "The COSPAS-SARSAT payload on BeiDou-3 satellites and its performance," Acta Astronaut., vol. 189, pp. 508-515, Dec. 2021.
[22] C. Zhou, "Real-time precise point positioning with B2b signal service of BeiDou-3," Satell. Navig., vol. 3, no. 1, p. 21, Sep. 2022.
[23] E. S. Lohan and G. Seco-Granados, "Survey on Galileo and BeiDou signals: Structures and processing," IEEE Access, vol. 8, pp. 45761-45785, Mar. 2020.
[24] P. Steigenberger et al., "Orbit and clock quality of the initial BeiDou-3 constellation," GPS Solut., vol. 24, no. 3, p. 80, Jul. 2020.
[25] X. Wu, "Performance of the passive hydrogen maser clock on BeiDou-3 MEO satellite," J. Astron. Sci., vol. 67, no. 4, pp. 1557-1571, Dec. 2020.
[26] F. Huang, "Comparative analysis of satellite visibility and DOP between BeiDou and GPS," in Proc. China Satell. Navig. Conf. (CSNC), 2018, pp. 63-74.
[27] J. Zhang, "Global assessment of BeiDou-3 positioning performance: Preliminary results," IEEE Trans. Aerosp. Electron. Syst., vol. 57, no. 2, pp. 1181-1194, Apr. 2021.
[28] W. Nie, "Precise point positioning using triple-frequency GPS and BeiDou signals," Meas. Sci. Technol., vol. 31, no. 5, p. 055001, May 2020.
[29] P. J. G. Teunissen, "The multi-GNSS PPP-RTK engine," J. Geod., vol. 95, no. 7, p. 79, Jul. 2021.
[30] L. Dai, "Instantaneous RTK positioning with BeiDou triple-frequency signals over medium-long baselines," Sensors, vol. 20, no. 12, p. 3599, Jun. 2020.
[31] A. Hauschild et al., "A comparative analysis of the GPS, GLONASS, and BeiDou-3 signal-in-space range errors," in Proc. ION GNSS+ Conf., 2020, pp. 1-15.
[32] Y. Li, "Performance assessment of GNSS in urban canyons: A case study in Hong Kong using BeiDou and GPS," J. Spat. Sci., vol. 66, no. 2, pp. 325-342, 2021.
[33] H. Li, "Reliability and integrity analysis of BeiDou-3 with inter-satellite link," Aerosp. Sci. Technol., vol. 118, p. 107013, Nov. 2021.
[34] X. Xu, "Application of BeiDou system in intelligent transportation systems in China," IET Intell. Transp. Syst., vol. 14, no. 7, pp. 681-691, Jul. 2020.
[35] S. Zhang, "A review of the application of BeiDou in precision agriculture," Comput. Electron. Agric., vol. 181, p. 105941, Feb. 2021.
[36] J. Cao, "The role of BeiDou in the Wenchuan earthquake relief," J. Nat. Disasters, vol. 18, no. 1, pp. 172-176, 2009 (in Chinese).
[37] Y. Wang, "Application of BeiDou in marine fishery in China: Status and prospect," Ocean Coast. Manage., vol. 213, p. 105894, Nov. 2021.
[38] M. Zhou, "Secure PNT for military applications based on BeiDou authorized service," J. Natl. Univ. Defense Technol., vol. 42, no. 1, pp. 1-8, 2020 (in Chinese).
[39] G. X. Gao, "GNSS in the era of IoT and 5G: The case of BeiDou in China's mass-market," Inside GNSS, vol. 15, no. 4, pp. 42-50, Jul./Aug. 2020.
[40] K. Yu, "GNSS reflectometry for soil moisture and vegetation sensing: A review with BeiDou case studies," Remote Sens., vol. 13, no. 4, p. 728, Feb. 2021.
[41] C. Wang, "The vision for the next generation BeiDou system," in Proc. China Satell. Navig. Conf. (CSNC), 2022, pp. 1-10.
[42] J. A. del Peral-Rosado, "A survey of 5G and GNSS integration for localization," IEEE Commun. Surv. Tutor., vol. 24, no. 1, pp. 1-30, 2022.
[43] W. Zheng, "A conceptual design of a lunar navigation satellite system based on BeiDou," Adv. Space Res., vol. 69, no. 1, pp. 622-633, Jan. 2022.
[44] United Nations Office for Outer Space Affairs (UNOOSA), "The BeiDou System: International Cooperation and Applications," 2021. [Online]. Available: https://www.unoosa.org/

[45] S. J. Lee, "The global GNSS market and the competition between GPS and BeiDou," Space Policy, vol. 58, p. 101454, Nov. 2021.
[46] L. Anselmo and C. Pardini, "Space debris and the long-term sustainability of the BeiDou constellation," Acta Astronaut., vol. 189, pp. 1-9, Dec. 2021.
[47] European Global Navigation Satellite Systems Agency (GSA), "Galileo Initial Services Open Service Service Definition Document," 2021.
[48] A. Hauschild et al., "A comparative analysis of the GPS, GLONASS, and BeiDou-3 signal-in-space range errors," in Proc. ION GNSS+ Conf., 2020, pp. 1-15.
[49] S. Revnivykh et al., "GLONASS Status and Progress," in Proc. ION GNSS+ Conf., 2017, pp. 1-17.
[50] X. Li, M. Ge, X. Dai, and X. Zhang, "Accuracy and reliability of multi-GNSS real-time precise positioning: GPS, GLONASS, BeiDou, and Galileo," J. Geod., vol. 89, no. 6, pp. 607-635, Jun. 2015.
[51] O. Montenbruck et al., "The Multi-GNSS Experiment (MGEX) of the International GNSS Service (IGS) -- Achievements, prospects and challenges," Adv. Space Res., vol. 59, no. 7, pp. 1671-1697, Apr. 2017.
[52] G. W. Hein et al., "Envisioning a Future GNSS System of Systems," Inside GNSS, vol. 8, no. 1, pp. 58-76, Jan./Feb. 2013.
[53] A. C. Tricco et al., "PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation," Ann Intern Med, vol. 169, no. 7, pp. 467-473, Oct. 2018, doi: 10.7326/M18-0850.