# An Overview of GNSS

As of early 2025, four primary Global Navigation Satellite Systems (GNSS) provide worldwide coverage: the United States' GPS, Russia's GLONASS, the European Union's Galileo, and China's BeiDou. These systems share similar structures, comprising three main segments: a space segment (satellite constellation), a ground control segment, and a user segment (navigation receivers). While GPS, GLONASS, and Galileo satellites operate in Medium Earth Orbit (MEO), BeiDou employs a hybrid constellation that includes MEO, Geostationary Orbit (GEO), and Inclined Geosynchronous Orbit (IGSO) satellites, enhancing coverage in the Asia-Pacific region. In addition to these global systems, several Regional Navigation Satellite Systems (RNSS) have been developed.

India's Navigation with Indian Constellation (NavIC) offers positioning services across India and up to 1,500 km beyond its borders, with plans to extend coverage further. The recent launch of the NVS-02 satellite in January 2025 marked a significant milestone in enhancing NavIC's capabilities. Japan's Quasi-Zenith Satellite System (QZSS), operational since 2018, supplements GPS signals to improve positioning accuracy in urban and mountainous regions. The addition of the Michibiki 6 satellite in February 2025 aims to expand the constellation to seven satellites by 2026, further enhancing regional coverage. These developments reflect a global trend toward enhancing satellite navigation capabilities, both regionally and globally, to meet the growing demand for precise positioning, navigation, and timing services. A summary of GNSS and RNSS are provided in Table 1.

**Table 1.** An Overview of GNSS.

| SYSTEM | GPS | GLONASS | BeiDou | GALILEO | QZSS | IRNSS/NavIC |
|---|---|---|---|---|---|---|
| Orbit Types | MEO | MEO | MEO, IGSO, GEO | MEO | IGSO, GEO | IGSO, GEO |
| Satellite Counts | 31 | 24 | 35 | 28 | 5 | 7 |
| Available Services | SPS, PPS | SPS, PPS | OS, AS, WADS, SMS | OS, CS, PRS | GCS, GAS, PRS, EWS, MCS | SPS, RS |
| Initial Service Date | Dec 1993 | Sep 1993 | Dec 2012 | Dec 2016 | Nov 2018 | 2018 |
| Country of Origin | USA | Russia | China | European Union | Japan | India |
| Coverage | Global | Global | Global | Global | Japan | India |
| Frequency (MHz) | L1: 1575.42<br>L2: 1227.60<br>L5: 1176.45 | L1: 1602.00<br>L2: 1246.00<br>L3: 1202.025 | B1: 1561.098<br>B2: 1207.14<br>B3: 1268.52 | E1: 1575.42<br>E5a: 1176.45<br>E5b: 1207.14<br>E6: 1278.75 | L1: 1575.42<br>L2: 1227.60<br>L5: 1176.45<br>E6: 1278.75 | L5: 1176.45<br>S: 2492.028 |

**AS:** Authorized Service; **CS:** Commercial Service; **EWS:** Early Warning Service; **GAS:** GPS Augmentation Service; **GCS:** GPS Complementary Service; **MCS:** Message Communications Service; **OS:** Open Service; **PPS:** Precise Positioning Service; **PRS:** Public Regulated Service; **RS:** Restricted Service; **SMS:** Short Message Service; **SPS:** Standard Positioning Service; **WADS:** Wide Area Differential Service.

## 1. GLOBAL NAVIGATION SATELLITE SYSTEMS

Global and regional navigation satellite systems are typically composed of three main segments. The space segment includes a network of satellites that orbit the Earth and transmit positioning signals at multiple microwave frequencies. The control segment ensures the system's reliability by monitoring satellite signals and uploading navigation data. This is managed through a network of ground control stations, uplink antennas, and a central master control facility, often backed up by a secondary site. The user segment encompasses all GNSS-enabled devices, used across various domains—from terrestrial and marine to aerial and space-based applications. GNSS systems function within the L-band frequency range of 1.1 to 1.6 GHz, which is segmented into two main sub-bands: the Upper L-band, ranging from 1559 to 1610 MHz, and the Lower L-band, spanning 1164 to 1300 MHz.

These are designated by the ITU for Radio Navigation Satellite Services (RNSS), while additional protections for aviation applications are provided under the Aeronautical RNSS (ARNS) band. The frequency allocation of global navigation satellite systems, ARNS and RNSS are depicted in Figure 1.

The L-band is ideal due to low atmospheric attenuation and availability of cost-effective components. All GNSS systems transmit using circular polarization (CP), initially adopted by GPS. CP ensures consistent signal reception regardless of antenna orientation and promotes interoperability across global systems by enabling a common receiving antenna design.

Building upon the foundational aspects of GNSS technology, we will now provide a brief overview of the four primary global navigation satellite systems: GPS (United States), Galileo (European Union), GLONASS (Russia), and BeiDou (China).

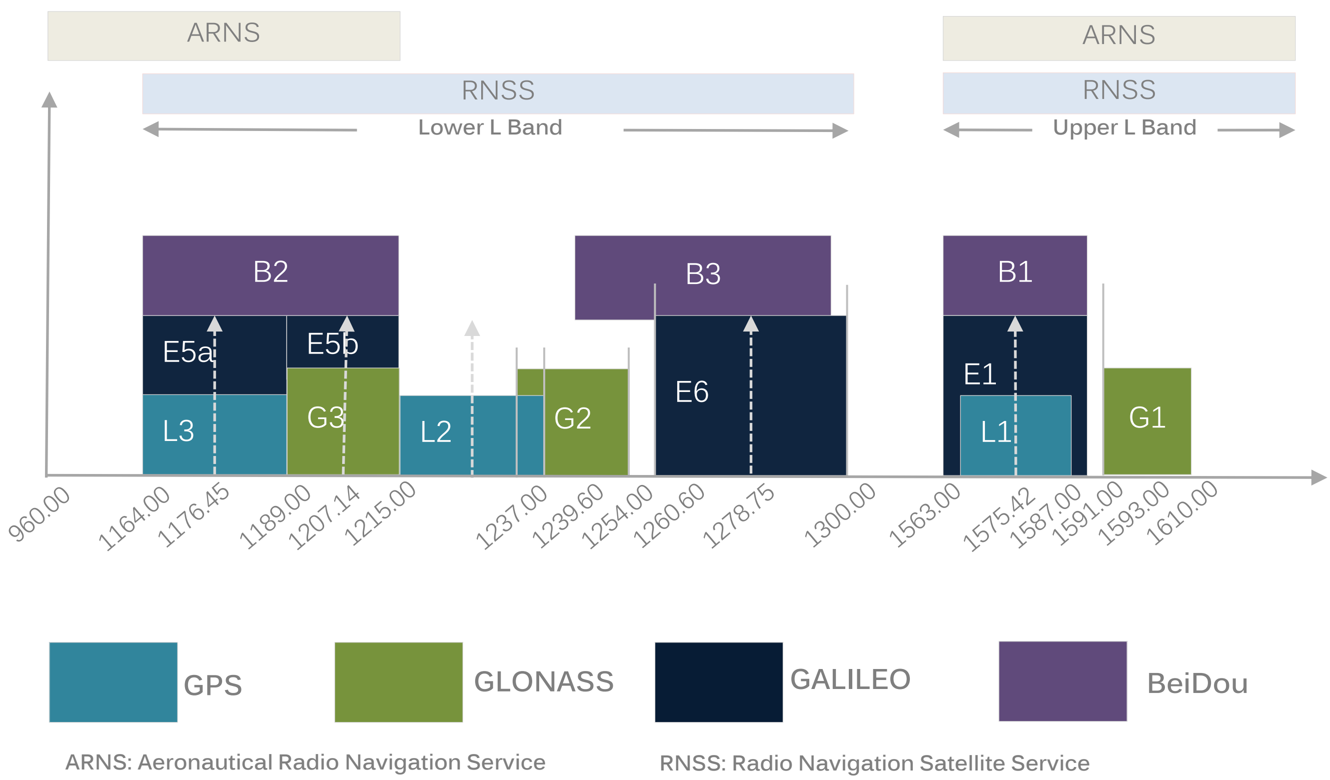



**Figure 1.** GNSS Frequency Allocation.

## 1. 1. GPS

The Global Positioning System (GPS), operated by the United States, is the world's first and most widely used GNSS. Although initially developed for military purposes, it was made available for civilian use in 1980s. The first satellite (Block I Navstar) was launched in 1978, and the system reached Initial Operational Capability in 1993, followed by Full Operational Capability in 1995 with a full constellation of 24 satellites.

GPS offers global, free access to positioning and timing services. It provides two service levels:

- Precise Positioning Service (PPS): Available only to authorized users, using encrypted Y-code signals on the L1 (1575.42 MHz) and L2 (1227.60 MHz) frequencies.
- Standard Positioning Service (SPS): Available to all users, utilizing the C/A code on the L1 band.

Modernization of GPS began in 2005 with the launch of Block IIR-M satellites. These introduced:

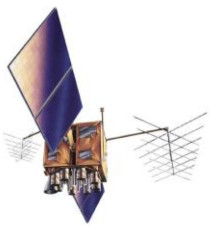
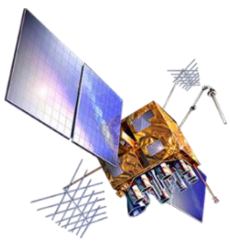
- L2C: A new civilian signal on L2 for improved accuracy.
- M-code: A new military signal on both L1 and L2, offering enhanced anti-jam capabilities.
- L5: A new civilian signal (1176.45 MHz), first deployed with the Block IIF series starting in 2010. This L5 signal is designed to be interoperable with similar signals from Galileo, QZSS, and NavIC.

GPS continues to evolve with a focus on improved accuracy, robustness, and interoperability with other GNSS systems. A summary of current GPS satellite constellation is given in Table 2.

## 1.2. GLONASS

GLONASS (Global'naya Navigatsionnaya Sputnikovaya Sistema) is Russia's satellite navigation system, developed during the Soviet era. The first satellite was launched in 1982, and by 1996, a full constellation of 24 satellites was in orbit. However, due to post-Soviet economic struggles, the system declined, reaching a low point in 2002 with only seven operational satellites. Revitalization efforts led by the Russian government enabled the system's recovery, achieving full operational capability again in December 2011, which has since been maintained.

**Table 2.** Current GPS Satellites.

| Block IIA | Block IIR | Block IIR-M | Block IIF | GPS III/IIF |
|---|---|---|---|---|
|  |  |  |  |  |
| **0 operational** | **6 operational** | **7 operational** | **12 operational** | **6 operational** |
| • Coarse Acquisition (C/A) code on L1 frequency<br>• Precise P(Y) code on L1 & L2 frequencies for military users | • C/A code on L1<br>• P(Y) code on L1 & L2<br>• On-board clock monitoring | • All legacy signals<br>• 2nd civil signal on L2 (L2C)<br>• New military M code signals for enhanced jam resistance | • All Block IIR-M signals<br>• 3rd civil signal on L5 frequency (L5)<br>• Advanced atomic clocks<br>• Improved accuracy | • All Block IIF signals<br>• 4th civil signal on L1 (L1C)<br>Enhanced signal reliability, accuracy, and integrity |

GLONASS satellites have evolved through several generations (See Figure 2.):

- GLONASS (Uragan): The original satellites launched between 1982 and 2005.
- GLONASS-M: Introduced in 2003, these satellites featured improved accuracy, extended lifespan, and the addition of the L2OF signal.
- GLONASS-K1: First launched in 2011, these satellites introduced CDMA signals in the G3 band, enhancing compatibility with other GNSS systems.
- GLONASS-K2: The latest generation, with the first satellite launched in August 2023. These satellites transmit CDMA signals in the G1, G2, and G3 bands, offer improved accuracy, and have a design life of 10 years.

Traditionally, GLONASS employs Frequency Division Multiple Access (FDMA), transmitting signals in:

- G1 band (1602–1615.5 MHz), with 0.5625 MHz spacing.
- G2 band (1246–1256.5 MHz), with 0.4375 MHz spacing.

Newer GLONASS-K and GLONASS-M satellites also broadcast CDMA signals, including a signal on the G3 band. This modernization aims to improve compatibility with other GNSS systems with higher accuracy. A summary of current GLONASS satellite constellation is given in Table 3.


**Figure 2.** GLONASS Modernization.

## 1.3. GALILEO

Galileo is the European Union's GNSS, developed jointly by the European Commission (EC) and the European Space Agency (ESA). The system began deployment with two In-Orbit Validation (IOV) satellites launched in October 2011, followed by two more in 2012. The first two full-operational-capability satellites were launched in 2014, although they ended up in incorrect orbits due to a rocket anomaly. By the end of 2015, six more satellites had been successfully deployed.

The planned full Galileo constellation consists of 30 satellites, with 24 active and 6 in-orbit spares.

**Table 3.** Current GLONASS Satellites.

| GLONASS | GLONASS-M | GLONASS-K1 | GLONASS-K2 |
|---|---|---|---|
|  |  |  |  |
| **0 operational** | **19 operational** | **4 operational** | **1 operational** |
| • Legacy FDMA signals on L1 and L2 bands<br>• Basic navigation capability<br>• Shorter operational lifespan | • Improved FDMA signals (L1OF, L2OF)<br>• Improved accuracy<br>• On-board clock stability<br>• Extended operational life (7+ years) | • FDMA signals (L1OF, L2OF)<br>• New CDMA civilian signal L3OC<br>• Improved interoperability with GPS and Galileo<br>• Enhanced accuracy | • FDMA signals (L1OF, L2OF)<br>• CDMA signals (L1OC, L2OC, L3OC)<br>• Advanced navigation message structures<br>• Extended operational lifespan |

Galileo uses Code Division Multiple Access (CDMA) and transmits signals in three frequency bands:

- E1 (1575.42 MHz): Carries the Open Service (OS) and Public Regulated Service (PRS), using Binary Offset Carrier (BOC) modulation. These signals are compatible with GPS L1 and use unique PRN codes per satellite.
- E6 (1278.75 MHz): Used for the Commercial Service (CS) and PRS, with Binary Phase Shift Keying (BPSK) and BOC modulations, respectively.
- E5 (centered at 1191.795 MHz): Offers both data and pilot (data-less) signals. It includes two components—E5a and E5b—which can be tracked separately or jointly, both using BOC modulation.

All signal types carry navigation messages essential for satellite acquisition, positioning, and time synchronization. Galileo emphasizes interoperability with other GNSS systems while offering high-precision services for both civilian and regulated users.

### 1.4. BeiDou

China's satellite navigation system, **BeiDou**, began as a regional demonstration project in the early 2000s following development efforts that started in 1980.

The original BeiDou-1 system included three geostationary (GEO) satellites, completed by 2003, and expanded with a fourth in 2007. The initial BeiDou system was succeeded by BeiDou-2 (Compass), which transitioned from a regional to a global navigation system. BeiDou-2 began regional operations in late 2011 and achieved full operational capability in the Asia-Pacific region by the end of 2012. The BeiDou-3 phase commenced with its first satellite launch in March 2015 and was completed by June 2020, establishing a constellation of 30 satellites that provide global coverage. BeiDou offers two service levels:

- Open Service: Freely available to civilians
- Authorized Service: Encrypted service for the Chinese government and military

BeiDou-2 satellites transmit three primary signals: B1I at 1561.098 MHz, B2I at 1207.14 MHz, and B3I at 1268.52 MHz.

BeiDou-3 enhances the system by introducing the B1C signal at 1575.42 MHz, designed for global interoperability with GPS L1C and Galileo E1 signals. It also continues to support the legacy B1I signal at 1561.098 MHz to maintain backward compatibility with existing user equipment. Additionally, BeiDou-3 transmits in the L5/E5 bands, further aligning with international GNSS standards. A summary of the current BeiDou-3 satellite constellation is given in Table 4.

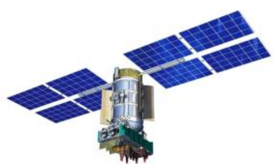
**Table 4.** Current BeiDou-3 Satellites.

**GEO and IGSO Satellites**

**3 + 3**
**operational**

- Civil signals on B1I, B1C, B2a (L5), and B3I bands
- Inclined geosynchronous orbit for enhanced regional coverage and accuracy, especially in Asia-Pacific regions
- Extended lifespan (~15 years)
- Improved availability and accuracy in complex terrains

**MEO Satellites**



**24**
**operational**

- Civil signals on B1I, B1C, B2a (L5), and B3I bands
  Advanced atomic clocks (Rubidium)
- Global coverage, similar to GPS and Galileo MEO satellites
- Extended operational lifespan (~10–12 years)
- Enhanced interoperability with other GNSS
- Improved global accuracy and integrity

## CONCLUSION

This white paper has presented a consolidated overview of the architectural principles underlying modern Global Navigation Satellite Systems (GNSS), with a focus on GPS, GLONASS, Galileo, and BeiDou. Key distinctions in constellation configurations, access schemes, have been examined.

Across all systems, the evolution toward multi-frequency, CDMA-based, and interoperable signals is evident. These developments enable improved positioning accuracy, robustness, and system interoperability. Signal formation theory—including processing gain, autocorrelation behavior, and signal-to-interference analysis—was linked to real-world GNSS formats as defined in system ICDs.

The continued refinement of GNSS signals through modulation techniques such as BOC, CBOC, and AltBOC—combined with coherent data/pilot channel architectures and circular polarization—ensures performance suitable for both civilian and high-integrity applications. Moreover, the adoption of high-processing-gain CDMA signals and advanced modulation schemes enhances GNSS resilience against jamming and interference, supporting robust operation even in challenging RF environments. This work provides a technical foundation for further study in GNSS receiver design, signal simulation, and interference mitigation.

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## FURTHER READING


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