SUPPORTING THE UK PUBLIC SECTOR IN PNT AWARENESS, RESEARCH AND KNOWLEDGE (SPARK)

PART 2

SATELLITE BASED AUGMENTATION SYSTEMS REPORT

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ABSTRACT

This document is Part 2 of a 2-part deliverable which encompasses all work package outputs of Project SPARK. Part 2 details the status of Satellite-Based Augmentation Systems (SBAS) globally, covering the technologies and services available for existing and planned capabilities. A comprehensive set of references is also provided.

RECORD OF ISSUE

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1. GENERAL

1.1. SCOPE & VAPPLICABILITY

This document is Part 2 of a 2-part deliverable which encompasses all work package outputs of Project SPARK. Part 2 details the status of Satellite-Based Augmentation Systems (SBAS) globally, covering the technologies and services available for existing and planned capabilities. A comprehensive set of references is also provided. It is not intended to be an SBAS tutorial; therefore, should the reader require SBAS tutorials, they are advised to analyse the referenced documents and/or online training courses, such as those available from the Royal Institute of Navigation, Satellite Applications Learning Hub (SALHUB).

1.2. GLOSSARY OF TERMS

AAI	Airports Authority of India
ADS	Automatic Dependent Surveillance
ADS-B	Automatic Dependent Surveillance - Broadcast
AFI	Africa and Indian Ocean
ANGA	the Augmented Navigation for Africa
ANSP	Air Navigation Service Provider
APV	Approach with Vertical Guidance
A-SBAS	SBAS for Africa & Indian Ocean
ASECNA	Agency for Air Navigation Safety in Africa and Madagascar
ASN.1	Abstract Syntax Notation One
ATM	Air Traffic Management
BDS	Beidou Navigation Satellite System
BDSBAS	BeiDou Satellite-Based Augmentation System
CAT	Category
CCF	Central Control Facility
CDMA	Code Division Multiple Access
CLAS	Centimetre-Level Augmentation Service
CNES	Centre National d’études Spatiales
CNS	Communications, navigation, surveillance
CONUS	Continental United States
CPF	Central Processing Facility
DGCA	Director General of Civil Aviation
DGNSS	Differential GNSS
DFMC	Dual Frequency Multi Constellation
DPC	Data Processing Centres
EAMAC	The African School of Meteorology and Civil Aviation
EASA	European Union Aviation Safety Agency
EC	European Commission
EDAS	EGNOS Data Access Service
EGNOS	European Geostationary Navigation Overlay Service
ERNAM	Regional School of Air Navigation and Management
ESA	European Space Agency
ESMAS	EGNOS Safety of Life (SoL) assisted service for Maritime users
ERSI	Regional Fire Safety School
ESSP	European Satellite Services Provider
EU	European Union
EUROCAE	European Organisation for Civil Aviation Equipment
EUROCONTROL	the European Organisation for the Safety of Air Navigation
EUSPA	European Union Agency for the Space Programme
eVTOL	electric Vertical Take-Off and Landing
EWA	EGNOS Working Agreement
EWAN	ENOS Wide Area Network
FAA	Federal Aviation Administration of the Unites States of America
FIR	Flight Information Region
FSAT	GAGAN Final System Acceptance Test

FTP	File Transfer Protocol
GAGAN	GPS Aided GEO Augmented Navigation
GEO	Geostationary Orbit
GAMES	GAGAN Message Service
GES	Ground Earth Stations
GIVEI	Grid Ionospheric Vertical Error Indicator
GLONASS	Globalnaya Navigazionnaya Sputnikovaya Sistema
GMS	Ground Monitoring System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSAT	Geostationary satellites
GUS	Ground Uplink Stations
HAL	Horizontal Alert Limit
HEO	Highly Elliptical Orbit
ICAO	International Civil Aviation Organisation
ICD	Interface Control Document
ICDs	ICD Interface Control Document
ICG	International Committee on GNSS
IEC	International Electrotechnical Commission
IGMA	International GNSS Monitoring and Assessment
IGM-MLDF	ISRO GIVE Model Multi-Layer Data Fusion
IGSO	Inclined Geo-Synchronous Orbit
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
IMO	International Maritime Organization
INLUS	Indian Land Uplink Stations
INMCC	A Master Control Centre in India
INRES	India Reference Station
ISRO	Indian Space Research Organisation
ITU	International Telecommunication Union
ITU-R	The International Telecommunication Union Radiocommunication Sector
JCAB	Japan Civil Aviation Bureau
KARI	Korea Aerospace Research Institute
KASS	Korea Augmentation Satellite System
KCS	South Korea Control Stations
KOREASAT	A series of South Korean communications satellites
KPS	South Korea Processing Stations
KRS	South Korea Reference Stations
KUS	South Korea Uplink Stations
LNAV	Lateral Navigation
LPV	Localiser Performance with Vertical Guidance
MADOCA-PPP	Multi-GNSS Advanced Orbit and Clock Augmentation – Precise Point Positioning
MASPS	Minimum Aviation System Performance Standards
MCC	Mission Control Centre
MCS	Master Control Station
MEASAT	A Malaysian satellite operator
MF	Multifrequency
MIFR	Master International Frequency Register
MLDF	Multi-Layer Data Fusion
MLIT	Japan's Ministry of Land, Infrastructure, Transport and Tourism
MOLIT	Korean Ministry of Land, Infrastructure and Transport
MOPS	Minimum Operational Performance Standards
MRD	Mission Requirements Document
MS	Member States (of the European Union)
MSAS	MTSAT Satellite Augmentation System

MSC	Maritime Safety Committee
MSO	Multiple System Operator
MTSAT	Multi-function Transport Satellite
NAS	National Air Space
NLES	Navigation Land Earth Stations
NOTAM	Notice to Airmen or Notice to Air Mission
NPA	Non-Precision Approach
NSP	Navigation Systems Panel
NTRIP	Networked Transport of RTCM via Internet Protocol
OCC	Operation Control Centres
OS	Open Service
OT&E	Operational Test & Evaluation
PBN	Performance-Based Navigation
PNT	Positioning, Navigation, and Timing
PPP	Precise Point Positioning
PVS	Precise Point Positioning via SouthPAN
QZSS	Quazi-Zenith Satellite System (aka Michibiki)
RIMS	Ranging and Integrity Monitoring Stations
RNAV	Radio Navigation
RNP	Required Navigation Performance
RTCA	Radio Technical Commission for Aeronautics
RTCM	Radio Technical Commission for Maritime
RTK	Real-Time Kinematic
SARPs	Standards and Recommended Practices
SALHUB	Satellite Applications Learning Hub
SBAS	Satellite-Based Augmentation System
SDCM	Systems for Differential Corrections and Monitoring
SDD	Service Definition Document
SES	Single European Sky
SF	Single Frequency
SIS	Signal-in-Space
SISNeT	Signal in Space through the Internet
SLAS	Sub-Metre Level Augmentation Service
SMSS	Service Monitoring Sub System
SNAS	Satellite Navigation Augmentation System
SoL	Safety of Life
SOLAS	Safety of Life at Sea
SouthPAN	Southern Positioning Augmentation Network
SPARK	Supporting the UK Public Sector in PNT Awareness, Research and Knowledge
SPS	Standard Positioning Service
SRD	System Requirements Document
TEC	Total Electron Content
TTA	Time-to-alert
UDRE	User Differential Range Error
UDREI	User Differential Range Error Indicator
UK	United Kingdom
UPL	User Protection Levels
USG	United States Government
UTC	Universal Coordinated Time
VAL	Vertical Alert Limit
WAAS	Wide Area Augmentation System
WAD	Wide Area Differential
WMS	WAAS Master Station
WRS	Wide Area Reference Station

2. INTRODUCTION

A Satellite-Based Augmentation System (SBAS) is a highly accurate and reliable system that enhances the performance of Global Navigation Satellite Systems (GNSS), such as the U.S. Global Positioning System (GPS), the Russian Globalnaya Navigazionnaya Sputnikovaya Sistema (GLONASS), and the European Union's Galileo system (European Union Agency for the Space Programme, 2025; Thales, 2020). SBAS improves the accuracy, integrity, and availability of GNSS positioning by providing correction data and integrity information to users over a wide area, typically covering entire countries or regions (Frontier SI, 2025).

2.1. GENERAL CONCEPT

The SBAS concept is built on a network of ground-based reference stations and geostationary satellites working together to augment primary GNSS constellations (European Union Agency for the Space Programme, 2024).

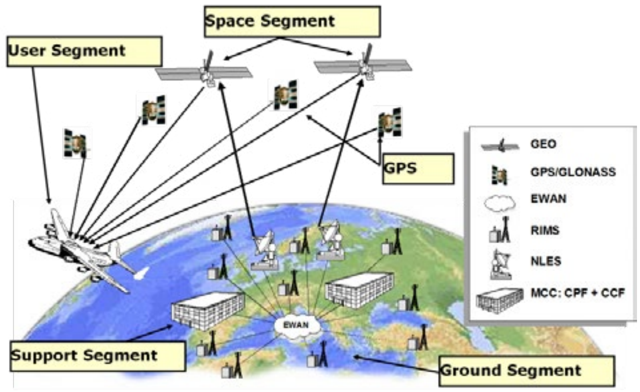

Figure 1: General SBAS Architecture (European Space Agency, 2011)

An SBAS (Figure 1) consists of the following elements:

- Ground Infrastructure[1]: A network of accurately located reference stations is deployed across a country, region, or continent (European Union Agency for the Space Programme, 2024).
- Data Collection: These stations continuously monitor GNSS signals and measure errors in positioning data (Frontier SI, 2025; European Union Agency for the Space Programme, 2024).
- Central Processing: The collected data is transferred to a central computing centre, where differential corrections and integrity messages are calculated (European Union Agency for the Space Programme, 2024).
- Satellite Broadcast: The computed corrections and integrity information are then broadcast over the covered area using geostationary satellites (Thales, 2020; European Union Agency for the Space Programme, 2024). SBAS transmissions are formatted similarly to GNSS signals to ensure compatibility with existing receivers. Most SBAS signals are broadcast on the same L1 frequency (1575.42 MHz) as GPS and use a similar CDMA (Code Division Multiple Access) modulation scheme. This allows SBAS data to be transmitted to any GPS receiver that has been modified or designed to accept augmentation data. The SBAS message structure includes correction data for satellite ephemeris, clock corrections, ionospheric delay, and integrity information, which are transmitted in packets and can be processed in receivers.
- User Reception: GNSS receivers equipped with SBAS capability receive and apply these corrections to improve their positioning accuracy (Global GPS Systems, 2025).

The primary purpose of an SBAS is to enhance the performance of GNSS for safety-critical applications, particularly in civil aviation. However, its benefits also extend to various other sectors. The main objectives of SBAS include:

- Improved Accuracy: SBAS significantly enhances positioning accuracy, reducing errors from several meters to less than one meter or even down to the centimetre level in some cases (Thales, 2020; Frontier SI, 2025).
- Integrity Monitoring: It provides real-time integrity information, allowing users to assess the reliability of the positioning data and receive alerts within seconds if the error becomes too large (European Space Agency, 2011).
- Wide Area Coverage: SBAS offers augmentation services over large geographical areas2, making it suitable for applications that require seamless navigation across countries or continents.
- Enhanced Availability: By providing additional ranging signals from geostationary satellites, SBAS can improve the availability of positioning services, especially in challenging environments (Novatel, 2025).
- Interoperability: Worldwide, SBAS comply with common global standards, ensuring compatibility and interoperability across different regions (European Union Agency for the Space Programme, 2024).

1 Different SBAS have the same fundamental building blocks but use terminology varies between systems (e.g., Ranging and Integrity Monitoring System (RIMS) in European Geostationary Navigation Overlay Service (EGNOS) vs Wide Area Reference Stations (WRS) in the case of WAAS).

2 All systems serving equatorial regions will suffer with poorer performance due to the relative instability of the ionosphere at the equator.

By providing highly accurate, reliable, and integrity-assured positioning information, SBAS enables a wide range of applications across various sectors, including aviation, maritime navigation, precision agriculture, and land transportation (Thales, 2020; European Union Agency for the Space Programme, 2024; Global GPS Systems, 2025).

2.2. INTERNATIONAL COLLABORATION

Several international organisations play key roles in setting standards for SBAS operation and equipment.

2.2.1. INTERNATIONAL CIVIL AVIATION ORGANISATION (ICAO)

The International Civil Aviation Organisation (ICAO) is a specialised UN agency responsible for developing and maintaining international aviation standards, known as Standards and Recommended Practices (SARPs). These standards address critical areas such as air traffic services, licensing, meteorology, security, and the safe transport of dangerous goods. ICAO regularly reviews and updates its standards to keep pace with advancing aviation technology and evolving needs. With its headquarters in Montréal and seven regional offices worldwide, ICAO operates as a forum for over 180 member states to collaborate on global aviation safety and efficiency. The Air Navigation Commission, consisting of 15 independent experts, advises ICAO's Council on technical aviation matters to support the organisation's mission. (ICAO, 2025; Britannica, 2025; ICAO, 2019)

2.2.2. EUROPEAN UNION AVIATION SAFETY AGENCY (EASA)

EASA works closely with ICAO on various activities to support global aviation safety and compliance. It coordinates with the European Commission and Member States (MS) on global aviation matters and aids in implementing ICAO standards through tools like compliance checklists. EASA and ICAO exchange safety information and coordinate audits to reduce duplication for MS. EASA experts contribute to over 50 ICAO panels and participate in ICAO audits under a joint Working Arrangement. With a liaison office in Montréal, EASA ensures ongoing collaboration with ICAO and supports initiatives like "No Country Left Behind" by coordinating global technical assistance (EASA, 2025; ICAO, 2012).

2.2.3. RADIO TECHNICAL COMMISSION FOR AERONAUTICS (RTCA)

RTCA, Inc. is a nonprofit organisation established in 1935 that develops consensus-based recommendations on communications, navigation, surveillance, and air traffic management (CNS/ATM) systems. Its recommendations guide the United States Federal Aviation Administration (FAA) policies and private sector decisions, with members including government agencies, airlines, unions, manufacturers, and academic institutions worldwide (U.S. Department of Transportation Federal Aviation Administration, 2009). RTCA's work is carried out by volunteer-led special committees, which explore technical and operational issues to produce actionable reports. These reports, approved by the Program Management Committee, are published and made available to the public. RTCA's global membership and open processes ensure its recommendations address contemporary aviation challenges effectively (SKYbrary, 2025).

2.2.4. EUROPEAN ORGANISATION FOR CIVIL AVIATION EQUIPMENT (EUROCAE)

EUROCAE, founded in 1963, develops performance specifications for aviation equipment and CNS/ATM systems. Its documents, such as Minimum Operational Performance Standards (MOPS) and Minimum Aviation System Performance Standards (MASPS), are recognised by European aviation authorities and organisations like EUROCONTROL (the European Organisation for the Safety of Air Navigation). Working groups of industry experts create these specifications, with oversight from the EUROCAE Council. EUROCAE's work supports regulatory compliance and advances aviation safety and efficiency (EUROCAE, 2025; SKYbrary, 2025).

2.2.5. INTERNATIONAL TELECOMMUNICATION UNION (ITU)

The International Telecommunication Union (ITU) has an oversight role for SBAS through its Radiocommunication Sector (ITU-R). The ITU-R manages the global radio-frequency spectrum and ensures that the frequencies used by SBAS do not interfere with other satellite or terrestrial services. This involves allocating spectrum bands and coordinating frequency assignments to prevent harmful interference (International Telecommunication Union, 2000; International Telecommunication Union (ITU), 2025).

It also oversees the use of satellite orbits, particularly geostationary orbits where many SBAS satellites are positioned. This includes the registration of satellite positions to ensure equitable access to these orbits for all countries, thus supporting the deployment and functionality of SBAS. The ITU-R develops technical standards and recommendations that guide the design, operation, and interoperability of SBAS. These standards ensure that SBAS can work seamlessly across different regions or countries, enhancing GNSS performance (Federal Communications Commission, 2024).

For each new SBAS or any modification to existing systems, member states must coordinate through the ITU. This involves notifying the ITU of planned services, after which the ITU then processes this information for eventual recording in the Master International Frequency Register (MIFR). This process helps in managing potential interference and ensuring international compliance (International Telecommunication Union's (ITU), 2025).

2.2.6. INTERNATIONAL COMMITTEE ON GLOBAL NAVIGATION SATELLITE SYSTEMS (ICG)

The International Committee on Global Navigation Satellite System (ICG) plays a significant role in fostering international collaboration on SBAS through various activities (United Nations Office for Outer Space Affairs, 2025; International Committee on GNSS Recent Developments, 2023):

- Harmonisation: The ICG works towards harmonising the different SBAS around the world to foster interoperability. By ensuring that these systems can interoperate or at least share common standards, the ICG helps in creating a seamless global navigation environment.
- Standard Development: Through its working groups, especially Working Group A on Compatibility and Interoperability and Working Group D on Reference Frames, Timing and Applications, the ICG promotes the development of international standards for SBAS signals, message formats, and performance metrics.
- Knowledge Exchange: The ICG facilitates the exchange of information, experiences, and best practices among SBAS service providers. This includes discussing technical issues, operational experiences, and strategies for system maintenance and expansion.
- Workshops and Meetings: Regular meetings and workshops provide platforms for dialogue where challenges and solutions related to SBAS deployment, operation, and future developments can be discussed.
- Support for New and Developing Systems: The ICG helps countries that are developing or planning to develop their own SBAS by offering technical assistance, sharing lessons learned, and providing guidance on regulatory, technical, and operational aspects.
- Policy Recommendations: The ICG can propose policies and recommendations to international bodies like ICAO and the ITU regarding the use and regulation of SBAS.
- Global Navigation Satellite System (GNSS) Providers' Forum: The ICG includes a forum where GNSS providers, including those with SBAS, can discuss mutual interests, coordination efforts, and potential collaborations.
- Encouraging Research: By linking various stakeholders, the ICG encourages research into new SBAS technologies, applications, and enhancements, potentially leading to innovations that benefit the global community. Through initiatives like the joint pilot projects with the ICG's IGMA (International GNSS Monitoring and Assessment) subgroup, the ICG explores new ways to monitor and assess the performance of SBAS globally.

2.3. MULTIFREQUENCY OPERATION

2.3.1. MULTIFREQUENCY (MF) GNSS

MF operation within a GNSS receiver is exceptionally effective at mitigating ionospheric errors because the ionosphere disrupts (or scintillates) GNSS signals in a frequency-dependent manner. This ionospheric delay, which can introduce significant positioning errors, varies inversely with the square of the signal frequency. By receiving signals on multiple frequencies, such as L1[3], L2[4], and L5[5], GNSS receivers can measure the time delay between these signals. Since the ionospheric effect is frequency-specific, comparing the delays between different frequency signals allows for the computation of the Total Electron Content (TEC) along the signal path, which is directly related to the ionospheric delay (Furuno, 2025; MDPI, 2019).

This differential approach enables the receiver to correct for the ionospheric delay accurately, reducing positioning errors from meters to centimetres. This capability is vital for applications requiring high precision, like surveying, precision agriculture, and autonomous navigation, where even small errors can lead to significant issues. Multifrequency GNSS can also support faster and more reliable ambiguity resolution in carrier phase measurements, further improving positioning quality.

SBAS use these MF receivers within their ground infrastructure to derive the most accurate correction information.

3 1575.42 megahertz (MHz)
4 1227.6 MHz
5 1176.45 MHz

For single-frequency user receivers, such as standard commercial grade L1 receivers, using and integrating SBAS corrections from the multiple-frequency monitoring SBAS can significantly improve single frequency accuracy and integrity.

For aviation, certified navigation equipment installed in aircraft that rely on these augmentation systems for precision approaches, such as LPV (Localizer Performance with Vertical Guidance), are constrained to using only the GPS L1 signal. This means they operate on a single frequency, which can impact performance in environments with potential signal interference or ionospheric delays, as single-frequency receivers do not have the capability to mitigate these effects as effectively as dual-frequency receivers. This may change in time as efforts to introduce multi-frequency user equipment are underway.

In the context of multifrequency GNSS and integrity monitoring, the Grid Ionospheric Vertical Error Indicator (GIVEI) and the User Differential Range Error (UDRE) are key metrics provided by SBAS to quantify and communicate correction uncertainties. GIVEI represents the confidence in ionospheric delay corrections computed for specific grid points based on the Total Electron Content model. Derived from statistical analyses of residual errors, GIVEI directly influences integrity bounds, enabling real-time evaluations of correction performance for applications such as aviation precision approaches. If residual ionospheric errors exceed integrity limits GIVEI triggers alerts, ensuring users are not exposed to unreliable corrections.

UDRE quantifies uncertainties in satellite-related GNSS signal corrections, including satellite clock biases and ephemeris inaccuracies (Springer Open, 2022). This metric is computed through continuous monitoring of satellite behaviours and residuals, determining the accuracy of pseudorange corrections and influencing the User Protection Levels (UPL). High UDRE values indicate unreliable corrections, prompting caution or exclusion in safety-critical applications (MDPI, 2023). Together, GIVEI and UDRE provide comprehensive integrity monitoring, enabling SBAS to ensure the safety and reliability of GNSS applications in aviation, maritime navigation, and geodetic surveying, while maintaining compliance with international standards.

The evolution from single-frequency to Dual-Frequency Multi-Constellation (DFMC) operations for SBAS user equipment is driven by the need to enhance aviation navigation accuracy, integrity, and availability. ICAO, through its Navigation Systems Panel (NSP), has actively worked on developing new Standards and Recommended Practices (SARPs) for DFMC SBAS. These draft SARPs aim to accommodate the use of both L1 and L5 frequencies, which are critical for mitigating ionospheric delays that affect positioning accuracy. The proposed changes include specifications for signal characteristics, message formats, and performance requirements to support DFMC operations. This includes the provision for broadcasting corrections and integrity information for multiple GNSS constellations like GPS, Galileo, GLONASS, and BeiDou, thereby ensuring that aircraft equipped with DFMC receivers can achieve superior navigation performance across different regions.

The direction of travel for regulatory and standards organizations is clearly towards the adoption of DFMC SBAS for aviation. This shift is evidenced by the ongoing efforts to finalise these SARPs, with a focus on interoperability and global consistency in GNSS augmentation. ICAO, along with other bodies like RTCA, is working closely with SBAS providers worldwide to facilitate completion and adoption. The emphasis is on ensuring that these new standards not only enhance safety and efficiency but also support seamless transitions between different SBAS regions. As DFMC SBAS becomes operational, it is expected to significantly improve the performance of precision approaches, particularly in environments with high ionospheric activity, thereby offering a more robust and globally harmonised GNSS augmentation service for aviation.

2.4. PRECISE POINT POSITIONING (PPP) OVER SBAS

Precise Point Positioning (PPP) is a technique that provides high precision positioning without the need for a local base station or differential corrections. It uses a single GNSS receiver to achieve centimetre-level accuracy by correcting for satellite orbit errors, clock biases, atmospheric delays, and other systematic errors through sophisticated modelling and the use of publicly available satellite data (Novatel, 2025).

This is achieved by processing data from a network of globally distributed reference stations to generate precise satellite orbit and clock corrections, which are then applied to the user's receiver data. PPP is particularly useful for applications requiring high accuracy, such as geodesy, surveying, precision agriculture, and autonomous vehicle navigation, where traditional Real-Time Kinematic (RTK) methods might be impractical or unavailable (MDPI, 2023).

SBAS and PPP techniques can work together to enhance navigation accuracy:

- Complementary Technologies: While SBAS improves the accuracy and reliability of GNSS positioning by correcting signal measurement errors and providing integrity information (European Union Agency for the Space Programme, 2024), PPP further refines this accuracy by using precise satellite orbit and clock data (Inside GNSS, 2024).

- Enhanced Accuracy: SBAS typically provides meter-level accuracy, but when combined with PPP, it can achieve decimetre-level (10-15 cm) or even centimetre-level accuracy (Thales, 2020; Inside GNSS, 2024).
- Enhanced Robustness: SBAS can offer real-time integrity information, which might help in identifying and mitigating errors more quickly during the PPP convergence phase, potentially speeding up the process.
- Global Applicability: PPP can be used anywhere in the world without the need for a local base station, making it ideal for integration with SBAS for global operations (Inside GNSS, 2024).

PPP significantly improves navigation accuracy through several key mechanisms:

- Precise Orbit and Clock Corrections: PPP utilises highly accurate satellite orbit and clock data, which are crucial for achieving centimetre-level positioning accuracy (Inside GNSS, 2024) (European Space Agency, 2011).
- Dual-Frequency Observations: By using both code and carrier phase measurements from dual-frequency GNSS receivers, PPP can eliminate first-order ionospheric effects, further improving accuracy (European Space Agency, 2011).
- Advanced Error Modelling: PPP incorporates sophisticated error models to account for various factors affecting GNSS signals, such as tropospheric delays (European Space Agency, 2011).
- Continuous Refinement: PPP solutions typically improve over time as the system continuously refines its estimates of carrier phase ambiguities.
- Multi-GNSS Integration: Modern PPP services often incorporate data from multiple GNSS constellations, enhancing accuracy and reliability (Inside GNSS, 2024).

PPP corrections can be delivered over SBAS by broadcasting additional or enhanced correction messages that include PPP data. This could involve new message types or an extension of existing ones to carry the more detailed PPP corrections on additional frequencies such as E6b[6].

GNSS receivers capable of PPP via SBAS need to be equipped to decode these enhanced messages to extract the corrections which are applied to the GNSS signals to compute positions with higher accuracy. This involves processing both the traditional SBAS corrections for initial positioning and then refining this with the PPP corrections.

A critical aspect is managing the convergence time, which is the period required for the PPP solution to reach its full accuracy. PPP over SBAS might still have a longer convergence time compared to traditional PPP using more direct internet or satellite delivery of corrections, but efforts are made to reduce this through sophisticated algorithms and by using initial SBAS corrections to start with a less accurate but faster solution.

There are limitations of PPP over SBAS:

- Frequency Limitation: Current SBAS primarily augment GPS L1 and sometimes L5, but not the full spectrum of frequencies used in modern multi-frequency GNSS receivers. Since PPP benefits significantly from multi-frequency signals (for better ionospheric correction), this might limit the full potential of PPP in terms of convergence speed until SBAS fully develop.
- Ambiguity Resolution: While SBAS can provide some level of correction, the resolution of carrier-phase ambiguities in PPP still largely depends on the receiver's capability to process multi-frequency data over time. SBAS alone does not directly aid in ambiguity resolution in PPP unless specifically integrated for this purpose.
- Update Rate and Latency: SBAS corrections are typically updated less frequently than what might be optimal for the fastest convergence in PPP, and there can be some latency in receiving these corrections, although the use of a higher rate on E6b could mitigate this.

2.5. KEY APPLICATIONS AND BENEFICIARIES

SBAS significantly improves GNSS performance, making it particularly valuable for applications requiring high accuracy and reliability. Below is a non-exhaustive list of applications and sectors that could benefit from the use of SBAS. Not all deployed SBAS address every application, so this section is provided as an overview of SBAS applications in a wide context and it is not system-specific.

2.5.1. AVIATION

Aviation is the primary sector to benefit from SBAS. (Skybrary, 2025; Federal Aviation Administration, 2025; European Space Agency, 2011) (NEC, 2025) (European Space Agency, 2011) (Inside GNSS, 2024) (Inside GNSS, 2024) (U R Rao Satellite Centre (URSC), 2016; Vajiram & Ravi, 2024) (Navipedia, 2011; Unoosa, 2015):

6 1278.75 MHz

Typically, the functions for its use are:

- Enhanced Safety: SBAS provides accurate notification capabilities, notifying users of GNSS system errors within six seconds.
- Improved Airport Access: SBAS enables Radio Navigation (RNAV) (GPS) approaches with Localizer Performance with Vertical Guidance (LPV) minimums as low as 200 feet, equivalent to Instrument Landing System (ILS) Cat 1 capabilities.
- All Flight Phases: SBAS supports navigation for all classes of aircraft during en-route, terminal, and approach phases of flight, including support in challenging weather conditions. (New Space Economy, 2024)
- Cost Savings: Airlines can reduce fuel loads and avoid diversions to alternate airports, resulting in significant cost savings. SBAS can also be used to reduce operating and maintenance costs associated with ground-based navigation aids (Federal Aviation Administration, 2024), which will continue to play a key role in maintaining the resilience and redundancy of aviation capabilities.
- Increased Accessibility: Smaller airports and the communities they serve benefit from increased accessibility during low visibility conditions and Non-Precision Approach (NPA).
- Safer landings: Helps pilots land more safely in poor visibility and avoid aborted landings (European Space Agency, 2025).
- Improved Communications: SBAS can facilitate improved voice and data communications between aircraft and control towers, as well as between aircraft.
- Automatic Dependent Surveillance (ADS): SBAS can enable aircraft to automatically report their positions to Air Traffic Control Centres, improving overall air traffic management (eoPortal, 2012).
- Enhanced flight safety: Drones used in logistics, aerial surveying, and agriculture operate with enhanced flight safety.
- Improved ATM: SBAS can be used to improve Air Traffic Management (ATM) efficiency and uniformity.
- In the future, it is expected that Advanced Air Mobility Systems (e.g., eVTOLs (electric Vertical Take-Off and Landings) for urban and regional passenger transport) will use SBAS for accuracy improvement and integrity functions.

2.5.2. MARITIME

- Supports safer navigation in harbour entrances, approaches, and coastal waters (European Union Agency for the Space Programme, 2025) (Federal Aviation Administration, 2015).
- Enables more precise operations for SOLAS (Safety of Life at Sea) activities (European Union Agency for the Space Programme, 2018).
- Improved maritime navigation in congested waters.
- In the future, Maritime Autonomous Surface Ships may also use SBAS for accuracy improvements and integrity functions.

2.5.3. AGRICULTURE:

- SBAS can[7] be used to improve precision farming techniques (New Space Economy, 2024) (ToitūTe Whenua Land Information New Zealand, 2025; Utility Magazine, 2023).
- Improvements can be made in spreading, seeding, and harvesting crops, thereby improving agricultural efficiency and productivity (Federal Aviation Administration, 2015).
- Precise field binding, automatic motion control for crop cultivation, small-seeded crop cultivation, yield mapping, and livestock management can all be improved through implementation of SBAS capabilities.

2.5.4. OTHER TRANSPORTATION APPLICATIONS

- Road and rail efficiency management
- Improved GPS accuracy can enhance vehicle tracking and navigation systems
- Enhanced traffic management and asset monitoring systems
- Improving the safety of unmanned level crossing warnings and train tracking (Indian Space Research Organisation, 2023)
- Cooperative intelligent transport systems
- Support for autonomous vehicles
- Location-based Services: Improves performance of various location-dependent applications (European Space Agency, 2025)

7 Agriculture applications often use paid for Real-Time Kinematic (RTK) services for precision capabilities, and providing PPP over the air via SBAS would lower the barrier to entry for use of precision agriculture.

2.5.5. CONSTRUCTION AND SURVEYING

- SBAS enables precise location identification, improving the accuracy and reliability of data collection for various survey and construction projects by providing higher accuracy geospatial information, including (Federal Aviation Administration, 2015):
  - Environmental monitoring, including wildlife resource management and forest monitoring
  - Ecological studies and surveys
  - Precise and effective construction site binding within absolute coordinate systems
  - Geofencing for worker safety

2.5.6. SCIENTIFIC AND OTHER

- Scientific applications requiring higher precision can benefit from SBAS, including those used for developing regional ionospheric models in areas such as space weather research or deformation monitoring.
- SBAS can enhance the accuracy of personal GPS units, making outdoor activities like hiking, camping, and geocaching more enjoyable and reliable. (Federal Aviation Administration, 2015)
- SBAS can serve as a means of time distribution and synchronisation within its coverage area, giving alternate sources of time for PNT systems that require multiple sources. (Institute of Navigation, 1998)
- SBAS will be crucial in providing integrity and improved positioning accuracy in the autonomy domain, for all types of autonomous platform (aviation and maritime as noted).

3. EXISTING SBAS

Several SBAS exist (Figure 2) or are in advanced planning stages.

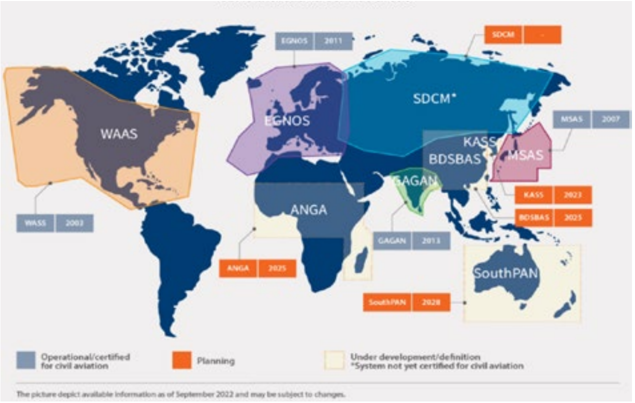

Figure 2: Existing (and planned) SBAS, shown for coverage on the earth (European Space Agency, 2023)

APPENDIX B gives a performance summary for the systems described in the following sections, for ease of reference.

3.1. EUROPEAN GEOSTATIONARY NAVIGATION OVERLAY SERVICE (EGNOS)

3.1.1. OWNERSHIP AND OPERATION

EGNOS is owned by the European Union (EU), with the European Commission (EC) taking ownership of the EGNOS infrastructure from the European Space Agency (ESA) on behalf of the EU on April 1, 2009 (European Union Agency for the Space Programme, 2025).

The European Union Agency for the Space Programme (EUSPA) is responsible for the exploitation of EGNOS, as delegated by the EC since January 1, 2014. The operational management and maintenance of EGNOS are assigned to the EGNOS service provider under a contract with EUSPA. The current service provider is "European Satellite Services Provider" (ESSP) (European Union Agency for the Space Programme, 2025).

ESSP is a private French company owned by seven key European Air Navigation Service Providers (ANSPs) (Canso, 2020).

- Skyguide (Switzerland)
- DFS IBS - Deutsche Flugsicherung – International Business Services (Germany)
- DSNA - Direction des Services de la Navigation Aérienne (France)
- ENAIRE (Spain)
- NATS - National Air Traffic Services (United Kingdom)
- ENAV - L'Ente Nazionale Assistenza al Volo (Italy)
- NAV Portugal E.P.E. – Navegação Aérea de Portugal (Portugal)

ESSP has been awarded this contract since 2009 and is responsible for (European Union Agency for the Space Programme, 2025):

- Operating and maintaining the EGNOS system
- Ensuring compliance with safety standards
- Delivering EGNOS services to users

The EU remains responsible for the research and development of new capabilities and future EGNOS versions, via EUSPA and ESA (as Systems Engineering lead).

EGNOS plays a crucial role in enhancing navigation capabilities across Europe and some neighbouring countries. Its primary functions include:

- Augmentation of GPS Signals: EGNOS improves the accuracy of GPS positioning information (European Space Agency, 2025; Skybrary, 2025).
- Integrity Monitoring: It provides crucial integrity messages, allowing users to get a reliable guarantee on residual positioning errors, both horizontal and vertical (European Union Agency for the Space Programme, 2025; European Union Agency for the Space Programme, 2025).
- Safety-Critical Applications: EGNOS makes satellite navigation signals suitable for safety-critical applications, particularly in aviation and maritime sectors (European Union Agency for the Space Programme, 2025; European Union Agency for the Space Programme, 2025).
- Multi-Sector Benefits: Beyond aviation and maritime, EGNOS enhances GNSS applications in various sectors, including road, rail, surveying, mapping, location-based services, and agriculture (European Union Agency for the Space Programme, 2025).
- Time Synchronisation: EGNOS signals provide users with accurate synchronisation to UTC time (to <50ns 3 sigma) (European Union Agency for the Space Programme, 2025).

3.1.2. GENERAL OPERATION

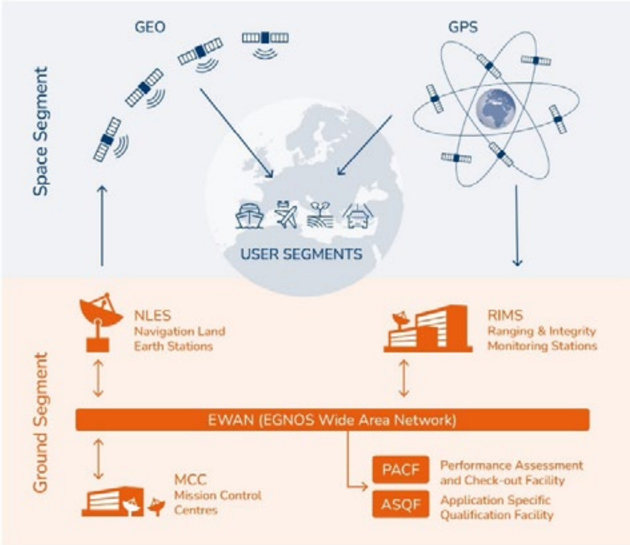

Figure 3: EGNOS Overview (European Union Agency for the Space Programme, 2025)

Ground Segment (European Union Agency for the Space Programme, 2025)**:**

- 40 Ranging and Integrity Monitoring Stations (RIMS) collect GPS satellite signals and data[8].
- 2 Mission Control Centres (MCCs) process this data to generate correction and integrity message.
- 6 Navigation Land Earth Stations (NLES) per geostationary satellite uplink these messages (European Union Agency for the Space Programme, 2025).

Figure 4: EGNOS RIMS Network (Navipedia, 2011)

Space Segment:

- [up to] 3 geostationary satellites broadcast the EGNOS signal (European Union Agency for the Space Programme, 2025).

Data Flow (European Union Agency for the Space Programme, 2025)**:**

- RIMS measure GPS satellite positions and compare them with accurate measurements.
- MCCs determine GPS signal accuracy and calculate position inaccuracies.
- Correction data is sent to uplink stations and then to EGNOS satellites.
- Satellites broadcast this information to users with EGNOS-enabled receivers.

This infrastructure allows EGNOS to gather GPS data, process it, and broadcast correction and integrity messages to users across its coverage area.

Supported Functionalities:

EGNOS provides several key functionalities:

1. Improved Accuracy: Enhances GPS positioning accuracy (European Union Agency for the Space Programme, 2025).
2. Integrity Monitoring: Provides integrity messages allowing users to assess the reliability of positioning information (European Space Agency, 2021).
3. Wide Area Differential (WAD) Corrections: Calculates and broadcasts corrections for the entire service area (European Space Agency, 2021).
4. Ionospheric Delay Correction: Corrects for signal delays caused by the ionosphere (European Space Agency, 2021).
5. GPS-like Signal Transmission: Broadcasts a GPS-like signal augmented with integrity and correction data (European Space Agency, 2021).
6. Time Synchronisation: Transmits an accurate time signal (European Union Agency for the Space Programme, 2025) which is implemented as a data message to provide the parameters for synchronisation of EGNOS Network time with UTC.
7. Safety-Critical Applications: Supports navigation services for aviation, maritime, and land-based users (European Union Agency for the Space Programme, 2025).

8 The UK RIMS stations are still operating at time of this report.

3.1.3. COVERAGE AREA

EGNOS coverage is primarily focused on:

- Europe
- North Africa
- Some neighbouring countries

The system's infrastructure is deployed across more than 20 countries to ensure comprehensive coverage of the European region (European Space Agency, 2021).

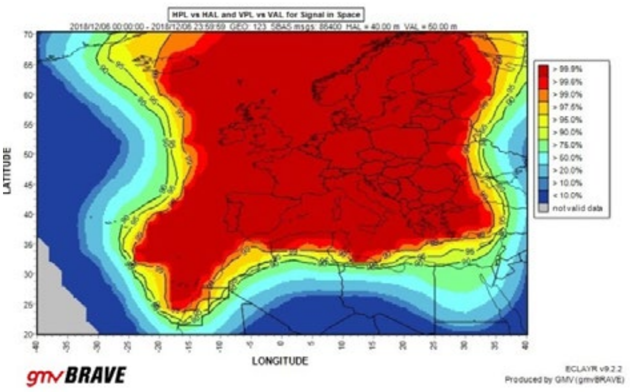

Figure 5: EGNOS Coverage map *(Navipedia, 2011)*

3.1.4. EGNOS SERVICES

3.1.4.1. OPEN SERVICE (OS)

The EGNOS Open Service is freely available to any user with an EGNOS-enabled satellite navigation receiver (European Union Agency for the Space Programme; European Space Agency, 2011). It was officially launched on October 1, 2009, and offers improved positioning accuracy compared to standalone GPS.

The EGNOS Open Service offers several key benefits (European Union Agency for the Space Programme, 2025):

- Enhanced Accuracy: EGNOS OS improves positioning accuracy to within 1-3 meters (EU Agency for the Space Programme, 2024), compared to the 17-meter accuracy of standalone single frequency GPS.
- Error Correction: It corrects various error sources affecting GPS signals, including satellite clocks, satellite positions, and ionospheric effects.
- Wide Applicability: The service is designed for a broad spectrum of applications, including smartphone navigation, public transportation, and logistics.
- High Availability: EGNOS OS is available more than 99% of the time, ensuring reliable service for users.
- No Direct Charges: The service is provided free of charge and without any specific authorization requirements.

3.1.4.2. SAFETY OF LIFE SERVICE (SOL)

The EGNOS SoL Service (Navipedia, 2011) is tailored for safety-critical transport applications, particularly in aviation (Skybrary, 2025) (European Space Agency, 2011).

Key features include:

- Certified for civil aviation in 2011
- Compliant with aviation requirements for Approach with Vertical Guidance (APV)-1 and Category I precision approaches
- Designed for applications where lives could be endangered if the performance is not adequate or is degraded

SoL was declared operational for aviation use on March 2, 2011. It is fully compliant with International Civil Aviation Organisation (ICAO) Standards and Recommended Practices for Satellite-Based Augmentation Systems (SBAS) and meets requirements for APV-I procedures (Navipedia, 2011).

The service provides augmentation to the Global Positioning System (GPS) Standard Positioning Service, offering high-precision timing and positioning signals across Europe, with recent expansions improving service in northern regions. It enables precision approaches and landings at airports, including those without expensive ground-based navigation aids, and supports Localizer Performance with Vertical Guidance (LPV)-200 procedures, allowing approaches to 200 feet above runway without visual ground contact. The latest version (3.6) of the SoL Service Definition Document introduced several enhancements, including updated commitment maps, expansion of the Ranging Integrity Monitoring Station network, and improvements in EGNOS architecture for both space and ground segments. Additionally, the service contributes to reducing the environmental footprint of aviation by enabling more efficient flight routes and approaches (Navipedia, 2011).

Following Brexit, the UK no longer has access to the EGNOS Safety of Life service, meaning UK users cannot rely on this feature for critical navigation applications, such as precision landing of aircraft.

3.1.4.3. EGNOS DATA ACCESS SERVICE (EDAS)

EDAS is the terrestrial data service of EGNOS, offering ground-based access to EGNOS data. It became officially available in July 2012 and provides (Navipedia, 2011):

- Real-time access to EGNOS data using a SISNeT protocol defined by ESA.
- Support for users who cannot always view EGNOS satellites (e.g., in urban canyons) or to access this service through a normal FTP client.
- Various data formats and services, including:
  - Service Level 0 (SL0): Raw data in ASN.1 format
  - Service Level 2 (SL2): Data in RTCM 3.1 standard
  - EDAS FTP, EDAS SISNET, and EDAS NTRIP services

EDAS aims to provide a basis for new applications beyond those from the nominal EGNOS Open Service and Safety of Life Service, allowing for the development of value-added services and research programs (Navipedia, 2011).

Following the UK's departure from the EU, UK entities no longer have direct access to the EDAS.

3.1.4.4. EGNOS SAFETY OF LIFE ASSISTED SERVICE FOR MARITIME USERS (ESMAS)

The ESMAS (European Union Agency for the Space Programme, 2024) offers a service tailored to maritime users to enable marine navigation in harbour entrances, harbour approaches and coastal waters of the European Union Member States and EGNOS contributing countries (Iceland, Norway and Switzerland) in line with IMO Resolution A.1046 (International Maritime Organisation, 2011). This service is designed to target a large variety of users and to increase the confidence that a user can have in the satellite information.

ESMAS is not a separate service, but a mode of working or guidance for use in the maritime sector which has been agreed internationally and published in IMO Resolution MSC.112(73) (International Maritime Organisation) and IEC 61108-7:2024 (International Electrotechnical Commission (IEC), 2024)

3.1.5. KEY PERFORMANCE METRICS

EGNOS performance is characterised by four key metrics: accuracy, integrity, availability, and continuity (Navipedia, 2011; Navipedia, 2011). These metrics are crucial for assessing the system's reliability and effectiveness, particularly for aviation applications.

Country	EU
Name of SBAS Service	EGNOS (European Geostationary Navigation Overlay Service)
Horizontal Accuracy (95%)	3 m (APV-I & LPV200), 220 m (NPA)
Vertical Accuracy (95%)	4 m (APV-I & LPV200), N/A (NPA)
Availability	0.99% (APV-I & LPV200) in most of ECAC, 0.999% (NPA)
Continuity	<1 x 10^-4 per 15s in core ECAC (APV-I & LPV200), <1 x 10^-3 per -3/ hour in most of ECAC (NPA)
Integrity	1 - 2 x 10^-7 / approach (APV-I & LPV200), 1 x 10^-7 / hour (NPA)
Time to Alert	< 6 seconds

Figure 6: EGNOS Performance Metrics, derived from (European Union Agency for the Space Programme, 2024)

3.1.5.1. ACCURACY

EGNOS significantly improves the positioning accuracy compared to standalone GPS:

The Open Service (OS) provides accuracy gains to <4m compared to GPS alone. Accuracy is enhanced by correcting various error sources affecting GPS signals, including satellite clocks, satellite positions, and ionospheric effects. Time accuracy is less than 50ns to UTC (3 sigma) (European Union Agency for the Space Programme, 2025).

3.1.5.2. AVAILABILITY

Availability refers to the percentage of time the service is accessible to users:

- For the Open Service, availability is more than 99% of the time (Navipedia, 2011).
- EGNOS availability is monitored continuously and mapped for different service levels by several entities, such as ESSP and ESA (Navipedia, 2011).
- For aviation, availability is measured for different approach types, including LPV200, APV-I, and NPA (European Union Agency for the Space Programme, 2025).

3.1.5.3. INTEGRITY

Integrity is a crucial aspect of EGNOS, especially for safety-critical applications. By providing real-time integrity messages and rapid alerts about any signal malfunctions, EGNOS enables users to make informed decisions quickly, reducing risks in high-stakes scenarios.

- EGNOS provides an integrity message to inform users within less than six seconds of any signal malfunction (Navipedia, 2011).
- Integrity is ensured with GIVEI (Grid Ionospheric Vertical Error Indicator) and UDREI (User Differential Range Error Indicator) values (European Union Agency for the Space Programme, 2025).
- The system is designed to be compliant with ICAO SARPs for SBAS, ensuring high integrity standards for aviation use (Inside GNSS, 2024).

Integrity risk and requirements are critical components of EGNOS performance. The integrity risk for EGNOS is defined as the probability that the position error exceeds the protection level without the user being informed within the timeframe for the alert. For aviation applications, the integrity risk requirement is extremely stringent, set at 2×10^{-7} in any approach of 150 seconds (MyCoordindates, 2014)/ 1×10^{-7} for en-route. EGNOS uses protection levels (horizontal and vertical) to represent an upper bound of the error, and the system is validated on the condition of Misleading Integrity Information (MII). The ICAO requirement for integrity is met within the entire EGNOS Service Area, with similar performance levels observed in both the core and edge regions (European Union Agency for the Space Programme, 2025)

3.1.6. KEY DOCUMENTS

Several key documents and standards are crucial for understanding and implementing EGNOS. These documents provide essential information on system design, performance requirements, and operational standards:

3.1.6.1. ICAO STANDARDS AND RECOMMENDED PRACTICES (SARPS)

EGNOS has been designed based on ICAO Annex 10, Volume I - Aeronautical Telecommunications - Radio Navigation Aids (SARPs) (ESSP, 2019). This document serves as the foundation for EGNOS system design and requirements.

3.1.6.2. EGNOS SERVICE DEFINITION DOCUMENTS (SDD'S)

- EGNOS Open Service (OS) Service Definition Document:
  - Details the OS service performance, system architecture, and Signal-in-Space (SIS) characteristics
  - Intended for receiver manufacturers, GNSS application developers, and end-users (European Union Agency for the Space Programme, 2017)
- EGNOS Safety of Life (SoL) Service Definition Document:
  - Describes the SoL service characteristics, performance, and limitations
  - Outlines terms and conditions for service use
  - Provides information on EGNOS system architecture and SIS characteristics (European Union Agency for the Space Programme, 2024)
- EGNOS Data Access Service (EDAS) Service Definition Document (European Union, 2024):
  - Outlines the EDAS system, its services, and minimum performance
  - Gives an overview of transmitted data (It is not a detailed technical guide or Interface Control Document (ICD). Registered users can access full technical documentation via the EDAS User Support Website.)
  - The document also covers how to register as an EDAS user and check monthly performance reports.

3.1.6.3. RTCA MOPS DO-229-C

The RTCA Minimum Operational Performance Standards (MOPS) DO-229-C document, titled "Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System airborne equipment," is essential for understanding EGNOS signal structure and format (Navipedia, 2006).

3.1.6.4. EUROPEAN REGULATIONS

Several European regulations are relevant to EGNOS implementation and use:

- EC 668/2008 Commission Regulation (EC) No 668/2008 of 15 July 2008, amending Annexes II to V of Regulation (EC) No 2096/2005, laying down common requirements for the provision of air navigation services, pertaining to working methods and operating procedures (European Union, 2008);
- EC 482/2008 : Commission Regulation (EC) No 482/2008 of 30 May 2008, establishing a software safety assurance system to be implemented by air navigation service providers and amending Annex II to Regulation (EC) No 2096/2005 (European Union, 2008);
- EU 1035/201 : Commission Implementing Regulation (EU) No 1035/2011 of 17 October 2011, laying down common requirements for the provision of air navigation services (European Union, 2011);

- EC 2096/2005: Commission Regulation (EC) No 2096/2005 of 20 December 2005, laying down common requirements for the provision of air navigation services (European Union, 2005);
- EC 551/2004: Regulation (EC) No 551/2004 of the European Parliament and of the Council of 10 March 2004 on the organisation and use of the airspace in the Single European Sky (European Union, 2004); and
- EC 1070/2009: Regulation (EC) No 1070/2009 of the European Parliament and of the Council of 21 October 2009, amending Regulations (EC) No 549/2004, (EC) No 550/2004, (EC) No 551/2004, and (EC) No 552/2004, to improve the performance and sustainability of the European aviation system (European Union, 2009).

These regulations provide the legal framework for EGNOS operations within the European airspace.

3.1.6.5. TECHNICAL AND SAFETY DOCUMENTS

1. System Requirements Document (SRD) (Eurocontrol, 1999)
2. Mission Requirements Document (MRD)
3. EGNOS Safety Case:
   - Demonstrates system compliance with safety requirements
   - Includes the EGNOS Operations Safety Case and EGNOS Signal-in-Space System Safety Case (ESSP, 2019)

3.1.6.6. EGNOS WORKING AGREEMENT (EWA)

The EWA is a core contractual document for aviation users, required by Single European Sky (SES) Regulation. It consists of a core contractual document (Annex I) which details the Safety of Life (SoL) Service Commitment, and Annex II covering Service Arrangements. The EWA facilitates compliance with SES regulations for various aviation stakeholders, including Air Navigation Service Providers, Aerodrome Operators, and Air Operators. It defines the liability scheme between parties, supports NOTAM proposal origination, and aids in contingency management. As of March 2024, there were 85 EWAs in force across 27 EU States and 7 non-EU States, demonstrating its importance in harmonizing the implementation of EGNOS-based procedures throughout Europe.

It includes:

- Safety of Life Service Definition Document (SoL SDD)
- NOTAM Proposal[9]
- Service notices
- Contingency plans
- Collaborative decision-making processes
- GNSS data recording terms

These documents collectively provide a comprehensive framework for understanding, implementing, and utilising EGNOS services across various applications, with a particular focus on aviation and safety-critical operations.

3.2. WIDE AREA AUGMENTATION SYSTEM (WAAS)

3.2.1. OWNERSHIP AND OPERATION

The Wide Area Augmentation System (WAAS) is owned by the United States Government (USG) and operated by the Federal Aviation Administration (FAA) (Skybrary, 2025; Navipedia, 2011). Its primary role is to enhance the accuracy, integrity, and availability of the Global Positioning System (GPS) for civil aviation and other users across North America.

3.2.1.1. KEY BENEFITS AND CAPABILITIES

WAAS offers several important advantages for navigation (Federal Aviation Administration, 2024):

- Improved Accuracy: WAAS enhances GPS accuracy to within 7.6 meters (25 feet) or less (specification, actual performance improves on this), both laterally and vertically; 95% of the time (Federal Aviation Administration, 2024) WAAS improves the navigational system accuracy for en-route, terminal, and approach operations over all the continental United States, Alaska and significant portions of Canada and Mexico. WAAS supports vertically guided instrument approaches to all qualifying runways in the US.
- Enhanced Safety: The system improves safety due to a WAAS LPV stabilized approach, provides runway backup and situational awareness during all final approaches to runway operations, and increases the margin of safety for pilots during low visibility, instrument meteorological conditions (IMC) weather.
- Interoperability: WAAS is interoperable with other SBAS such as EGNOS and Japan's Multi-functional Transport Satellite (MTSAT) Satellite-Based Augmentation System (MSAS). The list is growing for SBAS around the world with India, China, Russia, Korea, Australia, and New Zealand committing to the technology.

9 A Notice to Airmen (NOTAM), or Notice to Air Mission (FAA term), provides important information about changes, conditions, or hazards related to aeronautical facilities, services, or procedures that are crucial for flight operations.

- Wide Coverage: WAAS enables LPV/LP services throughout North America (Federal Aviation Administration, 2024). The system covers most of the U.S. National Airspace System (NAS) as well as portions of Canada and Mexico (Skybrary, 2025).

3.2.2. GENERAL OPERATION

A brief overview of how WAAS works, and its supported functionalities is given below (Federal Aviation Administration, 2015):

WAAS operates through a network of components that work together to improve GPS accuracy:

- Ground-based reference stations: WAAS utilizes a network of precisely surveyed Wide-area Reference Stations (WRS) spread across North America.
- Wide-area Master Stations (WMS): The data collected by the WRS is transmitted to WAAS Master Stations (WMS) via a terrestrial communications network. The WMS process this information to generate two types of corrections:
  - Fast corrections: Address rapidly changing errors in GPS satellite positions and clock errors.
  - Slow corrections: Handle long-term ephemeris and clock errors, as well as ionospheric delay information.
- Geostationary Satellites: WAAS utilises multiple geostationary communication satellites to broadcast correction messages back to Earth. These satellites also transmit GPS-like ranging signals, effectively increasing the number of satellites available for position fixing.
- WAAS-enabled GPS Receivers: Users with WAAS-enabled GPS receivers can receive and apply these corrections in real-time, significantly improving positioning accuracy (Federal Aviation Administration, 2025).
- Ground Uplink Stations (GUS): Once the correction messages are generated by the WMS, they are sent to Ground Uplink Stations (GUS). The GUS are responsible for transmitting these corrections to the WAAS geostationary satellites.

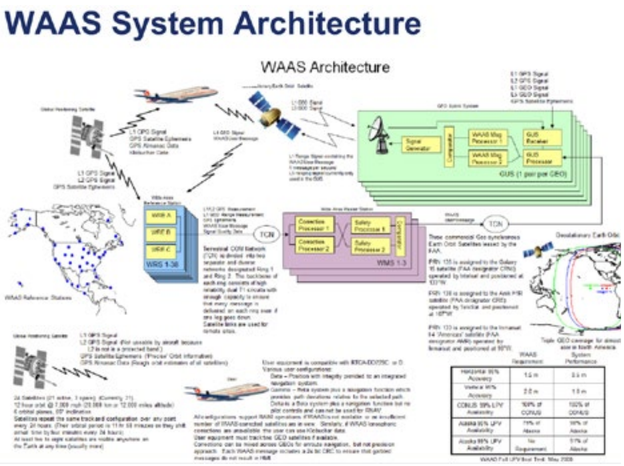

Figure 7: WAAS System Architecture Diagram (Federal Aviation Administration, 2015)

The system functions as follows:

- GPS signals are received throughout the National Airspace System (NAS) at various, strategically placed Wide Area Reference Station (WRS) sites. These WRS locations are accurately surveyed to detect any inaccuracies in the GPS signals received.
- The GPS data collected by the WRS sites is transmitted to WAAS Master Stations (WMS), which generate a WAAS User Message once per second. These messages provide GPS/WAAS receivers with information that corrects errors in the GPS signals, significantly enhancing both location accuracy and signal integrity.
- The messages from the WMS are sent to uplink stations, which then transmit them to navigation payloads on geostationary (GEO) communications satellites.
- These payloads receive and broadcast the messages as GPS-like signals throughout the NAS. GPS/WAAS receivers process these WAAS augmentation messages to refine position estimation. The GPS-like signal from the navigation transponder can also serve as an additional data source for calculating user location. This allows GPS/WAAS receivers to achieve position accuracy within a few meters across the NAS.

3.2.2.1. SUPPORTED FUNCTIONALITIES

WAAS supports several key functionalities (Skybrary, 2025; FAA/William J. Hughes Technical Center , 2005):

- Improved Accuracy: Improvements over standard GPS accuracy estimates
- Enhanced Integrity: The system provides timely warnings (within six seconds) when GPS signals should not be used for navigation due to errors or failures, ensuring the reliability of the navigation information (Bold Method, 2018).
- Precision Approaches: WAAS enables aircraft to perform precision approaches to airports, like Instrument Landing System (ILS) capabilities. It supports Area Navigation (RNAV) and Required Navigation Performance (RNP) procedures with vertical guidance. Aircraft equipped with WAAS LPV can access over 4,000 runway ends in poor weather conditions with minimums as low as 200 feet.
- Expanded Coverage: WAAS covers most of the U.S. National Airspace System (NAS) as well as portions of Canada and Mexico, providing consistent navigation capabilities across a wide area.
- Multi-Phase Flight Support: The system supports all classes of aircraft in all phases of flight, including en-route navigation, airport departures, and airport arrivals.
- Interoperability: WAAS is designed to be interoperable with other SBAS around the world, allowing WAAS-equipped aircraft to use similar systems in other regions.

3.2.3. COVERAGE AREA

WAAS covers a significant portion of North America, providing enhanced GPS navigation capabilities across a vast area:

- The Continental United States (CONUS)
- Alaska
- Canada
- Mexico

This extensive coverage area encompasses nearly all the U.S. NAS and extends into neighboring countries (Skybrary, 2025; European Space Agency, 2011).

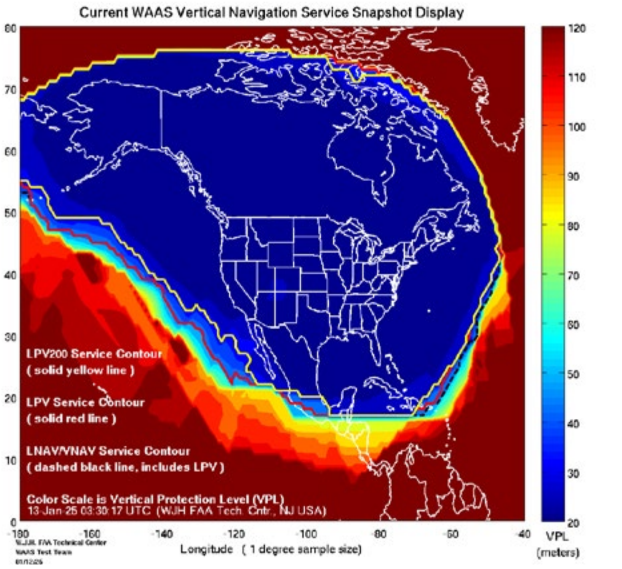

Figure 8: Wide Area Augmentation System (WAAS) Coverage Map (Federal Aviation Administration, 2021)

3.2.4. WAAS SERVICES

3.2.4.1. OPEN SERVICE

WAAS includes three services, the Open Service (OS) is primarily intended for mass-market applications that do not require the stringent safety standards of aviation or other safety-critical operations. It supports users who need enhanced GPS accuracy for general navigation, surveying, and other non-safety-critical uses.

The OS offers improved accuracy over standard GPS but does not include the high-integrity levels required for safety-critical operations. It does provide correction and health information to improve GPS positioning but does not offer the same level of integrity monitoring as the SoL service.

3.2.4.2. SAFETY-OF-LIFE (SOL) SERVICE

The Safety-of-Life service (where failure of the navigation system could lead to loss of life) is designed to meet the stringent requirements of aviation users. It offers (Skybrary, 2025; Navipedia, 2011):

- High levels of accuracy (<2m), integrity (6s alert), continuity, and availability (strict service level agreements) for all phases of flight
- Support for en-route navigation, airport departures, and airport arrivals
- Vertically guided landing approaches usable in Instrument Meteorological Conditions (IMC)
- Capability to support LPV (Localiser Performance with Vertical Guidance) approaches with minimums as low as 200 feet, equivalent to ILS Cat 1 capabilities

3.2.4.3. DATA ACCESS SERVICE

While not directly labeled as a "data access service" for WAAS, this service includes:

- WAAS Performance Data: This includes live coverage maps and performance statistics which are accessible to the public through the FAA's website. These data services provide users with information about the status, accuracy, and availability of WAAS signals.
- WAAS Correction Data: the corrections and integrity data transmitted by WAAS satellites can be accessed by any WAAS-enabled receiver. This data improves the accuracy and reliability of GPS signals for users within the WAAS coverage area.
- WAAS Test and Operational Data: For developers, researchers, or those interested in system performance, the FAA occasionally releases test data and operational statistics that can be used for analysis or integration into navigation systems.

3.2.5. KEY PERFORMANCE METRICS

The Wide Area Augmentation System (WAAS) is designed to enhance GPS navigation capabilities, particularly for aviation applications. Its performance is measured by three key metrics: accuracy, availability, and integrity. The performance of WAAS is published regularly by the FAA. The version available at the time of this report is dated October 2024 (Federal Aviation Administration, 2008).

Country	USA
Name of SBAS Service	WAAS (Wide Area Augmentation System)
Horizontal Accuracy (95%)	<1.5 m (LPV), <36 m (LNAV), 0.4 nm (En Route)
Vertical Accuracy (95%)	<2 M (LPV)
Availability	99% over 100% CONUS (LPV), 95% over 75% Alaska (LPV), 99.99% over 100% CONUS (LNAV), 99.9% over 100% Alaska (LNAV), 99.9% over 100% CONUS (En Route)
Continuity	1 - 8 10 ^-6/15s, 1 x 10^-5 / hour (LNAV & En Route)
Integrity	2 x 10 ^-7 / approach (LPV & LNAV), 1 x 10^-7 / hour (LNAV & En Route)
Time to Alert	6.2 seconds (LPV), 10s (LNAV), 15s (En Route)

Figure 9: Wide Area Augmentation System (WAAS) Performance Parameter Table, derived from (Federal Aviation Administration, 2024)

3.2.5.1. ACCURACY

WAAS significantly improves GPS position accuracy (FAA/William J. Hughes Technical Center , 2005):

- The WAAS specification requires position accuracy of 7.6 meters (25 feet) or less, both laterally and vertically, 95% of the time.
- In practice, WAAS often exceeds this requirement: (Federal Aviation Administration, 2024)
  - Horizontal accuracy: typically, better than 1.5m (3 feet 3 inches)
  - Vertical accuracy: typically, better than 2m (4 feet 11 inches)

These improvements in accuracy allow aircraft to perform precision approaches like Category I Instrument Landing System (ILS) approaches, with accuracy requirements of 16 meters laterally and 4.0 meters vertically. (FAA/William J. Hughes Technical Center , 2005)

3.2.5.2. AVAILABILITY

Availability refers to the probability that the navigation system meets its accuracy and integrity requirements (Federal Aviation Administration, 2024): Availability in WAAS is measured across different areas:

- 99% over 100% CONUS (LPV),
- 95% over 75% Alaska (LPV),
- 99.99% over 100% CONUS (LNAV)
- 99.9% over 100% Alaska (LNAV),
- 99.9% over 100% CONUS (En Route).

3.2.5.3. INTEGRITY

Integrity is crucial for safety-critical applications and refers to the system's ability to provide timely warnings when its signals are unreliable (FAA/William J. Hughes Technical Center , 2005):

- WAAS is required to detect errors in the GPS or WAAS network and notify users within 6.2 seconds.
- The system must maintain an extremely low probability of undetected errors exceeding accuracy requirements: 1×10^-7, equivalent to no more than 3 seconds of bad data per year.
- This level of integrity is equivalent to or better than Receiver Autonomous Integrity Monitoring (RAIM). As per Figure 9, integrity performance values are 2x10-7/approach (LPV & LNAV), 1x10-7/hour (LNAV & En Route)
- WAAS continuously assesses the integrity of GPS satellite signals and its own corrections, providing warnings to users within about 6 seconds of a failure.

3.2.6. KEY DOCUMENTS

WAAS is governed by several key documents and standards that ensure its performance, safety, and interoperability. These important documents include:

3.2.6.1. ICAO STANDARDS AND RECOMMENDED PRACTICES (SARPS)

The International Civil Aviation Organisation (ICAO) provides Standards and Recommended Practices for SBAS, including WAAS:

- ICAO Annex 10, Volume 1 (7th Edition, July 2018): This document includes standards regarding the type and content of data that must be generated and transmitted by SBAS (Navipedia, 2011).

3.2.6.2. FAA PERFORMANCE STANDARD

- WAAS Performance Standard (1st Edition, 2008): This document defines the levels of signal-in-space (SIS) performance provided by the U.S. Government to the WAAS user community. It serves as a companion to the GPS Standard Positioning Service (SPS) Performance Standard (Federal Aviation Administration, 2008).

3.2.6.3. RTCA MINIMUM OPERATIONAL PERFORMANCE STANDARDS (MOPS)

The Radio Technical Commission for Aeronautics (RTCA) has established several standards relevant to WAAS:

- DO-229F (2020): Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System
Airborne Equipment
- DO-228 (January 2000): MOPS for GNSS Airborne Antenna Equipment (Navipedia, 2011)
- DO-301 (December 2006): MOPS for GNSS Airborne Active Antenna for the L1 Frequency Band

These RTCA documents provide standards for WAAS receiver equipment and related components (RTCA, 2025).

3.2.6.4. ADDITIONAL SUPPORTING DOCUMENTS

The FAA Technical Center WAAS Test Bed website (http://www.nstb.tc.faa.gov/) provides reports on both GPS and WAAS performance (Federal Aviation Administration, 2008; Federal Aviation Administration, 2024).

These documents collectively report on the monitoring of the performance of WAAS to communicate the effectiveness of meeting the requirements for accuracy, availability, and integrity, which are all necessary for aviation applications. They also facilitate interoperability with other SBAS worldwide, allowing WAAS-equipped aircraft to use similar systems in other regions (Skybrary, 2025).

3.3. QUAZI-ZENITH AUGMENTATION SERVICES

3.3.1. OWNER AND OPERATOR

The former MTSAT Satellite Augmentation System (MSAS), now subsumed into the Quazi-Zenith Satellite System (QZSS), is owned and operated by Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and its Civil Aviation Bureau (JCAB) (European Space Agency, 2011). QZSS plays a crucial role in enhancing navigation capabilities, particularly for aviation purposes.

QZSS as one of its functions serves as a satellite-based augmentation system designed to improve the accuracy, integrity, and availability of GNSS signals (European Space Agency, 2011). The primary functions include:

- Augmentation Information: This pertains to L1 and L6 frequency signals, including DGNSS, Real-Time Kinematic (RTK) and Precise Point Positioning (PPP) methods, defined in RTCM STANDARD 10403.2 (Radio Technical Commission for Maritime (RTCM) Services, 2013).
- Air Traffic Management: The system is a key component of Japan's CNS/ATM (Communication, Navigation, Surveillance / Air Traffic Management) services, enhancing air traffic control capabilities in Japan and the Asia-Pacific region.
- Wide-Area Augmentation: QZSS transmits GPS-like signals, GPS health and integrity information, and ranging error corrections, making regional navigation more seamless, reliable, and accurate.
- Automatic Dependent Surveillance (ADS): The system enables aircraft to automatically report their current positions to Air Traffic Control Centres, improving overall air traffic management (eoPortal, 2012).

3.3.2. SYSTEM COMPONENTS AND OPERATION

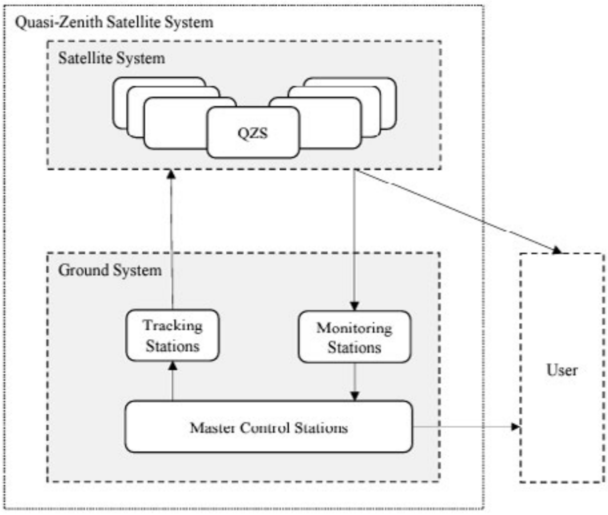

Figure 10: QZSS Overview (Quasi-Zenith Satellite System (QZSS), 2024)

QZSS consists of several key components (eoPortal, 2012):

- Space Segment: Initially, MSAS utilized MTSAT satellites. However, since April 2020, the SBAS signal is transmitted from the QZS-3 GEO satellite using the Quazi Zenith Satellite System (QZSS) SBAS transmission service (European Space Agency, 2011) (Quasi-Zenith Satellite System (QZSS), 2024)
  - The QZSS space segment consists of a unique constellation design (ESA, 2011):
  - Three satellites in Highly Elliptical Orbit (HEO) with perigee at about 32,000 km and apogee at about 40,000 km
  - One satellite in geostationary orbit (GEO)
  - QZSS's configuration ensures that at least one satellite is always visible near the zenith over Japan, with an elevation above 70° for more than 12 hours a day. The system is designed to have a 10-year operational lifespan for each satellite.
- Ground Segment: This includes Master Control Stations (MCS), Ground Monitor Stations (GMS), and Ground Earth Stations (GES) that monitor satellite signals, compute augmentation data, and generate correction messages (eoPortal, 2012).
- User Segment: Receivers equipped with SBAS capability that can receive and apply the augmentation signals to improve GPS positioning accuracy.

3.3.2.1. SUPPORTED FUNCTIONALITIES

- QZSS provides several key functionalities to enhance navigation (eoPortal, 2012):
- GPS/QZSS/Galileo Signal Enhancement[10]: QZSS improves user accuracy to sub-metre and to centimetre level in both horizontal and vertical dimensions.
- Wide-Area Augmentation: The system transmits:
  - GPS-like signals for ranging
  - GPS health and integrity information
- Differential Correction Function: Ranging error corrections
- Integrity Monitoring: provides real-time information on the condition of monitored constellations
- Automatic Dependent Surveillance (ADS): QZSS enables aircraft to automatically report their positions to Air Traffic Control Centres, enhancing air traffic management.
- Communication Services: The system facilitates voice and data communications between aircraft and control towers, as well as between aircraft.

3.3.3. SYSTEM ARCHITECTURE EVOLUTION

QZSS augmentation has undergone several phases of development (European Space Agency, 2011):

- MSAS V1 (2007-2020): Initial performance phase with MTSAT, 2 MCS, and 6 Ground Monitor Stations (GMS).
- MSAS (QZSS) V2 (2020-2023): System update phase with transition to QZS-3 GEO satellite, 2 MCS, 13 Ground Monitor Stations (GMS), and 3 Uplink Stations.
- MSAS (QZSS) V3 (2023-onwards): LPV (Localizer Performance with Vertical guidance) Performance Phase, aiming to achieve vertical guidance using two or more GEO satellites.

3.3.4. COVERAGE AREA

QZSS covers a large area in the Asia-Pacific region, primarily focusing on Japan and its surrounding areas. The system's coverage and services benefit several applications, with aviation being the primary beneficiary.

10 GLONASS CDMA Augmentation planned but not implemented (Quasi-Zenith Satellite System (QZSS), 2024)

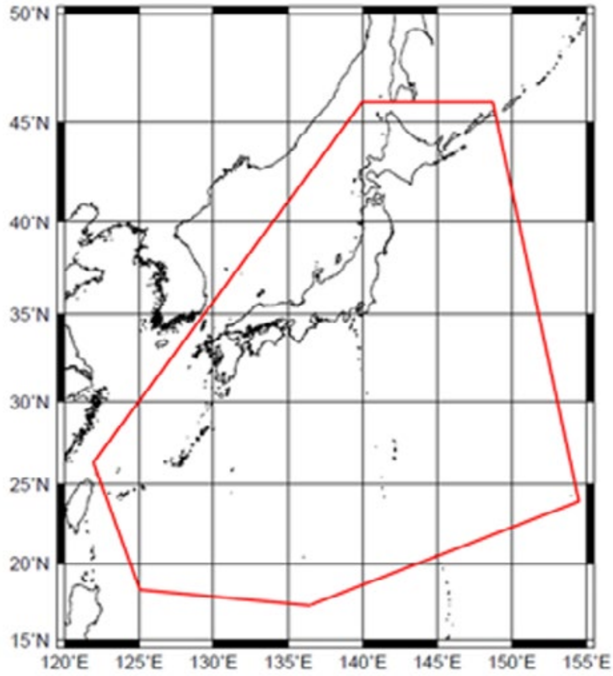

Figure 11: QZSS accuracy augmentation coverage (red line) map (Quasi-Zenith Satellite System (QZSS), 2024)

QZSS provides wide-area augmentation for signals across its coverage area at different levels of ionospheric corrections, by geography, as shown in Figure 12. The ionosphere parameter set for the Japan area is customised to provide more accurate ionosphere correction information around Japan.

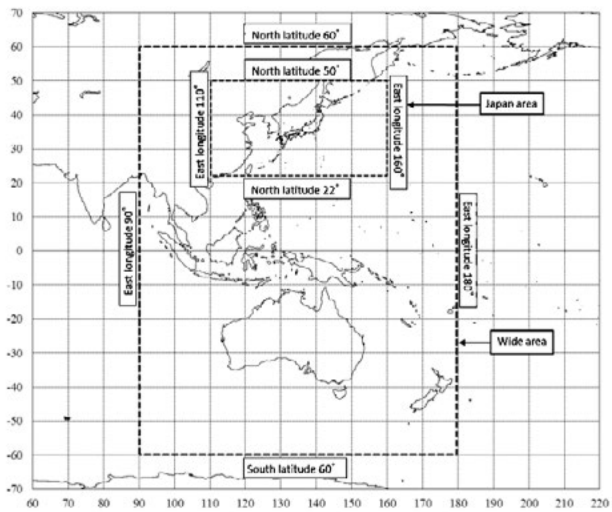

Figure 12: QZSS Target Areas of Ionospheric Parameters (Quasi-Zenith Satellite System (QZSS), 2024)

3.3.5. QZSS AUGMENTATION SERVICES

QZSS provides two main levels of service, the Sub-Metre Level Augmentation Service (SLAS) and the Centimetre Level Augmentation Service (CLAS).

3.3.5.1. SLAS

SLAS provides sub-meter level augmentation information through satellite signals at L1S. SLAS reflects a differential GNSS approach with all specifications published and open (Japan National Space Policy Secretariat, 2025), the coverage area for SLAS is shown in Figure 12, which is provided to show the difference relative to other services from QZSS.

There are two performance regions, Zone 1 and Zone 2, as shown in Figure 12, which have different specified performance levels. Other performance specifications are common between SLAS and the more accurate CLAS service.

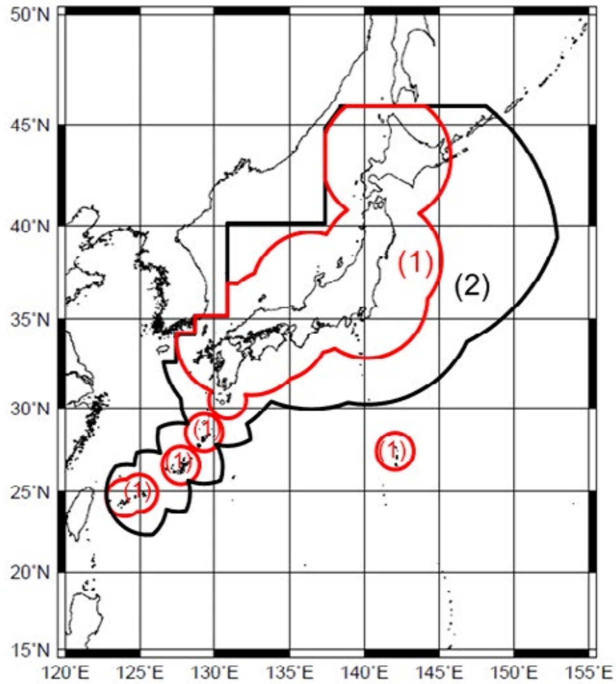

Figure 13: QZSS_SLAS Coverage Area showing zones (Quasi-Zenith Satellite System (QZSS), 2024)

3.3.5.2. CENTIMETER LEVEL AUGMENTATION SERVICE (CLAS)

The Centimeter Level Augmentation Service (CLAS) provides centimetre level augmentation information transmitted on the L6 band as separate signals to users. CLAS adopts RTK and PPP methods to provide its service and provides augmentation for GPS, Galileo and QZSS services across multiple frequencies. (L1, L2, l5, E1, E5)

The CLAS coverage area is much reduced compared to the SLAS, mainly due to the need for a network of ground stations to provide the fine correction information.

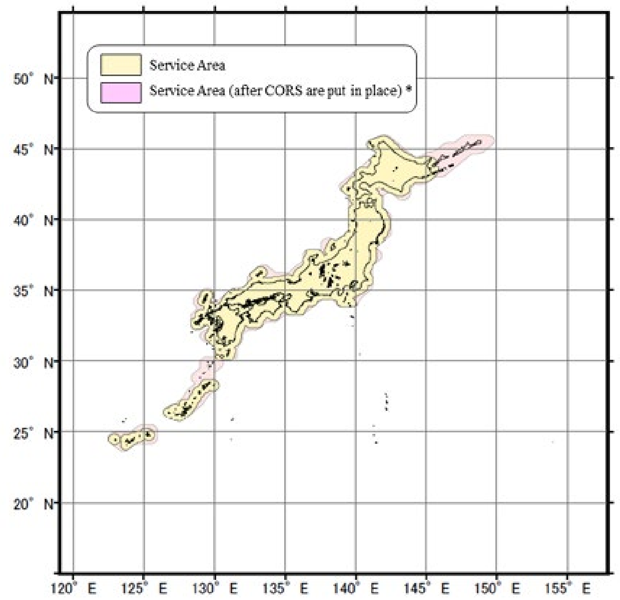

Figure 14: CLAS Service area (Quasi-Zenith Satellite System (QZSS), 2024)

The user estimation accuracies obtained from the CLAS are better than those specified for the SLAS.

3.3.6. MULTI-GNSS ADVANCED ORBIT AND CLOCK AUGMENTATION – PRECISE POINT POSITIONING (MADOCA-PPP)

MADOCA-PPP is a Precise Point Positioning (PPP) service provided by QZSS to provide correction information for PPP users via the L6 signal. To apply PPP methods, the globally applicable error corrections on satellite orbit, clock offset and code/phase biases are transmitted.

MADOCA-PPP augments the following signals:

- QZSS L1C/A, L1C/B, L1C, L2C, L5
- GPS L1C/A, L1P, L1C, L2C, L2P, L5
- GLONASS G1, G2
- Galileo E1, E5a

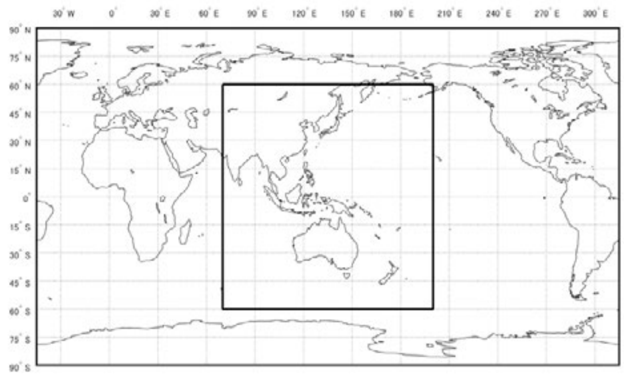

Figure 15: MADOCA-PPP Service area (inner square), from (Quasi-Zenith Satellite System (QZSS), 2024)

3.3.7. MADOCA-PPP COVERAGE

MADOCA-PPP is not used outside of Japan (for example in Australia, as shown below) for several reasons, despite its potential benefits:

- Geographical Focus: QZSS is primarily designed to serve Japan and the Asia-Pacific region, with its satellite orbits optimised for high elevation angles over Japan to improve GNSS signal availability in urban canyons and mountainous areas. Although the service extends to parts of Australia, the primary focus and infrastructure support are centered in Japan, which limits its adoption elsewhere.
- Infrastructure and Compatibility:
  - Receiver Compatibility: The use of QZSS PPP requires GNSS receivers that can decode the L6 signal used by MADOCA-PPP. Not all GNSS receivers in Australia are equipped to handle this signal, limiting the practical application of this service.
  - Infrastructure: The transmission of augmentation data for PPP via QZSS involves a network of monitoring stations. While there are international collaborations, the infrastructure for real-time data collection is not optimised for Australian conditions compared to Japan or other parts of Asia.
- Alternative Systems:
  - SouthPAN: Australia has been developing its own high-precision positioning infrastructure through the Southern Positioning Augmentation Network (SouthPAN), see Section 4.2 of this report.
- Local Trials and Adoption: Although there have been trials and demonstrations in Australia showing the capabilities of QZSS (Spatial Source, 2015), such as precision agriculture applications in New South Wales, these have not led to widespread adoption.
- Strategic imperative: The country's focus on developing indigenous solutions like SouthPAN reflects a strategic choice to tailor services to local needs and conditions.

3.3.8. KEY PERFORMANCE METRICS

The MTSAT Satellite Augmentation System (MSAS) is designed to enhance GPS performance, and its key performance metrics include accuracy, availability, and integrity. These metrics have improved over time, with the system evolving through different versions.

Country	Japan	Japan
Name of SBAS Service	Sub-Meter Level Augmentation Service	Centimeter Level Augmentation Service
Horizontal Accuracy (95%)	Zone 1 - ≤ 1.0 m (95%) (0.58 (RMS)); Zone 2 - ≤ 2.0 m (95%) (1.16 (RMS))	Static - <6 cm (95%) (3.47 (RMS)); Kinematic - ≤ 12 cm (95%) (6.94 (RMS))
Vertical Accuracy (95%)	Zone 1 - ≤ 2.0 m (95%) (1.02 (RMS)); Zone 2 - ≤ 3.0 m (95%) (1.53 (RMS))	Static - <12 cm (95%) (6.13 (RMS)); Kinematic - < 24 cm (95%) (12.25 (RMS))
Availability	Constellation ≥ 99.9%	Constellation ≥ 99.9%
Continuity	<1 - 2 x 10^-4 / hour	<1 - 2 x 10^-4 / hour
Integrity	<1 10^-5 / hour	<1 x 10^-5 / hour
Time to Alert	10 seconds	10 seconds

Figure 16: QZSS Satellite Augmentation Performance (Japan Cabinet Office, 2022)

3.3.8.1. ACCURACY

QZSS services provide accuracy improvements as per Figure 16 of down to <6cm when static and using the CLAS service. These have been demonstrated, as detailed in the QZSS CLAS Status and Progress document (Misubishi Electric Corporation, 2023).

3.3.8.2. AVAILABILITY

- Required Availability: The system is designed to maintain an availability of more than 99.9%.
- Observed Availability: In 2024, QZSS achieved an observed availability of 99.999% (Japan Cabinet Office Space Policy).

3.3.8.3. INTEGRITY

Integrity is a critical performance metric, especially for safety-of-life applications like aviation (Navipedia, 2011):

- Integrity Requirement: The probability of Hazardously Misleading Information (HMI) should be less than $1x10^{-7}$ per hour.

QZSS employs various techniques to ensure integrity (Springer Open, 2022):

- Real-time Monitoring: The system provides real-time information on the condition of the GPS constellation.
- User Differential Range Error (UDRE): MSAS determines and broadcasts UDRE to indicate the confidence level of differential corrections for each monitored satellite.
- Clock-Ephemeris Covariance: This information is used to deduce integrity probability, enhancing the system's reliability.

3.3.9. KEY DOCUMENTS

QZSS augmentation services adhere to several key documents and standards that govern its operation and performance. MSAS complies with the International Civil Aviation Organisation (ICAO) Standards and Recommended Practices (SARPs) for Satellite-Based Augmentation Systems (SBAS). These standards are outlined in:

- ICAO Annex 10 to the Convention on International Civil Aviation, Volume I (Radio Navigation Aids): This document specifies the required performance metrics for SBAS, including accuracy, availability, and integrity requirements (Japan Civil Aviation Bureau, 2007).

3.3.9.1. RTCA STANDARDS

QZSS also follows standards set by the Radio Technical Commission for Aeronautics (RTCA): RTCA DO-229 (Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment) (GlobalSpec, 2020).

This standard defines the minimum performance requirements for GPS/WAAS equipment, which are also applicable to QZSS as an SBAS system.

3.3.9.2. QZSS INTERFACE SPECIFICATION DOCUMENTS

The following documents detail the performance and interface specifications for QZSS and the augmentation services:

- PS-QZSS (Performance Specification for QZSS) (Quasi-Zenith Satellite System (QZSS), 2024)
- IS-QZSS (Interface Specification for QZSS) (Quasi-Zenith Satellite System (QZSS), 2024)

3.4. KOREA AUGMENTATION SATELLITE SYSTEM (KASS)

3.4.1. OWNERSHIP AND OPERATION

The Korea Augmentation Satellite System (KASS) is owned and operated by the Korean government, specifically under the management of the Korea Aerospace Research Institute (KARI) on behalf of the Korean Ministry of Land, Infrastructure and Transport (MOLIT) (Inside GNSS, 2024). KASS plays a crucial role in enhancing satellite navigation capabilities in South Korea.

3.4.2. KASS OVERVIEW AND DEVELOPMENT

KASS is South Korea's Satellite-Based Augmentation System (SBAS), designed to improve the accuracy and reliability of Global Navigation Satellite System (GNSS) signals, particularly GPS (Inside GNSS, 2024).

The system was developed through a collaboration between KARI and Thales Alenia Space, with the latter serving as the prime contractor (Thales Alenia Space, 2024). The project received support from various international entities, including the European Commission, the European Union Agency for the Space Programme (EUSPA), the European Space Agency (ESA), the European Aviation Safety Agency (EASA), and the French Space Agency (CNES or Centre National d'études Spatiales).

KASS serves several functions (Inside GNSS, 2024):

- Enhanced Accuracy: KASS significantly improves GPS positioning accuracy from 15-33 meters to approximately 1 metre (Sung-Hyun, Yong-Hui, Jin-Ho, & Jin-Mo, 2023).
- Aviation Safety: The system prioritizes aircraft applications, focusing on Safety of Life services during critical flight phases, including landing.
- Wide-ranging Applications: While initially focused on aviation, KASS is designed to benefit various sectors, including:
  - Public safety
  - Road transport
  - Shipping
  - Scientific applications (GNSS Asia, 2020)
- Augmentation Signal: KASS broadcasts an augmentation signal that provides corrections for GPS satellite orbits, clocks, and ionosphere delays, along with integrity bounds for these corrections (Inside GNSS, 2024).
- Interoperability: The system is engineered to be interoperable with other SBAS navigation systems worldwide, ensuring seamless flight safety across different zones.

3.4.3. SYSTEM ARCHITECTURE AND PERFORMANCE

KASS comprises several key components:

- 7 Reference Stations (KRS) across South Korea
- 2 Processing Stations (KPS)
- 2 Control Stations (KCS)
- Uplink Stations (KUS)
- Geostationary satellites for signal broadcast (Institute of Navigation, 2022)

Figure 17: KASS Architecture Overview (Inside GNSS, 2024)

The system is designed to provide four safety-critical service levels: En-Route, Terminal, Non-Precision Approach (NPA), and Approach Procedure with Vertical Guidance (APV-I).

KASS entered operational service at the end of 2023, initially using the MEASAT-3d geostationary satellite. It will soon be enhanced by the addition of KOREASAT 6A, which was successfully launched in November 2024 (Satellite Evolution Group, 2024).

By providing more accurate and reliable positioning information, KASS enables South Korea to reduce dependence on ground-based navigation facilities and develop advanced applications for various transportation and location-based services.

3.4.4. GENERAL OPERATION

The Korea Augmentation Satellite System is a satellite-based augmentation system designed to enhance the accuracy and reliability of GPS signals over South Korea.

KASS operates through a network of ground-based and space-based components (Inside GNSS, 2023; GPS World, 2024):

- Data Collection: KASS collects GPS data from 7 reference stations (KRS) strategically located across South Korea (Inside GNSS, 2023).
- Data Processing: The collected data is transmitted to 2 processing stations (KPS) where it undergoes analysis and correction.
- Message Generation: The processing stations compute corrections for GPS satellite orbits, clocks, and ionospheric delays. They also generate integrity bounds for these corrections.

- Uplink and Broadcast: The corrected data and integrity information are formatted into SBAS messages and uplinked to geostationary satellites via uplink stations (KUS).
- Signal Transmission: The geostationary satellites broadcast the augmentation signal over the Korean service area.
- User Reception: SBAS-enabled receivers in aircraft, vehicles, or other applications receive both the GPS signals and the KASS augmentation signal, allowing for improved positioning accuracy.

3.4.5. SUPPORTED FUNCTIONALITIES

KASS supports several key functionalities (Inside GNSS, 2024; Thales Alenia Space, 2024; GPS World, 2024):

- Enhanced Accuracy: KASS improves GPS positioning accuracy from 15-33 meters to approximately 1m (Sung-Hyun, Yong-Hui, Jin-Ho, & Jin-Mo, 2023) throughout South Korea.
- Safety-Critical Services: The system provides four safety-critical service levels for aviation.
- En-Route Navigation: This applies over the Incheon Flight Information Region (FIR).
- Terminal Navigation: for descent from cruise to initial approach.
- Non-Precision Approach (NPA).
- Approach Procedure with Vertical Guidance (APV-I): This applies over South Korean land masses, including Jeju Island.
- Integrity Monitoring: KASS continuously monitors the integrity of GPS signals and provides timely warnings if the system detects any anomalies.
- Interoperability: The system is designed to be interoperable with other SBAS worldwide, ensuring seamless navigation across different zones.
- Multi-Constellation Support: While initially focused on GPS, KASS can also enhance positioning when using Galileo and Beidou constellations (Sung-Hyun, Yong-Hui, Jin-Ho, & Jin-Mo, 2023).
- Wide-ranging Applications: Although primarily designed for aviation, KASS supports various other applications, including:
  - Public safety
  - Road transport
  - Maritime navigation
  - Scientific research

3.4.6. COVERAGE AREA

The Korea Augmentation Satellite System primarily covers the Korean peninsula and its surrounding airspace, providing enhanced satellite navigation services across this region. The system's coverage extends to several key areas and applications:

- The entire Korean peninsula, including South Korea and its territorial waters
- Jeju Island
- The Incheon Flight Information Region (FIR)

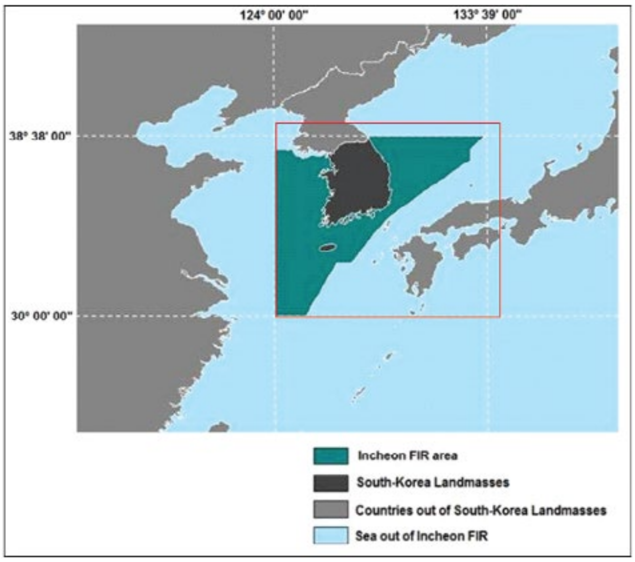

Figure 18: KASS Service Area Overview (Inside GNSS, 2024)

3.4.7. KASS SERVICES

The Korea Augmentation Satellite System (KASS) provides several key services to enhance satellite navigation capabilities in South Korea.

3.4.7.1. OPEN SERVICE (OS)

While primarily focused on aviation, KASS also provides an Open Service (Inside GNSS, 2024) for other applications:

- Available over the Incheon Flight Information Region (FIR).
- Usable by various forms of transportation and other position, navigation, and timing (PNT) applications. (Inside GNSS, 2023).
- Supports potential future applications in public safety, road transport, shipping, and scientific research. (Inside GNSS, 2024).
- Provides improved accuracy and reliability for general GNSS users without the stringent integrity requirements of aviation.

3.4.7.2. SAFETY-OF-LIFE (SOL) SERVICE

- The Safety-of-Life service is KASS's primary offering, designed to support critical aviation applications:
- Enhances flight safety during all phases, with a particular focus on approach and landing procedures.
- Improves GPS positioning accuracy from 15-33 meters to approximately 1 meter (Sung-Hyun, Yong-Hui, Jin-Ho, & Jin-Mo, 2023) (GPS World, 2024).
- Provides timely integrity information, alerting users within seconds if positioning data is incorrect (Sysgo, 2021).
- Supports various aviation operations, including en-route navigation, terminal navigation, non-precision approach (NPA), and approach procedures with vertical guidance (APV-I) (Inside GNSS, 2023).
- Offers a cost-effective alternative to instrument landing systems (ILS) for airports (Sysgo, 2024).

3.4.8. KEY PERFORMANCE METRICS

The Korea Augmentation Satellite System is evaluated based on five key performance criteria: accuracy, integrity, continuity, availability, and time-to-alert (TTA).

Country	South Korea
Name of SBAS Service	Korea Augmentation Satellite System (KASS)
Horizontal Accuracy (95%)	1.3 m (API-V), 21.04 m (NPA)
Vertical Accuracy (95%)	<2.6 m (APV-I)
Availability	99.87% (APV-I & NPA)
Continuity	6 x 10^-4 / 15s (APV-I), 0 / hour (NPA)
Integrity	2 x 10^-7 / approach (APV-I), 1 x 10 ^-7 / hour (NPA)
Time to Alert	10s (APV-I & NPA)

Figure 19: KASS Performance Metrics (Inside GNSS, 2024):

3.4.8.1. ACCURACY

KASS substantially enhances GPS positioning precision (Inside GNSS, 2024):

- KASS reduces GPS positioning inaccuracies from 15-33 meters to about 1m (Sung-Hyun, Yong-Hui, Jin-Ho, & Jin-Mo, 2023) (APV) throughout Korea. This significant improvement showcases the system's effectiveness in refining GPS performance (Inside GNSS, 2024).
- For Approach Procedure with Vertical Guidance (APV-I) service, KASS delivers:
  - Horizontal accuracy: 1.3 meters at 95% confidence level.
  - Vertical accuracy: 2.6 meters at 95% confidence level

3.4.8.2. AVAILABILITY

KASS availability performance (Inside GNSS, 2024) for both APV and NPA has been shown to be 99.87%.

3.4.8.3. ADDITIONAL PERFORMANCE METRICS

- Continuity: Fully ensured for APV-I service over South Korea's landmasses, including Jeju Island. NPA/Terminal/En-route services continuity is fully ensured over the complete Incheon Flight Information Region (FIR) (HAL Open Science, 2017).
- Time Synchronization: KASS network time synchronization with GPS system time is maintained within 5 nanoseconds, well within the specified maximum of 50 nanoseconds (Inside GNSS, 2024).

3.4.9. KEY DOCUMENTS

The Korea Augmentation Satellite System (KASS) adheres to several key documents and standards to ensure its compliance with international regulations and interoperability with other satellite-based augmentation systems. Below are the most important standards and documents for KASS.

3.4.9.1. INTERNATIONAL CIVIL AVIATION ORGANISATION (ICAO) STANDARDS

- ICAO SARPs Annex 10: This is the primary standard that KASS complies with, ensuring that its augmentation signal meets international requirements for civil aviation (Institute of Navigation, 2022; GPS World, 2024).
- ICAO Standards and Recommended Practices (SARPs): KASS follows these guidelines to provide safety-critical services for civil aviation (ICAO, 2019).

3.4.9.2. RTCA STANDARDS

RTCA MOPS 229-D Change 1: This standard is used for formatting KASS messages, ensuring compatibility with other SBAS and user equipment (Institute of Navigation, 2022).

3.4.9.3. KOREAN GOVERNMENT DOCUMENTS

The Korean Government's Mid- to Long-term Plan for Space Development includes the development of precision navigation as part of Korea's broader space development strategy (Korean National Space Committee, 2025).

3.5. SYSTEM FOR DIFFERENTIAL CORRECTIONS AND MONITORING (SDCM)

3.5.1. OWNERSHIP AND OPERATION

The System for Differential Corrections and Monitoring (SDCM) is owned and operated by Russia's Roscosmos space agency. As a satellite-based navigation augmentation system, SDCM plays a crucial role in enhancing the precision of the GLONASS satellite navigation system (Navipedia, 2011).

3.5.2. PURPOSE AND FUNCTIONALITY

SDCM serves as a component of GLONASS, with its primary function being to augment and improve the accuracy of satellite navigation in Russia. Its key features include (Navipedia, 2011):

- Coverage: The service area of SDCM covers the entire Russian Federation.
- Transmission Method: SDCM utilizes the Luch Multifunctional Space Relay System, which consists of geostationary communication satellites, to transmit correction and integrity data.
- Dual-System Monitoring: Unlike other SBAS, SDCM is designed to perform integrity monitoring for both GPS and GLONASS satellites.

3.5.3. CURRENT STATUS AND FUTURE PLANS

While SDCM is considered pre-operational, it was not yet fully certified for use in public aviation as of 2024 (ROSCOSMOS Space Corporation). The system's ongoing development includes plans for:

- Seamless SBAS L1 coverage across Russian territory
- Dual coverage of central Russia by 2018. Recent information and search results indicate that the system was under development and had not yet achieved full operational status, although it has reached pre-operational status and has successfully passed the preliminary certification tests, in accordance with the requirements for typical approach operations with vertical guidance (APV-I and APV-II) (ROSCOSMOS Space Corporation).
- Implementation of precise positioning services using SBAS L1/L5 and L1/L3 in the GLONASS band (ROSCOSMOS Space Corporation)
- Certification for LPV-200 requirements
- Potential use as a foundation for future precise point positioning services (ROSCOSMOS Space Corporation)

3.5.4. GENERAL OPERATION

The System for Differential Corrections and Monitoring (SDCM) is a satellite-based augmentation system developed by Russia to enhance the accuracy and reliability of GLONASS and GPS positioning.

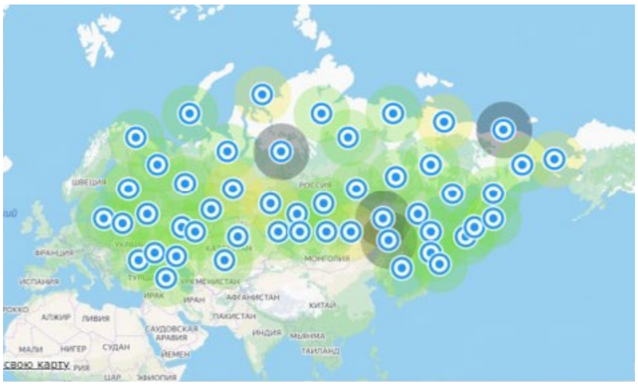

Figure 20: Current SDCM Station Network (Navipedia, 2011)

Below is an overview of how SDCM works and its key functionalities.

3.5.4.1. GROUND SEGMENT

SDCM's ground segment consists of several components (Navipedia, 2011):

- Reference Station Network: A network of 19 stations in Russia and 5 stations abroad, with plans to expand to 45 stations in Russia and 12 abroad.
- Central Processing Facilities: Located in Moscow with a reserve facility, these process the data from reference stations.
- Uplink Stations: Used to transmit correction data to geostationary satellites.
- Laser Ranging Stations: SDCM also uses laser ranging stations to accurately position the spacecraft in orbit (ROSCOSMOS State Space Corporation, 2019).

3.5.4.2. SPACE SEGMENT

SDCM utilizes the Luch Multifunctional Space Relay System, which includes geostationary communication satellites (Navipedia, 2011):

- Currently active satellites: Luch-5B (16° West) and Luch-5V (95° East).
- Plans include additional satellites to provide broader coverage.

The operational process for SDCM is (Navipedia, 2011):

- Data Collection: Reference stations collect raw measurements from GLONASS and GPS satellites, including L1 and L2 pseudorange and carrier-phase measurements.
- Data Processing: The central processing facility calculates precise satellite ephemerides and clocks, performs integrity monitoring, and generates SBAS messages.
- Data Transmission: Correction and integrity data are transmitted via the Luch satellites in the L1 bandwidth, following international standards (SARPs ICAO and MOPS RTCA-229).
- User Reception: GNSS receivers compatible with SDCM can use this data to improve positioning accuracy. (MDPI, 2022)

3.5.4.3. KEY FUNCTIONALITIES

Russia's SDCM enhances GNSS performance nationwide by providing these key functionalities (Navipedia, 2011):

-]Dual-System Monitoring: SDCM is designed to perform integrity monitoring for both GPS and GLONASS satellites, setting it apart from other SBAS.
- Wide Area Coverage: The service area covers the entire Russian Federation.
- Improved Positioning Accuracy: SDCM aims to provide horizontal positioning accuracy of 1 to 1.5 meters and vertical accuracy of 2 to 3 meters.
- Multiple Distribution Channels: In addition to satellite broadcast, SDCM plans to provide internet and GSM broadcast through SISNeT and NTRIP servers.
- Precise Point Positioning (PPP) Support: SDCM is designed to support future PPP services, potentially offering centimetre-level accuracy within 200 km of reference stations.
- Aviation Support: While not yet certified for public aviation use as of 2021, SDCM aims to meet LPV-200 requirements in the future.

3.5.5. AREA OF COVERAGE

The System for Differential Corrections and Monitoring (SDCM) primarily covers the Russian Federation (Navipedia, 2011).

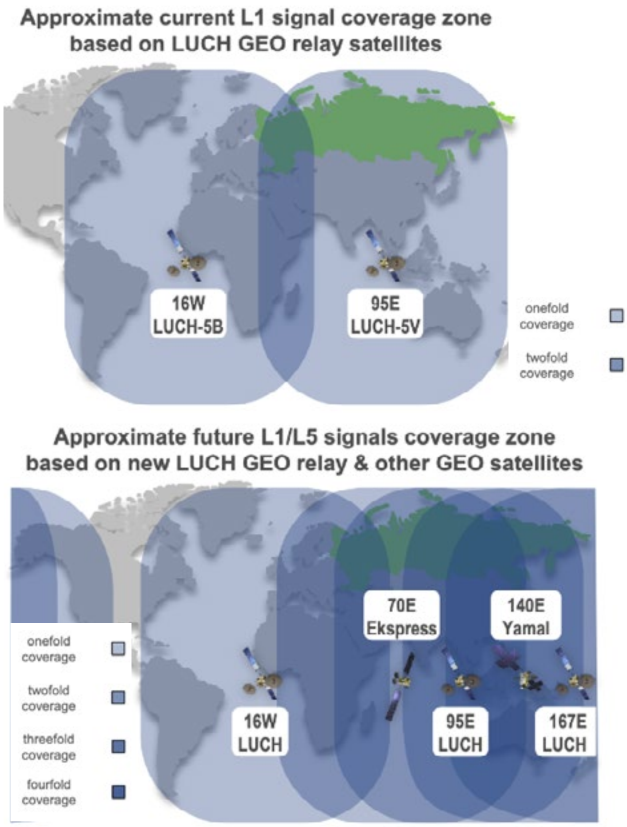

Figure 21: SDCM Current and planned coverage area (ROSCOSMOS Space Corporation)

3.5.6. SDCM SERVICES

The System for Differential Corrections and Monitoring (SDCM) provides several services to enhance GNSS positioning accuracy and reliability across the Russian Federation. While specific information about SDCM's services is limited, we can infer its offerings based on its objectives and similarities to other SBAS:

3.5.6.1. OPEN SERVICE (OS)

SDCM offers a standards compliant Open Service that provides enhanced positioning accuracy for general-purpose applications. This service is freely available to users with SDCM-compatible receivers within the coverage area. The positioning performance provided by SDCM is stated as (European GNSS Agency, 2020):

- Horizontal accuracy: 0.5 meters
- Vertical accuracy: 0.8 meters

3.5.6.2. SAFETY-OF-LIFE (SOL) SERVICE

While not explicitly mentioned for SDCM, the system is working towards certification for safety-critical applications (Navipedia, 2011):

- SDCM aims for certification to meet LPV-200 requirements.
- As of 2024, it had not yet been fully certified for use in public aviation (preliminary certification achieved (ROSCOSMOS Space Corporation)).

The SoL service, once certified, would likely provide performance like other SBAS for safety-critical applications, particularly in aviation.

3.5.6.3. SDCM DATA ACCESS SERVICE

SDCM reports to offer additional data distribution channels such as (European Union Agency for the Space Programme, 2025; Navipedia, 2011):

- Internet and GSM broadcast from SISNeT and NTRIP servers
- This service would be like the EGNOS Data Access Service (EDAS), providing ground-based access to SDCM data in real-time and potentially as a historical archive.

3.5.7. KEY PERFORMANCE METRICS

- Performance metrics for SDCM are given in Figure 22

Country	Russia
Name of SBAS Service	System for Differential Corrections and Monitoring (SDCM)
Horizontal Accuracy (95%)	0.5 m
Vertical Accuracy (95%)	0.8 m
Availability	>99% with coverage of Russian Federation + CIS countries
Continuity	1 - 8 x 10 ^-6/ 15s (APV-I & APV-II)
Integrity	1 - 2 x 10^-7 / approach (APV-I & APV-II)
Time to Alert	6 seconds (APV-II)

Figure 22: SDCM Performance metrics (Navipedia, 2011)

3.5.7.1. ACCURACY

SDCM's stated positioning accuracy is (European GNSS Agency, 2020):

- Horizontal accuracy: 0.5 meters
- Vertical accuracy: 0.8 meters

For users within 200 kilometers of reference stations, SDCM is expected to offer centimeter-level positioning service.

3.5.7.2. AVAILABILITY

While specific availability figures are not included, SDCM has pre-certified to ICAO performance parameters so these can be inferred to be achieved by the system (Navipedia, 2011) at >99% over the coverage area.

3.5.7.3. INTEGRITY

SDCM places a strong emphasis on integrity monitoring (Navipedia, 2011) and given ICAO pre-certification, this can infer at least $1.2x10^{-7}$ for approach operations.

3.5.8. KEY DOCUMENTS

3.5.8.1. GLONASS OPEN SERVICE PERFORMANCE STANDARD (OS PS)

This document is crucial for SDCM as it serves as a basis for certification of GLONASS services and GLONASS-based systems, including SDCM. Key features include:

- Latest version: Edition 2.2, June 2020
- Developed by the Information and Analysis Center for Positioning, Navigation and Timing
- Approved by the Russian Defense Ministry and Roscosmos State Corporation
- Specifies standards for GLONASS OS Signal-in-Space (SIS) performance
- Provides an overview of the GLONASS System and OS SIS (GLONASS, 2020).

3.5.8.2. INTERNATIONAL STANDARDS

SDCM adheres to international SBAS standards, including (Navipedia, 2011):

- ICAO Standards and Recommended Practices (SARPs)
- RTCA Minimum Operational Performance Standards (MOPS)

Specifically, SDCM data distribution is performed via L1-bandwidth, according to SARPs ICAO requirements and MOPS RTCA-229.

3.5.8.3. GLONASS INTERFACE CONTROL DOCUMENTS (ICDs)

These documents define parameters for the interface between GLONASS system satellites and user equipment, which are relevant to SDCM's operation. They are available on the GLONASS Information and Analysis Center website (GLONASS, 2023).

3.5.8.4. GOST 32454–2013

This intergovernmental standard, titled "Global Navigation Satellite System. Parameters of the Radionavigation Field. Technical Requirements and Testing Techniques," forms the basis for the GLONASS OS PS (GLONASS, 2020).

3.6. GPS AIDED GEO AUGMENTED NAVIGATION (GAGAN)

3.6.1. OWNERSHIP AND OPERATION

GPS Aided GEO Augmented Navigation (GAGAN) is jointly owned and operated by the Indian Space Research Organisation (ISRO) and the Airports Authority of India (AAI) (IASBABA, 2022; WION, 2022). This collaborative effort has resulted in India's first satellite-based navigation system, designed to enhance the accuracy and reliability of GPS signals over the Indian Flight Information Region (FIR) (TestBook, 2023).

GAGAN plays a crucial role in improving navigation services across various sectors but is focused on Air Traffic Management, which is enhanced by providing more precise aircraft positioning, enabling landings at regional airports with limited infrastructure (WION, 2022) and reducing dependency on high visibility requirements for landing (CNBC TV18, April).

Beyond aviation, GAGAN's navigation capabilities extend to:

- Wildlife resource management and forest monitoring
- Railway signalling and track alignment
- Road traffic management and asset monitoring
- Maritime emergency communication for fishermen (Indian Space Research Organisation, 2023)

3.6.2. GENERAL OPERATION

GAGAN functions as an SBAS that augments GPS signals to improve their accuracy and reliability (IASBABA, 2022).

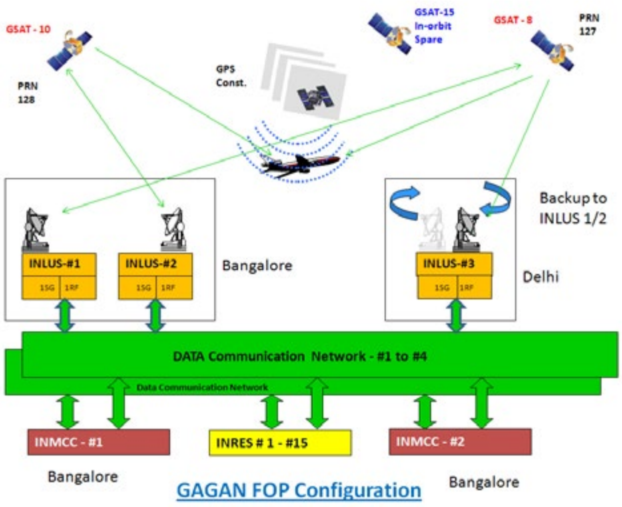

Figure 23: GAGAN System Overview (U R Rao Satellite Centre (URSC), 2016)

The system consists of:

- Ground Segment
  - 15 Indian Reference Stations (INRES) strategically located across India (Inside GNSS, 2016)
  - A Master Control Centre (INMCC) for data processing and error correction (WION, 2022)
  - Indian Land Uplink Stations (INLUS) (Aim-India)
- Space Segment
  - Three geostationary satellites: GSAT-8, GSAT-10, and GSAT-15 (WION, 2022)
- Functionality
  - Ground stations (INRES) receive GPS signals and detect errors by comparing them to known reference locations.
  - The Master Control Centre (INMCC) analyses and processes this data and generates correction messages relative to the known reference locations.
  - Corrected signals are transmitted to the geostationary satellites via the INLUS.
  - Satellites broadcast the enhanced navigation signals back to Earth (WION, 2022).
  - SBAS-enabled GPS receivers can use these corrected signals for improved positioning accuracy (Byjus, 2022).

3.6.3. COVERAGE AREA

GPS Aided GEO Augmented Navigation (GAGAN) provides coverage and services across a wide area, benefiting various applications. It extends well beyond the Indian subcontinent.

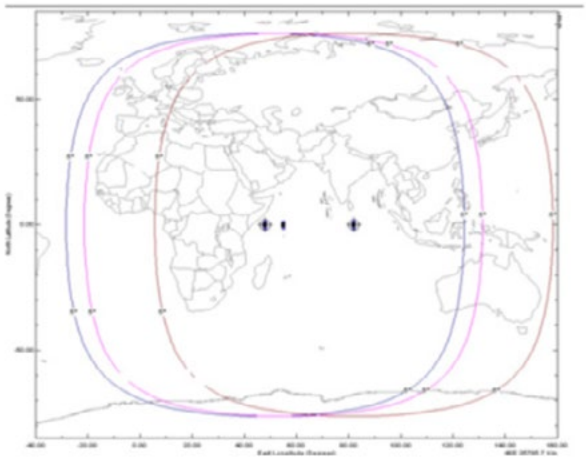

Figure 24: GAGAN Coverage Area (with the Indian Geostationary Satellites) (Airports Authority of India, 2025)

Coverage and key applications:

- The GAGAN GEO footprint spans from Africa to Australia (Byjus, 2022; Vajiram & Ravi, 2024).
- It covers the entire Indian Flight Information Region (FIR) (Airports Authority of India, 2019).
- The system has the capability to support up to 45 reference stations, enabling potential expansion of services (Byjus, 2022).

3.6.4. GAGAN SERVICES

GAGAN (GPS Aided GEO Augmented Navigation) provides several services to enhance GPS accuracy and reliability over the Indian region.

3.6.4.1. OPEN SERVICE (OS)

GAGAN OS operates on an open service transmission mode that complies with RTCA specifications and ICAO SARPs. It broadcasts on the L1 frequency (1575.42 MHz) compatible with GPS, and there are plans for capabilities for L5 (1176.45 MHz) to support future dual-frequency use (GeoAwesome, 2014).

Message Format: The SBAS message format used by GAGAN is like other SBAS such as WAAS, EGNOS, and MSAS, ensuring interoperability. The data includes corrections for satellite ephemeris, clock errors, ionospheric delays, and integrity information.

Service Level:

Accuracy: GAGAN OS will offer improvements over standard GPS but due to the geographical position of India, the reliability due to ionospheric scintillation of the service can be variable (Nepal Astronomical Society (NASO), 2023).

3.6.4.2. SAFETY-OF-LIFE (SOL) SERVICE

GAGAN's primary focus is on providing Safety-of-Life services, particularly for civil aviation (GeoAwesome, 2014; MyCoordinates, 2016):

- Certified for Approach with Vertical Guidance (APV-1.0/1.5) over Indian landmass.
- Supports Non-Precision Approach (NPA) services with RNP-0.1 over Indian Flight Information Region (Airports Authority of India, 2019).
- Enhances safety for aircraft navigation, including approach and landing procedures.
- Improves accuracy, integrity, availability, and continuity of GPS signals.

3.6.4.3. GAGAN DATA ACCESS SERVICE

GAGAN offers a unique service called GAGAN Message Service (GAMES) (MyCoordinates, 2016):

- Utilizes spare data transmission capacity (about 35%) to broadcast alert messages
- Provides early warnings or alert messages for disasters, cyclones, landslides, wildfires, etc.
- Offers free-to-air service accessible to users with GAGAN receivers (with minor software modifications)
- Ensures service availability in all weather conditions

Additionally, GAGAN supports various applications beyond aviation, including:

- Environmental monitoring and wildlife resource management
- Surveying and mapping
- Space weather studies
- Emergency services and disaster management

GAGAN's services are designed to be interoperable with other international SBAS like US-WAAS, European EGNOS, and Japanese QZSS, providing seamless navigation services across regional boundaries.

3.6.5. KEY PERFORMANCE METRICS

GAGAN (GPS Aided GEO Augmented Navigation) is evaluated based on several key performance metrics that are crucial for its operation, particularly in aviation applications.

The system's performance is continuously monitored and validated to ensure that it meets the required standards. Below is an overview of GAGAN's key performance metrics:

Country	India
Name of SBAS Service	GPS-Aided GEO Augmented Navigation (GAGAG)
Horizontal Accuracy (95%)	<7.6 m
Vertical Accuracy (95%)	<7.6 m
Availability	≥99% (APV-I)
Continuity	1 - 8 x 10 ^-6 / 15s (APV-I)
Integrity	1 - 2 x 10^-7 / approach (APV-I)
Time to Alert	6 seconds

Figure 25: GAGAN Performance metrics (Navipedia, 2011)

3.6.5.1. ACCURACY

GAGAN significantly enhances the accuracy of GPS signals (Inside GNSS, 2016) (Airports Authority of India, 2019):

- Position accuracy is improved from 20-30 meters to within 1-1.5 meters
- For aviation applications, GAGAN demonstrates high accuracy:
  - Horizontal accuracy: Less than 7.6 meters, 100% of the time
  - Vertical accuracy: Less than 7.6 meters, 100% of the time
- For APV-1 (Approach with Vertical Guidance) service:
  - Horizontal Accuracy: 7.6m, 95% of the time
  - Vertical Accuracy: 7.6m, 95% of the time

3.6.5.2. AVAILABILITY

Availability is a critical metric for GAGAN's operational reliability (Airports Authority of India, 2019):

- The system aims for greater than 99% availability for both APV-1 and RNP 0.1 services
- Current service availability is limited due to:
  - Ionospheric grid points only covering the Indian Region
  - Service degradation at the edge of INRES station coverage
  - The central latitude location of India and the impact of scintillation on the ionosphere
- GAGAN has the potential to support up to 45 Indian Reference Stations (INRES), though only 15 were being used

3.6.5.3. INTEGRITY

Integrity ensures the trustworthiness of the navigation information:

GAGAN maintains an integrity level of $1\text{-}10^{-7}$ per approach for both APV-1 and RNP 0.1 services (Airports Authority of India, 2019).

The system employs various tools to continuously validate integrity:

- Service Monitoring Sub System (SMSS)
- Software tools delivered by the System Integrator
- Operational Test & Evaluation (OT&E) tools developed by AAI
- Time-to-Alert:
  - For APV-1: 6.2 seconds
  - For RNP 0.1: 10 seconds

3.6.5.4. ADDITIONAL PERFORMANCE METRICS

- Continuity:
  - For APV-1: $1\text{-}8\times10^{-6}$ over 15 seconds
  - For RNP 0.1: $1\text{-}10^{-4}$ per hour

3.6.5.5. PERFORMANCE CHALLENGES

GAGAN faces some unique challenges due to its geographical location; the impact of ionospheric events is larger for GAGAN compared to established systems like WAAS and EGNOS (MyCoordinates, 2016).

The system employs the ISRO GIVE Model – Multi Layer Data Fusion (IGM-MLDF) to cope with ionospheric perturbations at the equatorial level (Navipedia, 2011).

While GAGAN demonstrates strong performance in many areas, achieving 99.99% availability for APV-1 remains a challenge, and APV-II capabilities are beyond reach (MyCoordinates, 2016). Ongoing efforts focus on improving these metrics to enhance GAGAN's overall performance and reliability (Navipedia, 2011).

3.6.6. KEY DOCUMENTS

GPS Aided GEO Augmented Navigation adheres to several key documents and standards to ensure its compliance with international regulations and interoperability with other SBAS. The following are the important documents and standards for GAGAN:

3.6.6.1. INTERNATIONAL CIVIL AVIATION ORGANISATION (ICAO) STANDARDS

GAGAN follows the ICAO Standards and Recommended Practices established by the Global Navigation Satellite System (GNSS) Panel (Inside GNSS, 2016). These standards ensure that GAGAN provides a civil aeronautical navigation signal consistent with international requirements.

3.6.6.2. DGCA CERTIFICATION DOCUMENTS

The Director General of Civil Aviation (DGCA) in India has issued important certification documents |for GAGAN (ICAO, 2012):

- Certification for en-route operations (RNP 0.1) issued on December 30, 2013
- Certification for precision approach services (APV 1) issued on April 21, 2015

These certifications are crucial for the operational use of GAGAN in Indian airspace.

3.6.6.3. ICAO ANNEX 10

GAGAN is allocated Service ID number 03 in Amendment 87 to ICAO Annex 10. This allocation is essential for the system's global recognition and interoperability (ICAO, 2012; ICAO, 2025).

3.6.6.4. COMMON DOCUMENTS

GAGAN adheres to the following standard documents common to SBAS:

- RTCA DO-229 - Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment
- RTCA DO-208 - Minimum Operational Performance Standards for Airborne Supplemental Navigation Equipment Using Global Positioning System (GPS)

By adhering to these standards and documents, GAGAN ensures its compatibility with international SBAS providing seamless navigation services across regional boundaries (Inside GNSS, 2016).

3.6.6.5. SYSTEM-SPECIFIC DOCUMENTS

- GAGAN Final System Acceptance Test (FSAT) documentation, completed on July 16-17, 2012
- GAGAN System Stability Test documentation for June-July 2013.

These documents are crucial for validating GAGAN's performance and readiness for operational use.

3.7. BEIDOU SATELLITE-BASED AUGMENTATION SYSTEM (BDBSAT)

3.7.1. OWNERSHIP AND OPERATION

The BeiDou Satellite-Based Augmentation System (BDSBAS), formerly known as the Satellite Navigation Augmentation System (SNAS), is owned and operated by the China National Space Administration (Navipedia, 2011). It is an integral part of the BeiDou Navigation Satellite System (BDS), which is China's global navigation satellite system developed as an alternative to GPS, GLONASS, and Galileo (The Associated Press, 2020; Airport Technology, 2019).

BDSBAS enhances navigation capabilities by providing:

- Augmentation Services: BDSBAS provides satellite-based augmentation system services in China and surrounding regions, improving the accuracy and reliability of navigation (Navipedia, 2011).
- Dual-Frequency Services: It offers both single frequency (SF) and dual-frequency multi-constellation (DFMC) services, which have been available since July 2020 (NAVIGATION, 2021).
- Aviation Support: The system aims to achieve Approach with Vertical Guidance I (APV-I) and CAT-I precision approach capabilities for civil aviation (NAVIGATION, 2021).

- Performance Enhancements: BDSBAS significantly improves positioning accuracy. The single-frequency service achieves a horizontal accuracy of 1.29 m and vertical accuracy of 1.99 m (95% confidence), while the dual-frequency service provides even better accuracy at 0.77 m horizontally and 1.41 m vertically (95% confidence) (GPS World, 2024).
- Integration with BeiDou: BDSBAS is integrated into the BeiDou system and uses BDS-3 type satellites to broadcast SBAS L1/L5 signals, augmenting both BDS and GPS (Navipedia, 2011).

3.7.2. GENERAL OPERATION

The BeiDou Satellite-Based Augmentation System is an integral part of the BeiDou Navigation Satellite System that enhances navigation capabilities in China and surrounding regions.

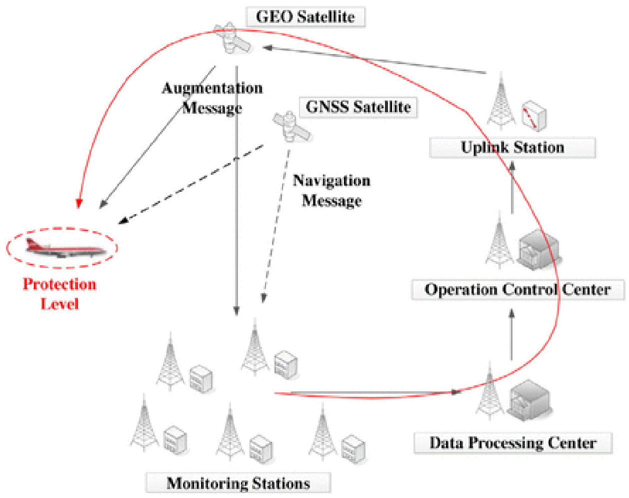

Figure 26: Architecture of BeiDou Satellite-Based Augmentation System (BDSBAS) (NAVIGATION, 2021)

General Operation and Supported Functionalities:

BDSBAS consists of three main segments (Navipedia, 2011; NAVIGATION, 2021):

- Space Segment: This includes three Geosynchronous Earth Orbit (GEO) satellites positioned at 140°E, 110.5°E, and 80°E.
- Ground Segment: A network of ground stations for monitoring and data processing, including:
  - Data Collection Stations
  - Data Processing Centres (DPC)
  - Operation Control Centres (OCC)
  - Uplink Stations
- User Segment: Receivers and applications that utilize the augmented navigation services.

The BDSBAS operates through the following process (NAVIGATION, 2021):

- Data Collection Stations continuously monitor BDS and GPS satellites, collecting raw observation data.
- The Data Processing Centre generates correction information (ionospheric, ephemeris, and clock corrections) and integrity information (User Differential Range Error, Grid Ionospheric Vertical Error, Dual Frequency Range Error).
- The Operation Control Centre creates augmentation messages based on this information.
- Uplink Stations transmit these messages to the BDSBAS GEO satellites.
- GEO satellites broadcast the augmentation messages to users in China and surrounding areas.

3.7.3. COVERAGE AREA

BDSBAS provides coverage and services primarily in China and its surrounding regions. The system's planned service coverage extends from 10°N to 55°N latitude and 75°E to 135°E longitude. The service primarily covers the landmass of China, with plans for expansion to other parts of Asia (NAVIGATION, 2021).

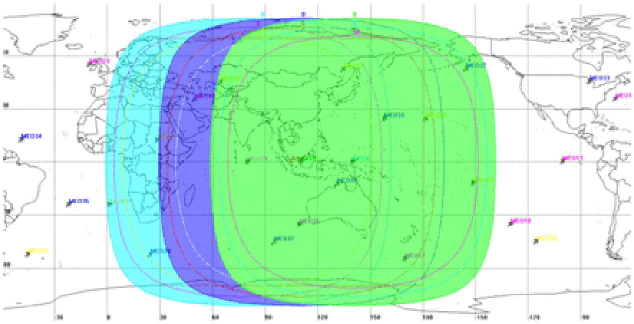

Figure 27: Signal Coverage Map of BDSBAS (NAVIGATION, 2021)

- Primary Coverage: Mainland China
- Planned Coverage: 10°N to 55°N latitude and 75°E to 135°E longitude
- Future Expansion: Surrounding regions in Asia

3.7.4. BDSBAS SERVICES

The BeiDou Satellite-Based Augmentation System provides several key services to enhance navigation and positioning capabilities in China and surrounding regions. The main services offered by BDSBAS are outlined below.

3.7.4.1. OPEN SERVICE (OS)

BDSBAS Open Service offers free augmentation services to improve positioning accuracy for general users (GPS World, 2024).

- Single-Frequency Service: Achieves a horizontal accuracy of 1.29 m and vertical accuracy of 1.99 m (95% confidence)
- Dual-Frequency Service: Provides even better accuracy with 0.77 m horizontal and 1.41 m vertical accuracy (95% confidence)
- Coverage: Primarily covers mainland China, with planned expansion to surrounding regions in Asia

3.7.4.2. SAFETY-OF-LIFE (SOL) SERVICE

The Safety-of-Life service is crucial for applications requiring high reliability and integrity, particularly in aviation (GPS World, 2024):

- Aviation Support: Aims to achieve Approach with Vertical Guidance I (APV-I) and CAT-I precision approach capabilities for civil aviation
- Integrity Information: Provides User Differential Range Error, Grid Ionospheric Vertical Error, and Dual Frequency Range Error data to ensure safety in critical applications
- Performance: Meets APV-I requirements for single-frequency service and CAT-I requirements for dual-frequency multi-constellation service in China and surrounding regions

3.7.4.3. BDSBAS DATA ACCESS SERVICE

While not explicitly named as such, the BDSBAS system provides various data access services (GPS World, 2024):

- Real-time Corrections: Broadcasts augmentation messages containing ionospheric, ephemeris, and clock corrections to users
- Signal Characteristics: Utilizes SBAS L1/L5 signals broadcast by BDS-3 type satellites to augment both BDS and GPS

Additionally, the BeiDou system offers other related services:

- PPP-B2b Service: Provides precise orbit and clock corrections for GPS and BDS-3 IGSO and MEO satellites, enabling decimeter-level positioning accuracy (Springer Open, 2024; GPS World, 2024).
- Ground-based Augmentation: Offers wide-area augmentation, regional augmentation, and post-processing high-precision data products through the BDS Ground-based Augmentation System (BeiDou Navigation Satellite System, 2020).

3.7.5. KEY PERFORMANCE METRICS

The BDSBAS key performance are shown in Figure 28.

Country	China
Name of SBAS Service	BeiDou Satellite-Based Augmentation System (BDSBAS)
Horizontal Accuracy (95%)	0.77 m (DFMC), 1.29 (SF), <3 m (NPA)
Vertical Accuracy (95%)	1.41 m (DFMC), 1.99 m (SF), <4 m (NPA)
Availability	≥99% (SF), 99.9% (DFMC)
Continuity	2 x 10 ^-6 / hour
Integrity	2 x 10^-7 / 150 seconds
Time to Alert	6 seconds

Figure 28 BDSBAS Performance metrics, derived from (GPS World, 2024)

3.7.5.1. AVAILABILITY

BDSBAS aims for high service availability:

- The single-frequency positioning availability is greater than 99.99% in general across China, with some western regions reaching 99.97% (Springer Open, 2022).
- For the BDS-3 system, the B1C/B2a availability from January to December 2023 was 0.9968 (China Satellite Navigation Project, 2024).

3.7.5.2. INTEGRITY

Integrity is crucial for safety-critical applications like aviation. BDSBAS integrity metrics include:

- Time-to-Alert (TTA): 6 seconds for B1C/B2a signals, improved from 10 seconds for older signals
- Integrity Risk: 2×10^{-7} per 150 seconds for B1C/B2a signals
- Horizontal Alert Limit (HAL): 40 m
- Vertical Alert Limit (VAL): 10 m for B1C/B2a (improved from 50 m for older signals) (China Satellite Navigation Project, 2024).

3.7.6. KEY DOCUMENTS

Several key documents and standards are important for the BeiDou Satellite-Based Augmentation System (BDSBAS).

3.7.6.1. INTERFACE CONTROL DOCUMENTS (ICDs)

- BDSBAS B1C ICD: Published by the China Satellite Navigation Office in July 2020, this document specifies the interface control for the BDSBAS B1C signal (ICAO, 2020).
- BDS-SIS-ICD-BDSBAS-B1C-1.0: Released in July 2020, this ICD provides detailed information on the BDSBAS-B1C signal characteristics and interface specifications (BeiDou Navigation Satellite System, 2020).

3.7.6.2. INTERNATIONAL STANDARDS

- ICAO Standards and Recommended Practices: BDSBAS is being developed in accordance with ICAO standards for satellite-based augmentation systems.
- RTCA DO-229E: This standard specifies requirements for single frequency user equipment.
- DFMC SBAS Standards: China is actively participating in the development of dual frequency multiple constellation SBAS standards (NAVIGATION, 2021).

3.7.6.3. PERFORMANCE STANDARDS

- Approach with Vertical Guidance I (APV-I): BDSBAS aims to meet the requirements for APV-I approach operations (NAVIGATION, 2021).
- CAT-I Service: BDSBAS is designed to provide CAT-I services to civil aviation users in China and surrounding areas (China Satellite Navigation Office, 2016).

3.7.6.4. INTERNATIONALISATION EFFORTS

- DFMC SBAS ICD: China co-signed the interface control document (ICD) and definition document for DFMC SBAS with other international service providers.
- EUROCAE and RTCA Joint Effort: These organisations are working on modifying the DFMC SBAS Minimum Operational Performance Standard (MOPS) (ED-259A) (NAVIGATION, 2021).

4. FUTURE SYSTEMS

4.1. AIR NAVIGATION SAFETY IN AFRICA AND MADAGASCAR (ASECNA)

The Agency for Air Navigation Safety in Africa and Madagascar (ASECNA) plays a pivotal role in the development and implementation of the Augmented Navigation for Africa (ANGA) programme. ANGA, formerly known as "SBAS for Africa and the Indian Ocean" or "A-SBAS," is ASECNA's flagship initiative aimed at providing SBAS services throughout the Africa and Indian Ocean (AFI) region.

ASECNA leads the ANGA programme, which is recognized by the International Civil Aviation Organisation (ICAO) and is a key enabler of the African Union Space Policy. Through ANGA, ASECNA is committed to developing solutions to significantly improve flight safety and efficiency in African airspace, with the goal of progressively providing operational SBAS services from 2025 onward (ANGA-AFRICA, 2022). ESA is providing technical support to ASECNA through an agreement signed in 2022 (European Space Agency, 2022).

4.1.1. OWNERSHIP AND OPERATION

ASECNA is an international public organisation owned and operated by 18 member states: 17 African countries and France (CANSO, 2020; ASECNA).

The member states are Benin, Burkina Faso, Cameroon, Central African Republic, Chad, Comoros, Congo, Ivory Coast, Equatorial Guinea, France, Gabon, Guinea-Bissau, Madagascar, Mali, Mauritania, Niger, Senegal, and Togo (Thales Group, 2020).

ASECNA's primary role is to ensure air navigation safety across a vast airspace covering approximately 16.1 million square kilometers, which is about 1.5 times the surface area of Europe (ASECNA). Its main responsibilities include:

- Air Navigation Services: ASECNA provides en-route air navigation services, organizes airspaces and air routes in compliance with ICAO provisions, and publishes aeronautical information.
- Meteorological Services: The agency forecasts and transmits aviation meteorology information crucial for safe flights.
- Safety Management: ASECNA defines specifications for functions, systems, and devices related to air navigation. It also implements safety and quality management systems in accordance with ICAO standards and recommended practices.
- Airport Services: At aerodromes under its control, ASECNA provides air traffic, approach, and aerodrome services, as well as firefighting and aircraft rescue services.
- Training: The agency manages schools and offers courses to address civil aviation challenges, including three specialized training schools: EAMAC in Niamey, Niger, ERSI in Douala, Cameroon, and ERNAM in Dakar, Senegal.
- Satellite Navigation: ASECNA is working on developing a satellite-based augmentation system for Africa and the Indian Ocean to enhance navigation and surveillance operations for all phases of flight (Thales Group, 2020).

By pooling resources and expertise across its member states, ASECNA plays a crucial role in ensuring air navigation safety and promoting cooperation in African aviation (ASECNA). Its services cover not only its member states' airspace but also Oceanic airspace in the central Atlantic Ocean, Gulf of Guinea, and Indian Ocean entrusted by the international community (CANSO, 2020; ASECNA).

The Agency for Air Navigation Safety in Africa and Madagascar is making significant progress in implementing SBAS services in Africa. The agency aims to provide operational SBAS services starting in 2024, which will enhance aviation safety and performance across the continent (ICAO, 2022).

The "SBAS for Africa & Indian Ocean" (A-SBAS) initiative, led by ASECNA, aims to independently deliver operational SBAS services to airspace users starting in 2025. The initiative focuses on improving Performance-Based Navigation (PBN) and ADS-B operations across all flight phases, with the potential for a progressive coverage across the African continent (ICAO, 2022). Beyond 2028-2030, the plan is to upgrade to dual-frequency multi-constellation (DFMC) SBAS services. (ICAO, 2019).

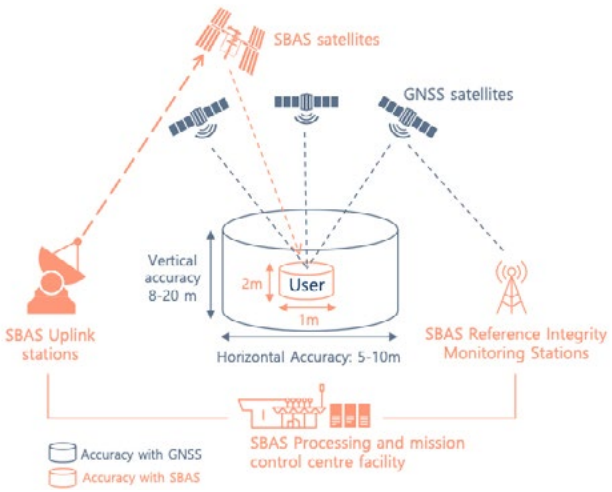

Figure 29: Agency for Aerial Navigation Safety in Africa and Madagascar (ASECNA) Architecture (AUDA-NEPAD, 2022)

4.1.1.1. SUPPORTED FUNCTIONALITIES

ASECNA plans to provide a wide range of services to ensure safe and efficient air navigation (CANSO, 2020; ASECNA):

- Air Traffic Management (ATM)
  - Air Traffic Control: ASECNA guides aircraft, transmits traffic and technical messages, and provides flight information.
  - Flow Management: The agency optimizes the flow of aircraft movements to balance airspace capacity and airport demands.
  - Approach and Landing Services: ASECNA offers terminal aids services at 31 main aerodromes across its 17 African member states.
- Navigation Services
  - En-route Navigation: ASECNA organizes airspaces and air routes in compliance with ICAO provisions.
  - Aeronautical Information: The agency publishes and manages crucial aeronautical information for safe flights.

In addition, ASECNA also considers (ASECNA, 2025):

- Meteorological Services
  - Weather Forecasting: ASECNA provides aviation meteorology information, including forecasts and real-time weather data.
- Safety and Quality Management
  - System Specifications: The agency defines specifications for functions, systems, and devices related to air navigation.
  - Safety Standards: ASECNA implements safety and quality management systems in accordance with ICAO standards.
- Airport Services
  - Ground Operations: At controlled aerodromes, ASECNA provides air traffic, approach, and aerodrome services.
  - Emergency Services: The agency offers firefighting and aircraft rescue services at 32 aerodromes.
- Training and Development
  - Aviation Schools: ASECNA manages three specialized training schools: EAMAC in Niger, ERSI in Cameroon, and ERNAM in Senegal.
  - Skill Development: These schools offer courses to address civil aviation challenges and train staff.
- Technical Support
  - Equipment Maintenance: ASECNA is responsible for maintaining all installations necessary for its services, except for runways.
  - Calibration Services: The agency operates an ATR 42 aircraft equipped with advanced calibration equipment for periodic in-flight control of radio-electric aids and landing systems.

4.1.2. COVERAGE AREA

ASECNA covers a substantial airspace of approximately 16.5 million square kilometers. This area is divided into six Flight Information Regions (FIRs): Antananarivo, Brazzaville, Dakar Oceanic, Dakar Terrestrial, Niamey, and N'Djamena (ESA, 2014).

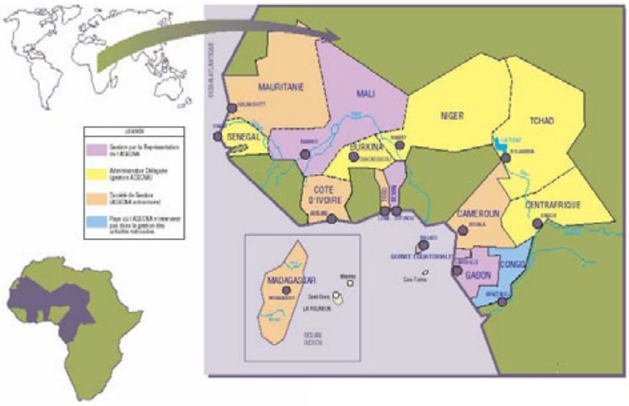

Figure 30: ASECNA Coverage Map (ASECNA)

4.1.3. AESCNA SERVICES

4.1.3.1. OPEN SERVICE (OS)

The Open Service offers positioning and synchronization information for mass applications within the coverage area. Earlier in September 2020, ASECNA started broadcasting an SBAS signal over Africa and the Indian Ocean, marking the first SBAS open service in the region (European Union Agency for the Space Programme, 2020).

4.1.3.2. SAFETY-OF-LIFE (SOL) SERVICE

The SoL service provides positioning information for users where safety is essential. It meets strict availability, continuity, and accuracy requirements and includes an integrity function to warn users of malfunctions and a non-availability alert function (NOTAM bulletin) (Augmented Navigation for Africa, 2022).

4.1.3.3. ASECNA DATA ACCESS SERVICE (SDAS)

This service, also referred to as A-SBAS Data Access Service, provides access to system data, including raw measurements, broadcast messages, and system operating parameters. It is available to users or service providers connected to a system data server (Augmented Navigation for Africa, 2022).

ASECNA's comprehensive approach to air navigation safety and services demonstrates its commitment to ensuring safe and efficient air travel across its member states in Africa and Madagascar. The agency is also preparing for the transition to satellite navigation systems through its ongoing satellite-based augmentation system called ANGA, which aims to enhance SBAS services for all phases of flight (Indra, 2023).

4.1.4. KEY PERFORMANCE METRICS

The Agency for Air Navigation Safety in Africa and Madagascar aims to provide high-quality air navigation services across its vast airspace. While specific performance metrics for ASECNA are not directly available, key performance metrics can be inferred based on the standards and goals of satellite-based augmentation systems that ASECNA is implementing through its ANGA programme.

Country	Africa
Name of SBAS Service	Agency for Air Navigation Safety in Africa and Madagascar (ASECNA)
Horizontal Accuracy (95%)	<0.9 m
Vertical Accuracy (95%)	<1.6 m
Availability	>99%
Continuity	Not specified
Integrity	Safety Index < 0.47
Time to Alert	6 seconds

Figure 31: ASECNA Performance Metrics (proposed) (ASECNA)

4.1.4.1. ACCURACY, AVAILABILITY, AND INTEGRITY

At present, specific data regarding the accuracy, availability, and integrity performance of ASECNA's SBAS is not available.

ASECNA's ANGA program is focused on providing safety-of-life services in Africa and the Indian Ocean region. The ANGA programme primarily aims to autonomously provide airspace users with operational SBAS services from 2025, to enhance PBN and ADS-B operations for all phases of flight. The SBAS services are intended to support en-route/NPA, APV-1 and CAT-I (LPV-200) operations (Demonfort, et al., 2023).

Key aspects of this program include (Space in Africa, 2024):

- Improving flight safety through enhanced accuracy, continuity, and integrity of GPS information.
- Focusing on geometric guidance to prevent accidents like controlled flight into terrain.
- Aligning with ICAO requirements and receiving international recognition (identification number 7 in Volume One of the International Civil Aviation Convention).

ASECNA has been conducting tests and demonstrations to evaluate the performance of its SBAS, indicating that the ICAO specifications can be met with a fully defined system (Space in Africa, 2024) (Demonfort, et al., 2023).

4.1.5. KEY DOCUMENTS

ASECNA operates under several key documents and standards that govern its activities and international cooperation. The most important documents for ASECNA include:

4.1.5.1. THE REVISED DAKAR CONVENTION

This is the foundational document that establishes ASECNA as an international public institution. It outlines the agency's purpose, missions, and governance structure. The convention was adopted in Ouagadougou, Burkina Faso, and endorsed in Libreville, Gabon (ASECNA).

4.1.5.2. ASECNA'S INTERNATIONAL STATUTES

These statutes are annexed to the Revised Dakar Convention and provide detailed regulations for the agency's operations (ASECNA).

4.1.5.3. COOPERATION AGREEMENT WITH THE EUROPEAN UNION

This agreement, which entered into force on November 1, 2018, focuses on developing satellite navigation and providing associated services in ASECNA's area of competence for the benefit of civil aviation (European Union, 2020).

4.1.5.4. ICAO STANDARDS AND RECOMMENDED PRACTICES

ASECNA aligns its operations with ICAO standards, particularly:

- Annex 19 - Safety Management
- Doc 9859 - Manual of Safety Management (ICAO, 2016)

4.2. SOUTHERN POSITIONING AUGMENTATION NETWORK (SOUTHPAN)

4.2.1. OWNERSHIP AND OPERATION

The Southern Positioning Augmentation Network (SouthPAN) is jointly owned and operated by the Australian and New Zealand governments (Geosciences Australia & Land Information New Zealand, 2024).

Specifically, Geoscience Australia and ToitūTe Whenua Land Information New Zealand (LINZ) are responsible for SouthPAN under the Australia New Zealand Science, Research and Innovation Cooperation Agreement (ANZSRICA) (ToitūTe Whenua Land Information New Zealand, 2023; Geoscience Australia, 2023).

While the government agencies oversee SouthPAN, its operational capability is delivered by a consortium of private companies (Inside GNSS, 2023):

- Lockheed Martin Australia: Contracted to build the ground segment, including the network of ground reference stations and satellite uplink facilities.
- GMV: Responsible for developing the processing and control centers.
- Inmarsat Australia: Provides the satellite service for broadcasting SouthPAN signals.

SouthPAN will play a role in improving navigation and positioning across Australia and New Zealand (Frontier SI, 2024):

- Enhanced Accuracy: It significantly improves positioning accuracy from the current 5-10 meters to as little as 10 centimeters in some cases.
- Wide Coverage: SouthPAN provides services across Australia and New Zealand's land and maritime zones, overcoming gaps in mobile and internet coverage (Frontier SI, 2024).
- Multiple Services: It offers three early Open Services (Geosciences Australia & Land Information New Zealand, 2024)
  - L1 SBAS: Augments GPS L1 C/A signal
  - Dual Frequency Multi-Constellation (DFMC SBAS): Augments GPS and Galileo signals
  - Precise Point Positioning via SouthPAN (PVS): Provides the highest accuracy
  - Industry Applications: SouthPAN benefits various sectors, including maritime navigation, aviation, agriculture, forestry, construction, and transport.
  - Safety Improvements: By 2028, SouthPAN will be Safety of Life certified for aviation, allowing aircraft to operate in adverse weather conditions they currently cannot.

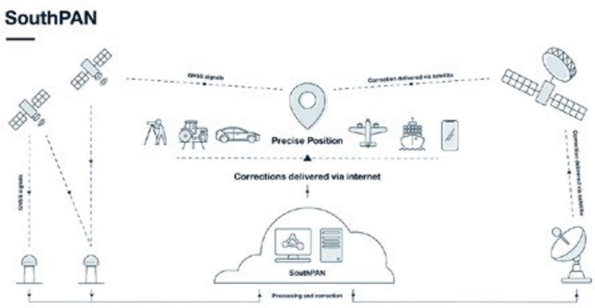

Figure 32: SouthPAN Architecture (Geosciences Australia & Land Information New Zealand, 2024)

4.2.2. GENERAL OPERATION

SouthPAN (Southern Positioning Augmentation Network) is a Satellite-Based Augmentation System that enhances the accuracy and reliability of Global Navigation Satellite Systems across Australia and New Zealand (ToitūTe Whenua Land Information New Zealand, 2023; Frontier SI, 2024):

- Ground Reference Stations: A network of stations across Australia and New Zealand collects raw positioning data from GNSS satellites.
- Computation Centres: The collected data is processed at two computation centres to calculate corrections for satellite orbit, clock errors, and ionospheric changes.
- Uplink Stations: Corrected data is transmitted from uplink facilities to geostationary satellites.
- Geostationary Satellites: Two industry-owned satellites with SBAS payloads broadcast the correction signals across the service area.
- User Receivers: SouthPAN-compatible devices receive both the original GNSS signals and the correction data, allowing for significantly improved positioning accuracy.

4.2.2.1. SUPPORTED FUNCTIONALITIES

SouthPAN offers three main services:

- L1 SBAS (Open Service) (Geosciences Australia & Land Information New Zealand, 2024)
  - Augments the GPS L1 C/A signal
  - Primarily designed for safety-critical operations in civil aviation
- Dual Frequency Multi-Constellation (DFMC) SBAS (Open Service):
  - Augments GPS L1 C/A, GPS L5, Galileo E1, and Galileo E5a signals
  - Provides improved integrity and precision compared to L1 SBAS

- Precise Point Positioning via SouthPAN (PVS) (Open Service) (Geosciences Australia & Land Information New Zealand, 2024)
  - Offers the highest accuracy among the three services
  - Provides accuracies ≤0.40m horizontal and ≤0.55m vertical (95% confidence) after a convergence period
  - Achieves full position accuracy after a convergence period greater than 80 minutes during early Open Services.

4.2.3. COVERAGE AREA

SouthPAN (Southern Positioning Augmentation Network) provides coverage across a wide area, benefiting numerous applications in Australia and New Zealand.

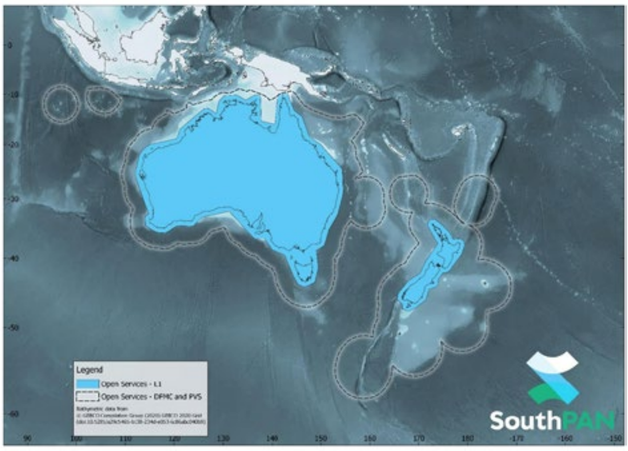

Figure 33: SouthPAN Early Open Services Coverage Map (Geosciences Australia & Land Information New Zealand, 2024)

SouthPAN services are available throughout:

- Australia and New Zealand's land areas
- Surrounding maritime zones
- A wider coastal area around both countries

The coverage is transmitted via geostationary satellite and can be received by compatible GNSS devices with a clear sky view. Specifically:

- L1 SBAS early Open Service is available on and around the mainlands of Australia and New Zealand
- DFMC SBAS and PVS early Open Services cover a broader coastal area around both countries.

The economic benefits of SouthPAN are estimated to be more than $6 billion over 30 years, with advantages for regional areas lacking mobile phone or internet coverage.

4.2.4. SOUTHPAN SERVICES

SouthPAN (Southern Positioning Augmentation Network) provides several services to enhance positioning accuracy and reliability across Australia and New Zealand. An overview of the main services appears below.

4.2.4.1. OPEN SERVICES (OS)

SouthPAN currently offers three early Open Services:

- L1 SBAS (OS-L1) (GeoScience Australia, 2024)
  - Augments the GPS L1 C/A signal
  - Available on and around the mainlands of Australia and New Zealand
- Dual Frequency Multi-Constellation SBAS (OS-DFMC) (GeoScience Australia, 2024)
  - Augments GPS L1 C/A, GPS L5, Galileo E1, and Galileo E5a signals
  - Covers a wider coastal area around Australia and New Zealand
- Precise Point Positioning via SouthPAN (OS-PVS) (Frontier SI, 2024)
  - Augments GPS L1 C/A, GPS L5, Galileo E1, and Galileo E5a signals
  - Currently provided on the SouthPAN L5 navigation signal
  - Will be migrated to the new L5b navigation signal in 2027

These Open Services are freely available and accessible to any compatible GNSS device with a clear sky view (GeoScience Australia, 2024) (ToitūTe Whenua Land Information New Zealand, 2025).

4.2.4.2. SAFETY-OF-LIFE (SOL) SERVICE

While not currently operational, SouthPAN is developing a Safety-of-Life service (GeoScience Australia, 2024):

- Planned to commence in late 2027 to early 2028
- Initially certified for aviation use
- Will enable aircraft to operate in adverse weather conditions
- May expand to other sectors such as maritime, road, and rail in the future

4.2.4.3. SOUTHPAN DATA ACCESS SERVICE

In addition to satellite-based services, SouthPAN also provides data access services via the internet (Geoscience Australia, 2023):

- Complements the satellite-based services
- Allows users to access SouthPAN data through internet connections
- Provides an alternative method for obtaining augmentation information

This is detailed in the SouthPAN Service Definition Document for Data Access Services.

4.2.5. KEY PERFORMANCE METRICS

SouthPAN key performance metrics:

Country	Australia/NZ
Name of SBAS Service	Southern Positioning Augmentation Network (SouthPAN)
Horizontal Accuracy (95%)	≤1.5 m (OS-DFMC), ≤ 3 m (OS-L1)
Vertical Accuracy (95%)	≤2.5 m (OS-DFMC), < 4 m (OS-L1)
Availability	≤99.5%
Continuity	Not specified
Integrity	Not specified
Time to Alert	Not specified

Figure 34: SOUTHPAN Performance Metrics (Geoscience Australia, 2022)

4.2.5.1. ACCURACY

SouthPAN substantially improves positioning accuracy compared to standalone GNSS:

The accuracy varies depending on the specific service used:

- L1 SBAS (OS-L1):
  - Horizontal accuracy: ≤3m (95% confidence interval)
  - Vertical accuracy: 4m (95% confidence interval)
- Dual Frequency Multi-Constellation SBAS (OS-DFMC):
  - Horizontal accuracy: ≤1.5m (95% confidence interval)
  - Vertical accuracy: ≤2.5m (95% confidence interval)
- Precise Point Positioning via SouthPAN (OS-PVS):
  - Horizontal accuracy: ≤0.0375m (95% confidence interval)
  - Vertical accuracy: ≤0.525m (95% confidence interval)

4.2.5.2. AVAILABILITY

SouthPAN proposes to have an availability figure of 99.5% for the OS-L1 and DFMC services. (Geosciences Australia & Land Information New Zealand, 2024)

4.2.5.3. INTEGRITY

SouthPAN has not specified the target integrity factors. (Geosciences Australia & Land Information New Zealand, 2024)

4.2.5.4. ADDITIONAL PERFORMANCE METRICS

- Convergence Time: For the PVS service, full position accuracy is achieved after a convergence period better than 80 minutes during early Open Services (Geoscience Australia, 2023).
- Reliability: SouthPAN improves the reliability of positioning information by using a network of ground reference stations, multiple satellites, and dual computation centers (ToitūTe Whenua Land Information New Zealand, 2025).

SouthPAN's performance is expected to further improve as the system progresses towards full operational capability. By 2028, it aims to achieve Safety-of-Life certification, primarily for aviation use, which will require meeting stringent performance standards for accuracy, integrity, and availability (Australian Maritime Safety Authority, 2023).

4.2.6. KEY DOCUMENTS

Several key documents and standards are crucial for understanding and implementing the Southern Positioning Augmentation Network. These include the key documents identified below.

4.2.6.1. SERVICE DEFINITION DOCUMENTS

- Service Definition Document for Signal-in-Space Services (Geosciences Australia & Land Information New Zealand, 2024)
  - Provides details on the reference frames used by SouthPAN
  - Contains information about SouthPAN system architecture, radio frequency characteristics, and navigation message structures

- Service Definition Document for Data Access Services (Geoscience Australia, 2023)
  - Describes the SouthPAN system architecture, navigation message contents, and indicative performance
  - Outlines connection details and service specifications

4.2.6.2. INTERNATIONAL STANDARDS

SouthPAN will confirm to the following standards:

- RTCA DO-229F
  - Minimum Operational Performance Standards for GPS/SBAS Airborne Equipment
  - Essential for implementing SouthPAN's L1 SBAS Data Access Service (Geoscience Australia, 2023; Geoscience Australia, 2023)
- EUROCAE ED-259
  - Minimum Operational Performance Standards for Galileo/GPS/SBAS Airborne Equipment
  - Important for multi-constellation SBAS implementations (Geoscience Australia, 2023; Geoscience Australia, 2022)

4.2.6.3. OFFICIAL PUBLICATIONS

- SouthPAN Service Definition Document for Open Services (SBAS-STN-0001)
  - Document code: SBAS-STN-0001
  - Revision 01, dated 14 September 2022
  - Provides comprehensive information on SouthPAN's Open Services
- AMSA Marine Notice
  - Issued by the Australian Maritime Safety Authority
  - Provides information on the new SBAS system for maritime users (Australian Maritime Safety Authority, 2023)

APPENDIX

APPENDIX A - BIBLIOGRAPHY

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APPENDIX B - SBAS SYSTEM PERFORMANCE SUMMARY

Country	Name of SBAS Service	Horizontal Accuracy (95%)	Vertical Accuracy (95%)	Availability	Continuity	Integrity	Time to Alert
USA	WAAS (Wide Area Augmentation System)	<1.5 m (LPV), <36 m (LNAV), 0.4 nm (En Route)	<2 M (LPV)	99% over 100% CONUS (LPV), 95% over 75% Alaska (LPV), 99.99% over 100% CONUS (LNAV), 99.9% over 100% Alaska (LNAV), 99.9% over 100% CONUS (En Route)	1 - 8 10 ^-6/15s, 1 x 10^-5 / hour (LNAV & En Route)	2 x 10 ^-7 / approach (LPV & LNAV), 1 x 10^-7 / hour (LNAV & En Route)	6.2 seconds (LPV), 10s (LNAV), 15s (En Route)
EU	EGNOS (European Geostationary Navigation Overlay Service)	3 m (APV-I & LPV200), 220 m (NPA)	4 m (APV-I & LPV200), N/A (NPA)	0.99% (APV-I & LPV200) in most of ECAC, 0.999% (NPA)	<1 x 10^-4 per 15s in core ECAC (APV-I & LPV200), <1 x 10^-3 per -3/ hour in most of ECAC (NPA)	1 - 2 x 10^-7 / approach (APV-I & LPV200), 1 x 10^-7 / hour (NPA)	< 6 seconds
India	GPS-Aided GEO Augmented Navigation (GAGAG)	<7.6 m	<7.6 m	≥99% (APV-I)	1 - 8 x 10 ^-6/15s (APV-I)	1 - 2 x 10^-7 / approach (APV-I)	6 seconds
Japan	Sub-Meter Level Augmentation Service	Zone 1 - ≤ 1.0 m (95%) (0.58 (RMS)); Zone 2 - ≤ 2.0 m (95%) (1.16 (RMS))	Zone 1 - ≤ 2.0 m (95%) (1.02 (RMS)); Zone 2 - ≤ 3.0 m (95%) (1.53 (RMS))	Constellation ≥ 99.9%	<1 - 2 x 10^-4 / hour	<1 x 10^-5 / hour	10 seconds
Japan	Centimeter Level Augmentation Service	Static - <6 cm (95%) (3.47 (RMS)); Kinematic - ≤ 12 cm (95%) (6.94 (RMS))	Static - <12 cm (95%) (6.13 (RMS)); Kinematic - < 24 cm (95%) (12.25 (RMS))	Constellation ≥ 99.9%	<1 - 2 x 10^-4 / hour	<1 x 10^-5 / hour	10 seconds
China	BeiDou Satellite-Based Augmentation System (BDSBAS)	0.77 m (DFMC), 1.29 (SF), <3 m (NPA)	1.41 m (DFMC), 1.99 m (SF), <4 m (NPA)	≥99% (SF), 99.9% (DFMC)	2 x 10 ^-6 / hour	2 x 10^-7 / 150 seconds	6 seconds
Russia	System for Differential Corrections and Monitoring (SDCM)	0.5 m	0.8 m	>99% with coverage of Russian Federation + CIS countries	1 - 8 x 10 ^-6/15s (APV-I & APV-II)	1 - 2 x 10^-7 / approach (APV-I & APV-II)	6 seconds (APV-II)

Country	Name of SBAS Service	Horizontal Accuracy (95%)	Vertical Accuracy (95%)	Availability	Continuity	Integrity	Time to Alert
Australia/ NZ	Southern Positioning Augmentation Network (SouthPAN)	≤1.5 m (OS-DFMC), ≤ 3 m (OS-L1)	≤2.5 m (OS-DFMC), < 4 m (OS-L1)	≤99.5%	Not specified	Not specified	Not specified
South Korea	Korea Augmentation Satellite System (KASS)	1.3 m (API-V), 21.04 m (NPA)	<2.6 m (APV-I)	99.87% (APV-I & NPA)	6 x 10^-4 / 15s (APV-I), 0 / hour (NPA)	2 x 10^-7 / approach (APV-I), 1 x 10 ^-7 / hour (NPA)	10s (APV-I & NPA)
Africa	Agency for Air Navigation Safety in Africa and Madagascar (ASECNA)	<0.9 m	<1.6 m	>99%	Not specified	Safety Index < 0.47	6 seconds

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PART 2

SPACE BASED AUGMENTATION SYSTEMS REPORT