GNSS Satellite-Based Augmentation Systems for Australia

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ABSTRACT

This paper provides an overview of various Satellite-Based Augmentation Systems (SBAS) options for augmented GNSS services in Australia, and potentially New Zealand, with the aim to tease out key similarities and differences in their augmentation capabilities. SBAS systems can technically be classified into two user categories, namely SBAS for aviation and “non-aviation” SBAS. Aviation SBAS is an International Civil Aviation Organisation (ICAO) certified civil aviation safety critical system providing wide-area GNSS augmentation by broadcasting augmentation information using geostationary satellites. The primary aim is to improve integrity, availability and accuracy of basic GNSS signals for aircraft navigation. On the other hand, “non-aviation” SBAS systems support numerous GNSS applications using positioning techniques such as wide-area Differential-GNSS (DGNSS) and Precise Point Positioning (PPP). These services mainly focus on delivering high accuracy positioning solutions and guaranteed levels of availability and integrity remains secondary considerations. Next generation GNSS satellites capable of transmitting augmentation signals in the L1, L5 and L6 frequency bands will also be explored. These augmentation signals have the data capacity to deliver a range of augmentation services such as SBAS, wide-area DGNSS and PPP, to meet the demands of various industry sectors. In addition, there are well-developed plans to put in place next generation dual-frequency multi-constellation SBAS for aviation. Multi-constellation GNSS increases robustness against potential degradation of core satellite constellations and extends the service coverage area. It is expected that next generation SBAS and GNSS will improve accuracy, integrity, availability and continuity of GNSS performance.

Keywords: Satellite-Based Augmentation Systems (SBAS), Precise Point Positioning (PPP), Differential-GNSS (DGNSS), Aviation, Multi-GNSS

INTRODUCTION

Satellite-based positioning and navigation plays a vital and growing role in areas as diverse as transportation, agriculture, emergency services, engineering, mapping and mining. Over the next five years there will be a surge of new navigation satellites launched: the U.S. modernised GPS constellation, Russia's revitalised GLONASS, European Union's Galileo and China's BeiDou systems, collectively referred to as Global Navigation Satellite Systems (GNSS). Furthermore, the deployment of Regional Navigation Satellite Systems (RNSS) and Satellite-Based Augmentation Systems (SBAS) brings additional satellites and signals to augment GNSS Position, Navigation and Timing (PNT) capabilities. However, standalone GNSS navigation solutions – even with the large number of signals from multiple satellite constellations – can only provide positioning resolution of the order of several metres. This is not adequate to satisfy the stringent requirements of many PNT applications, particularly in mission- and safety-critical applications such as aviation requiring high integrity information, maritime, land transportation and emergency services.

GNSS augmentation is a method to improve PNT accuracy, reliability, availability, and continuity through the integration of external information into the calculation process. Real-Time Kinematic (RTK) and Precise Point Positioning (PPP) were developed for high accuracy positioning, which the mining, civil construction and precision agriculture sectors require; the SBAS service was established mainly to provide integrity assurance for aviation operations; and submetre-level Differential-GNSS (DGNSS) for Location-Based Services (LBS), maritime users and many other applications. These augmentation services have significantly improved GNSS PNT capability over the past several decades. Other augmentation methods have also been developed such as assisted GNSS and integrated GNSS and inertial navigation systems. However the term "GNSS augmentation" is used here to specifically describe satellite-based augmentation systems that support wide-area augmentation through the use of additional satellite-broadcast correction messages.

A report prepared for the Australian Department of Industry, Innovation, Climate Change, Science, Research and Tertiary Education in 2013 by ACIL-Allen Consulting Inc. (ACIL Allen Consulting 2013) stated that “Augmented GNSS, which provides greater performance in terms of accuracy, integrity, availability and reliability, are delivering significant economic benefits in several key sectors of the economy, as well as environmental, safety and other social benefits.” In 2012, Australia’s GDP was between $2.3 billion and $3.7 billion higher than it would have been without accumulated productivity improvements arising from augmented GNSS compared to the GDP of 2000. Furthermore, the study found if Australia focused on the extension of augmentation services to increase adoption, an associated GDP increase is projected to be between $7.8 billion and $13.7 billion by 2020 (compared to the GDP of 2012).

GNSS augmentation systems can be divided into ground-based and satellite/space-based augmentation systems. Both systems require ground-monitoring stations to verify the validity of GNSS signals, and generate augmentation information to enhance accuracy, integrity, availability and continuity. The key distinction between ground- and satellite-based augmentations is the communication link used to disseminate information. Ground-based systems use radio beacons to transmit information to users via a variety of radio frequencies, from low-frequency (LF) to ultra-high frequency (UHF) bands. For example, the current standard for delivering high accuracy RTK augmentation in Australia is the licensed UHF band in the 450 – 470 MHz range (unlicensed Spread Spectrum in the 915 – 928 MHz and 2400 – 2483.5 MHz are also available with limited range and compatibility). As of February 2016, the Australian Communications and Media Authority (ACMA) Register of Radiocommunication Licences shows over 26300 UHF (450 – 470) frequency licences in Australia. Managing the frequency assignment and interference is increasingly becoming an issue in densely populated areas. The transmission range of UHF is generally limited to 10 km in optimal conditions. However, in practice a reduced range of a few km can be expected due to rough terrain and vegetation cover. To combat this reduction in range, radio repeaters can be used to extend the range of the data-link. When using LF band transmission, as in the case of DGNSS, the augmentation data link stretches to 300 km or more, but with lower bandwidth and data rate. Internet or mobile broadcasting is also a ground-based solution, commonly used for delivering network-RTK augmentation. Depending on telecommunication coverage, it must deal with issues of connectivity, coverage and roaming charges (Elneser 2016). Communication and GNSS satellites on the other hand can deliver augmentation information via a satellite communication link. This mode of communication is well suited for wide-area and/or regional augmentation of GNSS and can be broadcast to a very large number of users across a broad coverage area. It can also provide homogenous positioning quality within a consistent reference frame using a single GNSS receiver.

The Australian Government through Geoscience Australia has developed a National Positioning Infrastructure (NPI) Plan which examines investment in domestic infrastructure to deliver accurate and reliable PNT information to users across Australia (Hausler 2014). One of the visions of the Australian NPI is to provide multi-GNSS products and services anywhere (outdoor) and at any time across the Australian landscape and its maritime jurisdiction. In an Australian perspective, large coverage gaps between existing radio and mobile/Internet communications infrastructure prohibit delivery of a nationwide augmented GNSS service using ground-based communications alone. As Australia is fortuitously situated in the GNSS "hotspot" where GNSS satellite visibility is at a global high (Dempster and Hewitson 2007; Rizos 2008), Australia will be able to take advantage of the opportunities provided by GNSS, RNSS and SBAS satellites to deliver improved GNSS PNT performance across the region. Therefore, options for satellite-based delivery of GNSS augmentation must be explored as part of the NPI implementation in order to ensure GNSS augmentation information can be delivered anywhere and at any time in Australia.

This paper provides an overview of satellite-based augmentation systems options for augmented GNSS services in Australia, and potentially New Zealand, with the aim to tease out key similarities and differences in their augmentation capabilities. SBAS systems can technically be classified into two user categories: 1) SBAS for aviation, and 2) "non-aviation" SBAS. It is worthwhile to note that this paper focuses on L-band frequencies associated with GNSS. The advantage of transmitting corrections using an L-band frequency is that GNSS receivers are already equipped with L-band antennas and radio frequency front-ends, which could simplify the reception of data, and that no new frequency licensing is necessary.

SATELLITE-BASED AUGMENTATION SYSTEM (SBAS) FOR AVIATION

The term SBAS, in its strictest sense, refers to a civil aviation safety critical system providing wide-area GPS augmentation by broadcasting augmentation information using geostationary (GEO) satellites. As its primary aim is to improve integrity, availability and accuracy of basic GPS signals for aircraft navigation, SBAS transmits (a) integrity, (b) ranging information, and (c) correction messages, which include satellite and ionospheric corrections, so that:

(a) Integrity is enhanced by sending alerts to users to not track the failed satellites identified as having large signal errors.

(b) Signal availability is improved as the SBAS satellite transmits additional L1 ranging signal.

(c) Accuracy is enhanced through the transmission of wide-area corrections for range errors, such as satellite orbits, clocks and improved ionospheric information.

In addition to corrections and integrity data, SBAS satellites also transmit ancillary information such as timing and degradation parameters through messages encoded in the signal. SBAS deliver corrections free of charge for users to obtain improved GPS positioning performance in region of SBAS coverage. In fact, moist commercial GNSS receivers are SBAS-capable.

All aspects of aviation SBAS operation are defined in the Radio Technical Commission for Aeronautics (RTCA) Minimum Operational Performance Standard (MOPS) and are International Civil Aviation Organisation (ICAO) compliant (RTCA 2006). Its standard determines the format of the messages, the integrity levels required for certain operations, and the methods to calculate event probabilities, which in turn determine if the required integrity for a certain operation is met. However, it should be noted that SBAS is widely used in a range of non-aviation applications.

SBAS L1 Signal

SBAS GEO satellites transmit an L1 signal (1574.42 MHz), modulated with a Coarse/Acquisition (C/A) Pseudo-Random Noise (PRN) code. This signal uses the same carrier frequency as the GPS C/A code signal and many other systems' civil signals in the upper L-band. The SBAS L1 radiofrequency characteristics are shown in Table 1.

The SBAS performances are defined with respect to civil aviation navigation safety operations and requirements. Table 2 shows the different performance requirements, on which ICAO certification is based. As the ICAO certification completely specifies the functions and details of a SBAS, any system that does not follow the specification cannot be certified, and thus not allowed to be used for aircraft safety operations. For example, even though is it not explicitly stated, the specification continuously refers to 'geostationary orbit'. Thus, satellites in other orbits would not be allowed, at least in the first generation SBAS.

Existing SBAS

Several countries have implemented SBAS, or are in various stages of deploying their own SBAS. The U.S. has the Wide Area Augmentation System (WAAS); the EU has the European Geostationary Navigation Overlay Service (EGNOS); Russia has the System for Differential Correction and Monitoring (SDCM); Japan has the Multi-functional Satellite Augmentation System (MSAS); India has launched the Geo-Augmented Navigation system (GAGAN); Nigeria deployed NIGCOMSAT geostationary satellite; and Korea has approved and is developing its Korean Augmentation Satellite System (KASS). China, South Africa and South America are currently in the conceptual phases of design for their own systems. Figure 1 shows existing SBAS coverage.

It is worthwhile to note that the coverage of SBAS is dictated by the availability of the SBAS signal and ground reference stations network for monitoring of ranging information and computing of satellite and ionospheric corrections. Currently operating SBAS can be referred to as first generation SBAS, as they currently only augment the GPS constellation with the exception of SDCM which augments both GPS and GLONASS. Although the current ICAO specification does cover augmentation of GLONASS, it does not make any reference to other GNSS or RNSS.

The U.S. WAAS covers the United States of America, Canada and Mexico, and was the first to be employed with its first satellite launched in 2003 (US Federal Aviation Adminstration 2008). As it is the oldest system and satellites reach their end of life, they are currently developing the next generation SBAS, which will be discussed in section 5.

The Japanese MSAS and European EGNOS followed with their first satellites launched in 2005. MSAS was put in operation in 2007, but can only be used for non-precision approach (Fujiwara 2011). EGNOS started operation in 2009 for its open service, while its safety-of-life service started operation in 2011 (European Global Navigation Satellite Systems Agency 2015). Similar to WAAS, EGNOS is capable of providing full CAT-I (LPV-200) performance.

In 2011, the first Indian GAGAN satellite and the first Russian SDCM satellite were launched. GAGAN became operational after it received ICAO certification in 2014 (Aguilera et al. 2014; International Civil Aviation Organisation 2015), even though its planned third satellite did not launch at that stage. Information about the operational status of SDCM is difficult to find, but all satellites have been launched and a 2014 meeting report indicates they aim for APV-II certification, but had not yet received this (International Civil Aviation Organization 2014).

Nigeria launched the Nigerian communication satellite named NIGCOMSAT-1 in 2007 carrying two L-band payloads to provide correction information for the African continent. However in November 2008, NIGCOMSAT-1 failed in orbit due to a technical error of the solar array and the satellite could not be recovered. In 2011, a replacement satellite called NIGCOMSAT 1R was lunched into position at 42.5°E.

The only SBAS not yet operational, but certain to be employed, is the Korean Augmentation Satellite System (KASS). Its development was initiated in 2002 (Kee 2014), is expected to provide open services in 2018, full operational capabilities in 2019-2020, and safety-of-life (APV-I) services in 2022 (Aguilera et al. 2014).

Tables 3 and 4 provide an overview of current SBAS systems. The "year" column shows the date when the first SBAS satellite became operational and the "total" column gives the number of satellites in the complete constellation. Within the "Australian visibility" column, "Y" means yes, "N" means no and "P" means partial. Partial visibility can exist in the case that only part of the constellation is visible to all of Australia or part of Australia.

It is also worthwhile to mention GMV's magicSBAS testbed which can be used to support the design and implementation of an SBAS in a given region. It can be used in post-processed and real-time mode to demonstrate the feasibility and benefits of SBAS technology to potential user community. Another useful technology is the SISNeT (Signal-in-Space through Internet) developed by the European Space Agency (ESA) for relaying EGNOS messages. SISNeT is a technology that allows streaming of SBAS information in real-time over the Internet instead of a geostationary satellite.

SBAS FOR AUSTRALIA

Australia is one of the few large Organisations for Economic Co-operation and Development countries without SBAS services, including both wide-area DGNSS, ranging and integrity services via satellites (Austroads 2013). According to a white paper produced by the Australian Space Industry Innovation Council in 2011 (Australia Department of Infrastructure and Transport 2011), Australia could consider a SBAS capability that is:

i. Solely owned and operated by Australia
ii. An extension of other existing SBAS, such as MSAS or GAGAN
iii. A global SBAS model, either implemented as part of a government or commercial arrangement

Possible Utilisation of Existing SBAS in Australia

In 2010 the possibility of developing an indigenous SBAS capability for Australia with a modest investment of USD$30M arose, but became unlikely in 2011 (Collier et al. 2011). The option proposed was to add a GNSS augmentation payload to the Australian National Broadband Network (NBN) communication satellites, and to supplement ground infrastructure with ground reference stations and Master Control Stations. However, it was noted that, on the basis of information available in 2011, it was difficult to justify the significant investment involved in establishing a SBAS in Australia based on supporting aviation operations at smaller aerodromes alone. It was recommended that consideration of any future investment in SBAS would require a whole-of-Government approach. The significant cost of developing a SBAS could then be considered against potential benefits across a range of industries beyond aviation.

An alternative option for an Australian SBAS is to work in collaboration with neighbouring countries to extend the service area of existing or newly developed SBAS, such as Japan's MSAS, India's GAGAN or Korea's KASS systems. Currently visible in Australia are the full MSAS constellation, i.e., MTSAT-1R and MTSAT-2 satellites, two of the three SDCM satellites, two of the three GAGAN satellites (of which one visible in the west of Australia only), and the future KASS constellation. Even though these SBAS GEO satellites are visible in Australia, they cannot be used under current arrangements as the satellites do not transmit ionospheric information valid for the Australian region, i.e., the ionospheric data these SBAS GEO satellites transmit are for their own coverage region.

For an existing SBAS to work in Australia, it needs to have ground stations in Australia monitoring the satellite constellation for Australian-specific integrity and measuring ionospheric delay. In 2012, researchers from Electronic Navigation Research Institute (ENRI) in Japan conducted a study hypothesising the expansion of the MSAS service area toward Australia through the installation of 15-20 ground stations in Australia and the submission of correction messages to Australian users through MSAS satellites. They confirmed the technical possibility of expanding the MSAS service area to Australia. In addition, they also noted two possible scenarios when considering the expansion of MSAS to Australia: (a) Australia has its own Master Control Station and the MSAS GEO satellite works as a transponder, independently of Japan, meaning that Australia has a specific PRN code different from MSAS; or (b) the Master Control Station currently located in Japan will service both countries simultaneously by using a single PRN signal.

AUGMENTED GNSS USING "NON-AVIATION" SBAS

There are several "non-aviation" augmentation services delivered via satellite-based communication channels to support many GNSS PNT applications using positioning techniques such as wide-area DGNSS and PPP. In most instances, these services are also known as SBAS. However, to highlight their differences, these services will be referred herein as "non-aviation" SBAS.

The augmented GNSS services are not aviation SBAS compliant due to:

1) *Differences in data message structures*.

   The message structure used in "aviation-style" SBAS are defined in the RTCA format, whilst the message structure for DGNSS, RTK and PPP methods are defined by RTCM (Radio Technical Commission for Maritime Services), or a proprietary format in the case of commercial service providers.

2) *Different frequencies used for transmission of corrections*.

The existing aviation SBAS signals are broadcast from SBAS GEO satellites using the L1 frequency, which share similar design to the GPS L1C/A signals. As all aspects of SBAS operation are defined in the RTCA MOPS (RTCA/DO-229), and are ICAO compliant, aircraft flying from the U.S. to Europe and Japan will be fully compatible with the European and Japanese SBAS systems. "Non-aviation" SBAS on the other hand uses other L-band frequencies, e.g. Japan's Quasi-Zenith Satellite System (QZSS) L6 signal or commercial communication satellites providing L-band communication like Inmarsat. There is no standardisation with respect to "non-aviation" SBAS.

3) *Absence of the extra ranging signals from the GEO satellites*.

   The L1C/A code transmitted by the aviation SBAS GEO satellites can be used as an additional ranging signal thus further improving the availability of the service. "Non-aviation" SBAS uses L-band channels as communication links only without additional ranging signals.

4) *Missing integrity data and monitoring*.

   Given that SBAS is implemented primarily for the civil aviation sector, one of the most important functions for aircraft landings and/or any safety- and mission-critical applications is "integrity" – the ability to provide timely warnings when the system is providing erroneous information and should not be used. Although GNSS satellites broadcast integrity messages as part of their navigation message, the latency of the message is not adequate for aviation use. Thus, SBAS transmits, in addition to ranging signal and correction information, integrity data to support safety-critical application in the aviation sector. "Non-aviation" SBAS services on the other hand do not typically transmit integrity data that meets the specification for safety-of-life applications. "Non-aviation" SBAS services mainly focus on delivering accurate positioning solutions, guaranteed levels of availability and integrity (reliability) remain secondary considerations when accuracy is the key driver (Collier et al. 2011).

The success of SBAS is attributable to the fact that it is an open and free service that removes the need for separate hardware to receive SBAS messages, as well as the use of a common L1 frequency that leads to ease of signal reception. Vast majority of commercial GNSS receivers including those in smartphones for LBS applications are SBAS-capable, which means that it can provide higher positioning accuracy in region of SBAS coverage. As aviation SBAS must comply with RTCA MOPS standards and be ICAO compliant, all systems are compatible and interoperable. A user with a standard GPS receiver can benefit from the same level of service and performance whether located in the WAAS or EGNOS coverage area. "Non-aviation" SBAS services, on the other hand, were mostly developed on an *ad-hoc* basis and differ predominantly with respect to their delivered positioning accuracies and their targeted applications, e.g., offshore positioning versus precision agriculture. Figure 2 shows accuracies comparison of different GNSS positioning techniques, e.g., SBAS, DGNSS, PPP and RTK.

Commercial Satellite-Based Augmentation Services

While SBAS for aviation requires ICAO certification, a range of commercial ventures exist providing commercial GNSS augmentation services via satellite communication to support various PNT applications. Table 5 lists the companies providing increased accuracy positioning services using GEO satellites transmitting L-band frequencies.

Unlike aviation SBAS, these commercial SBAS services are not standardised and cannot be ICAO certified. This means not all GNSS receivers are able to receive the augmentation signals and dedicated hardware and subscriptions are required. OmniSTAR is the largest satellite augmentation service provider, and there are 33 receivers from different manufacturers that can decode OmniSTAR messages. Trimble RTX services work on 17 Trimble receivers; the NavCom StarFire service on two NavCom receivers; C-Nav services on two C-Nav receivers; and Fugro Starfix services only work on the one Fugro StarPack GNSS receiver. The augmentation services of

Veripos, TerraStar and Novatel can be used on a select number of receivers from multiple manufacturers. Neither Veripos, Terrastar nor Novatel provide a list, and thus users should check for service availability from the receiver manufacturers. Essentially the receiver must be able to receive and demodulate the augmentation information.

While SBAS uses the L1 to transmit augmentation information, commercial providers lease frequency transponders on GEO communication satellites. The services are delivered using different L-band frequencies, depending on the service and region. For example, the Trimble CenterPoint RTX service is provided through a range of different frequencies and data transmission speeds as shown in Table 6.

Table 7 lists the communication satellites utilised by commercial service providers to deliver augmentation services to their customers. Further investigation confirms that all companies use the same satellites, which is the Inmarsat satellite series.

Table 8 provides a summary of the currently available commercial communication satellites between 100°E and 180°W, which provide L-band transmission communications. These satellites could transmit augmentation corrections to GNSS PNT users in Australia and New Zealand. Excluded in the table are existing aviation SBAS satellites visible to Australia: SDCM Luch-5A, MSAS MTSAT-1R, and MSAS MTSAT-2 satellites already covered in Table 4. It is apparent there are only a few L-band communication satellites in this region, which most likely means that they are already allocated for specific services. The only satellites having available L-band channels visible to Australia are Inmarsat-4F1 and Inmarsat-3F3.

NEXT GENERATION SBAS

Next Generation Aviation SBAS

As stated previously, the current SBAS coverage is limited by the availability of localised ionospheric corrections derived from ground reference receivers, and the present SBAS services only support L1 frequency and mostly single-constellation positioning, i.e., GPS; which further limits the availability and continuity of the SBAS service.

Key SBAS providers such as WAAS and EGNOS are already planning improvements to expand their coverage areas and improve their performance. Next generation SBAS satellites will incorporate transmission of a second civilian signal in the protected aeronautical band (the L5 signal) and incorporate measurements from new GNSS constellations. EGNOS SES-5 and ASTRA 5B satellites for example are capable of transmitting dual-frequency signals compatible with GPS L1/L5 and Galileo E1/E5 signals.

The L5 frequency band is especially suitable for safety-of-life applications because users are not allowed to interfere with their signals. The dual-frequency (L1 and L5) system will also be fully robust against ionospheric gradients that currently limit vertical guidance at times of severe ionospheric disturbances. In fact, the largest benefit of the next generation dual-frequency SBAS system is that the service coverage area can be extended farther away from the ground reference station network by taking advantage of both L1 and L5 frequencies. It is expected that next generation SBAS will improve accuracy, availability and continuity of GNSS performance (EU-US Cooperation on Satellite Navigation Working Group C 2010).

GPS has already launched 12 Block IIF satellites transmitting the L5 signal and is scheduled to achieve L5 Full Operational Capability (FOC) with 24 satellites broadcasting the signal by 2024 (US Government 2014). GLONASS has started to broadcast CDMA signals at both the L1 and L5 frequencies. The Galileo and BeiDou constellations are currently being deployed, and also will broadcast in both the L1 and L5 (or near L5) bands. The Japanese Quasi-Zenith Satellite System (QZSS) has launched 1 satellite in 2012, with 3 additional satellites to be launched by 2018, and complete a 7 satellite constellation by 2023. All QZSS satellites will transmit the L5 signal. The use of multi-constellation satellites and receivers will provide additional redundancy thereby improving the systems' reliability and availability. This is especially important for liability critical applications such as those for Intelligent Transport System (ITS).

The official message specification and ICAO certification of dual-frequency multi-constellation SBAS are not yet in place. The SBAS Interoperability Working Group (IWG) recently agreed on the common GNSS SBAS message design. It is worth noting that the procedure for next-generation SBAS to become fully operational is in fact a lengthy one. The Federal Aviation Administration (FAA) of the United States originally planned to enter the dual-frequency next generation SBAS phase in 2014, with completion planned in 2019. However, as the launch schedule of the newer GPS satellites has changed, the integration schedule has consequently been modified and is now divided into two phases. The first phase, planned to take 5-7 years, focuses on infrastructure improvements to enable the use of the L5 signal. The second phase, also planned to take 5-7 years, follows the declaration of Final Operational Capability (FOC) of the GPS L5 signal and focuses on the implementation of the dual-frequency user capability, e.g., dual-frequency multi-constellation SBAS receivers operating on two frequencies (Lawrence 2015). As such, dual-frequency SBAS is expected, at the earliest, to be fully operational by 2024.

The use of dual-frequency SBAS, as well as expansion of the ground reference network, shows significant potential to create a global LPV-200 level SBAS coverage (Walter et al. 2010). Figures 3-5 show the various possible scenarios of dual-frequency SBAS with the hypothetical expansion of the ground reference stations network.

Adding additional GNSS constellations to improve the coverage and availability of existing SBAS LPV-200 service also provides benefits (Walter et al. 2010). Figure 5 (left) shows the improved coverage when adding Galileo satellites to a single GPS-only system using the existing reference stations network as shown in Figure 3 (left). The additional satellites have potential to fill in the coverage gaps in the northern hemisphere and provide more reliable coverage well beyond the reference stations network. Figure 5 (right) shows the availability of the service coverage area when using the combined dual-frequency SBAS systems with both GPS and Galileo together with hypothetical expansion of the ground stations network in the southern hemisphere as shown in Figure 4 (left). Global service coverage could potentially be obtained with a multi-constellation dual-frequency SBAS using the expanded network of ground reference stations.

Next Generation GNSS and RNSS Satellites with Augmentation Capabilities

GNSS and RNSS satellites such as Galileo, GLONASS, BeiDou and QZSS will transmit augmentation signals with the aim to improve the performance of GNSS. These augmentation signals offer extra data transmission channels and spreading code-encrypted signals purely for civil purposes. One of the advantages of using GNSS satellites for transmission of augmentation corrections instead of GEO satellites is that the coverage at high latitudes (above 60º) is significantly improved with respect to that of GEO satellites.

European Union's Galileo

The Galileo program plans for a complete 30-satellite system by 2020. In addition to the free open service provided by E1 and E5 navigation signals, Galileo satellites also deliver high accuracy positioning capabilities (e.g., PPP) for paying commercial users using the data (E6b) and pilot (E6c) component transmitted in the E6 (or L6, 1278.75 MHz) frequency band (Hernandez et al. 2015). The Galileo commercial service is mainly based on the E6b and E6c signals, which permits the transmission of 448 bps per satellite and spreading code encryption (Rodriguez et al. 2014). Early test results indicate that positioning accuracies at the decimetre level using a standalone receiver with two-day-old orbit and clock predictions can be achieved (Hernandez et al. 2015). Also, research conducted by Thales Alenia Space and the French Centre National d'Etudes Spatiales

(CNES) in 2015 has demonstrated the feasibility of using the E5b signal (250 bps) transmitted by the EGNOS ASTRA 5B[1] satellite payload to deliver a PPP solution (Charlot et al. 2014).

Russia's GLONASS

The first GLONASS-K satellite launched in 2011 transmits CDMA signals in addition to the system's traditional FDMA signals. Of particular interest is the new GLONASS L3 CDMA signal centred at 1207.14 MHz, sharing the same frequency as Galileo E5b signal in the protected aeronautical frequency band. Apart from the SDCM SBAS technology development, PPP service is also planned for transmission on the L1/L3 GLONASS bands by 2018 enabling high accuracy positioning and navigation services (Stupak 2013).

China's BeiDou

The GNSS of the People's Republic of China is known as the BeiDou Satellite Navigation System (BDS), or simply BeiDou. BeiDou has gone through two phases of regional navigation satellite system development (Ding 2011), i.e., BeiDou-1 (Compass Satellite Navigation Experimental System) and BeiDou-2. The BeiDou-2 system began offering regional navigation satellite service in the Asia-Pacific region in December 2012 with six GEO, five IGSO and four MEO satellites. The global navigation satellite system service will be delivered by the BeiDou-3 system. The BeiDou-3 constellation will consist of five GEO satellites, 27 MEO satellites and three IGSO satellites, totalling 35 satellites. Although the original plan aims for completion of the BeiDou-3 constellation by 2020, rapid development of both the ground and space components suggests BeiDou-3 might be finished by as early as 2018.

China has plans to provide its own SBAS service, called Satellite Navigation Augmentation System (SNAS)(Ding 2011). However, there is little information publicly available on the development of SNAS at the time of writing this paper.

[1] The Astra 5B satellite will replace the transponder on Inmarsat 3F2 satellite once the Astra 5B satellite enters EGNOS service planned in late 2016.

Japan's Quasi-Zenith Satellite System (QZSS)

The Japanese QZSS program has launched one IGSO satellite in 2012, and plans are in place to launch three additional satellites (2 IGSO + 1 GEO) by 2018, and complete a seven satellite constellation by 2023. QZSS is intended as a regional augmentation system for GNSS, aimed at enhancing the availability and the performance of GNSS PNT in Japan and its coverage area. QZSS satellites will transmit navigation signals that are fully compatible and interoperable with GPS, i.e., L1C/A, L1C, L2C, and L5. In addition to the navigation signals, QZSS will also transmit two augmentation signals known as L1S and L6; and one experimental augmentation signal in 2018 known as L5S.

The L1S signal will be compatible with the aviation SBAS system, providing sub-metre accuracy wide-area corrections as well as integrity from the GEO satellite to support safety-of-life services. In fact, the MSAS SBAS signal that is currently transmitted from MTSAT satellites operated by the Japanese Ministry of Land, Infrastructure, Transport and Tourism will be transferred to QZSS for transmission via the L1Sb signal using the QZSS geostationary satellite around 2020. The Civil Aviation Bureau of Japan will be responsible for the provision of the L1Sb SBAS signal.

The L6 signal is aimed at providing centimetre-level real-time augmentation service to support high accuracy positioning and navigation applications such as surveying, precision agriculture, and machine guidance. The QZSS L6 signal is transmitted on a 1278.75 MHz carrier frequency, the same frequency as the Galileo E6b signal. The L6 signal is unique in that it has a 2000 bps data capacity, eight times that of an L1 SBAS signal (250 bps). The QZSS L6 signal has sufficient data capacity to deliver real-time positioning accuracies of ±5 cm in the horizontal component and ±10 cm in the vertical component using PPP techniques as demonstrated in Australia and New Zealand (Choy et al. 2015; Harima et al. 2015).

CONCLUSION

This paper provides an overview of potential SBAS availability in Australia and New Zealand, with the intent to identify key similarities and differences in their augmentation capabilities. SBAS systems can be divided into two user categories, namely aviation SBAS and "non-aviation" SBAS. Aviation SBAS is an ICAO certified civil aviation safety critical system providing wide-area GNSS augmentation by broadcasting augmentation information using GEO satellites. As its primary aim is to improve integrity, availability and accuracy of basic GNSS signals for aircraft navigation, aviation SBAS transmits integrity, ranging information, and correction messages that include satellite and ionospheric corrections. Examples of aviation SBAS are WAAS, EGNOS, SDCM, GAGAN and MSAS.

On the other hand, "non-aviation" SBAS systems support numerous GNSS PNT applications using positioning techniques such as wide-area DGNSS and PPP with lesser ground reference station density. These systems are not ICAO compliant because of the difference in data message structures, difference in signal frequencies used to transmit the corrections, absence of the extra ranging signals from the GEO satellites, and absence of integrity data that meet certification requirements by ICAO. Most of these "non-aviation" SBAS systems are commercial in nature, and operated by companies such as Trimble, Fugro and Veripos. It must be stressed that these services mainly focus on delivering accurate positioning solutions through wide-area DGNSS and/or PPP services, guaranteed levels of availability and integrity therefore remain secondary considerations when accuracy is the key driver (Collier et al. 2011).

Next generation GNSS and RNSS such as Galileo, BeiDou and QZSS transmit augmentation signals in the L1, L5 and L6 frequency bands. These augmentation signals have the data capacity to deliver a range of augmentation services such as SBAS, wide-area DGNSS and PPP, to meet the demands of various industry sectors. In addition, there are well developed plans to put in place next generation dual-frequency multi-constellation SBAS. Multi-constellation GNSS increases robustness against potential degradation of core satellite constellations. The use of dual-frequency increase robustness against ionospheric gradients that currently limit vertical guidance in times of severe ionospheric disturbances. In fact, the greatest benefit of dual-frequency multi-constellation SBAS is that the service coverage area can be extended farther away from the ground reference station network as well as using a sparse density of ground stations. It is expected that next generation SBAS and GNSS will improve accuracy, integrity, availability and continuity of GNSS performance.

Australia is fortuitously situated in the GNSS "hotspot" (Dempster and Hewitson 2007; Rizos 2008). It has the advantage over North America and Europe of being able to receive signals from all next generation GNSS and SBAS satellites. Therefore, the opportunity to access these signals as a form of satellite-based augmentation delivery system in Australia offers substantial benefits to improve the performance of GNSS PNT, which could lead to significant increases in the productivity of many industries.

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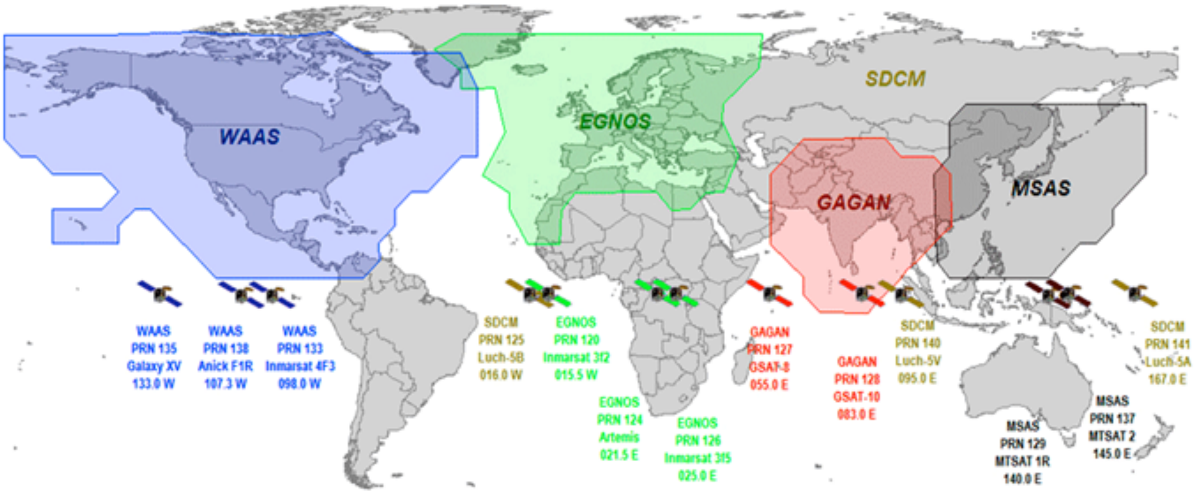


Fig. 1 Existing SBAS Coverage (GENEQ Inc 2015).

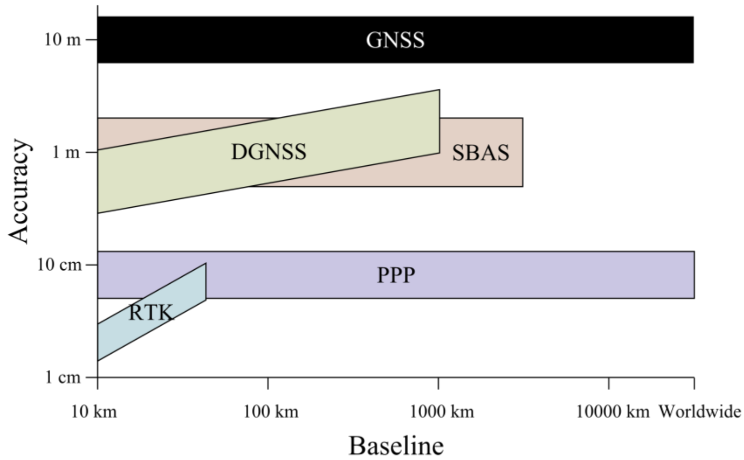


Fig. 2 Comparison of positioning accuracies provided by SBAS, DGNSS, PPP and RTK methods (NovAtel Inc 2015). It should be noted that the positioning accuracies provided by some positioning techniques such as DGNSS and RTK are a function of baseline length.

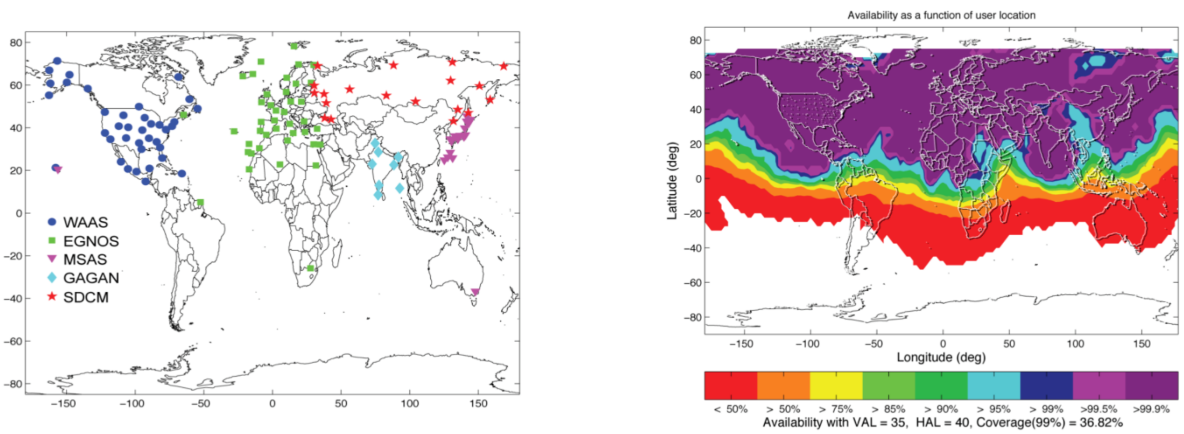
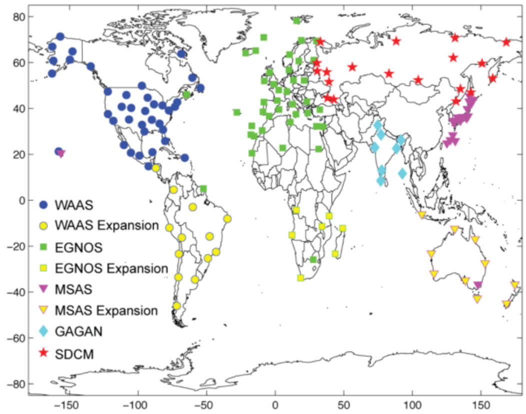


Fig. 3 (Left) Ground reference stations network of the five SBAS systems: WAAS, EGNOS, MSAS, GAGAN and SDCM. (Right) The LPV-200 availability of the five combined dual-frequency SBAS systems (Walter et al. 2010).



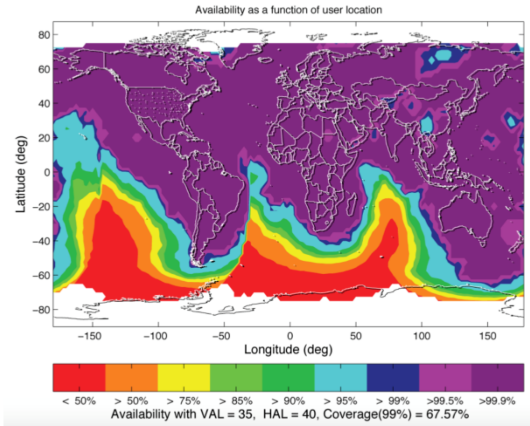


Fig. 4 (Left) Hypothetical expansion of the ground reference stations network of the five SBAS systems (i.e., WAAS, EGNOS, MSAS, GAGAN and SDCM) into the southern hemisphere. (Right) The LPV-200 availability of the combined dual-frequency SBAS systems with hypothetical expansion of ground stations (Walter et al. 2010).

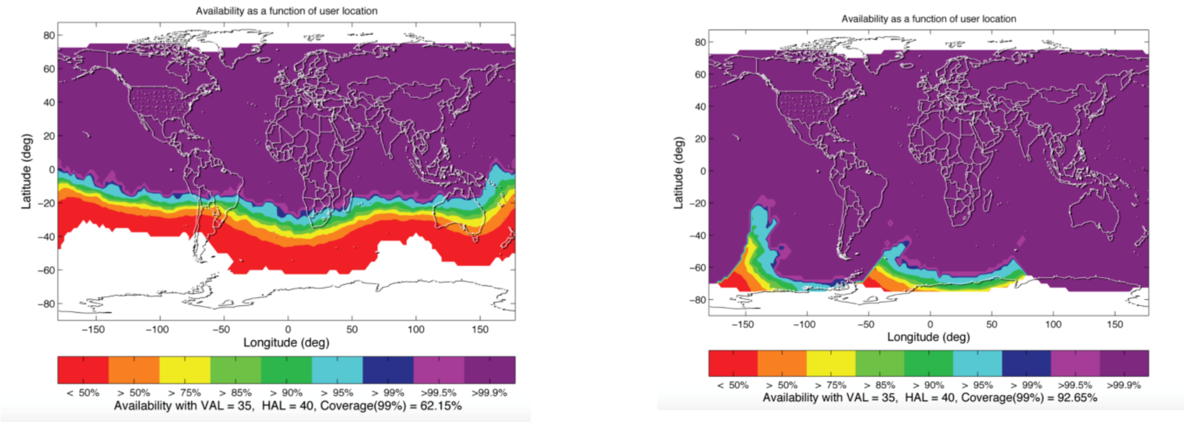


Fig. 5 (Left) Availability of the five combined dual-frequency SBAS systems (i.e., WAAS, EGNOS, MSAS, GAGAN and SDCM) with both GPS and Galileo. (Right) The LPV-200 availability of the five combined dual-frequency SBAS systems with both GPS and Galileo together with hypothetical expansion of ground stations in the southern hemisphere (Walter et al. 2010).

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Table 1 The SBAS L1 radio frequency characteristics.

Parameter	Description
Carrier frequency	1575.42 MHz (L1 frequency)
Modulation	Bi-phase shift key (BPSK) modulated by a bit train comprising the PRN code and SBAS data
Data rate and bandwidth	250 effective bits per second, 500 symbols per second
Ranging codes	Length 1023-bit Gold codes, duration of 1 ms
Minimum received power	-158.5 dBW

Table 2: ICAO certification of performance requirements for various aviation operations (Organization 2008).

Applications	**Accuracy (95%)**		**Availability**	**Integrity**	**Continuity**	**Time to Alert**
	Horiz.	**Vert.**				
En-route	3.7 km	N/A	0.99 to 0.99999	$1\text{-}1\times10^{-7}$/hr	$1\text{-}1\times10^{-4}$/hr to $1\text{-}1\times10^{-8}$/hr	5 min
Terminal	0.74 km	N/A	0.99 to 0.99999	$1\text{-}1\times10^{-7}$/hr	$1\text{-}1\times10^{-4}$/hr to $1\text{-}1\times10^{-8}$/hr	15 s
Non-precision approach (NPA)	220 m	N/A	0.99 to 0.99999	$1\text{-}1\times10^{-7}$/hr	$1\text{-}1\times10^{-4}$/hr to $1\text{-}1\times10^{-8}$/hr	10 s
Approach with vertical guidance (APV-I)	16 m	20 m	0.99 to 0.99999	$1\text{-}2\times10^{-7}$/hr in any approach	$1\text{-}8\times10^{-6}$ per 15s	10 s
Approach with vertical guidance (APV-II)	16 m	8 m	0.99 to 0.99999	$1\text{-}2\times10^{-7}$ in any approach	$1\text{-}8\times10^{-6}$ per 15s	6 s
Precision approach (CAT-I)	16 m	6-4 m	0.99 to 0.99999	$1\text{-}2\times10^{-7}$ in any approach	$1\text{-}8\times10^{-6}$ per 15s	6 s

Table 3: Overview of all current and future SBAS constellations.

Name	Year	Country	Satellites		Australian visibility	Certification
			Total	Operational		
WAAS	2003	USA	3	3	N	CAT-I[2]
EGNOS	2005	EU	4	2	N	CAT-I[2]
MSAS	2005	Japan	2	2	Y	NPA
GAGAN	2011	India	3	2	P	APV-I
SDCM	2011	Russia	3	3	P	APV-II[3]

[2] No details on the exact certification found, but precision approach (CAT-I) is supported.

[3] Currently not yet certified, but shows its intended performance classification.

Table 4: Geostationary satellites used by existing SBAS. Satellites marked with asterisk (*) are not providing SBAS services (as of May 2016). Note that the current SBAS satellites broadcast L5 ranging and data signal, but augmentation service only applies to GPS L1 service.

SBAS	PRN	Satellite name	Position	Signals	Year	Lifespan	Australian visibility
WAAS	135	Intelsat Galaxy 15	133°W	L1/L5	2005	15 year	N
	138	Telesat Anik F1R	107.3°W	L1/L5	2005	15 year	N
	133	Inmarsat-4F3	98°W	L1/L5	2008	15 year	N
MSAS	129	MTSAT-1R	140°E	L1	2005	10 year	Y
	137	MTSAT-2	145°E	L1	2006	10 year	Y
EGNOS	120	Inmarsat-3F2	15.5°W	L1	1996	13 year	N
	126	Inmarsat-4F2*	64°E	L1	2005	13 year	N
	136	SES-5	5°E	L1/L5	2012	15 year	N
	123	ASTRA 5B*	31.5°E	L1/L5	2014	15 year	N
GAGAN	127	GSAT-8	55°E	L1/L5	2011	12 year	N
	128	GSAT-10	83°E	L1/L5	2012	15 year	P
	139	GSAT-15	93.5°E	L1/L5	2015	12 year	Y
SDCM	140	Luch-5A	167°E	L1	2011	10+ year	Y
	125	Luch-5B	16°W	L1	2012	10+ year	N
	141	Luch-5V	95°E	L1	2014	10+ year	Y

Table 5: Commercial GNSS augmentation services that deliver correction information through satellite communication channels.

Company	Services	Accuracy (horizontal)[4]	Convergence time	Notes
OmniSTAR	OmniSTAR HP	5-10 cm (95%)	< 45 min	
	OmniSTAR G2	8-10 cm	< 20 min	
	OmniSTAR XP	8-10 cm	< 45 min	
	OmniSTAR VBS	< 1 m (95%)	< 1 min	Pseudo-range corrections.
Trimble	CenterPoint RTX	< 4 cm (95%)	< 5 min	
	RangePoint RTX	< 50 cm (95%)	< 5 min	
	ViewPoint RTX	< 1 m (95%)	< 5 min	
Fugro	Starfix.G2+	3 cm	Not provided	Uses ambiguity resolution.
	Starfix.G4	10 cm	Not provided	
	Starfix.G2	10 cm	Not provided	
	Starfix.XP2	10 cm	Not provided	Third party corrections.
	Starfix.HP	10 cm (95%)	Not provided	
	Starfix.L1	< 1.5 m (95%)	Not provided	
NavCom	StarFire	< 5 cm (68%)	Not provided	
C-Nav	C-NavC2	8 cm (95%)	Not provided	StarFire algorithms.
	C-NavC1	15 cm (95%)	Not provided	StarFire algorithms.
Veripos	Apex 2	< 5 cm (95%)	Not provided	Own reference station network and calculations.
	Apex	< 5 cm (95%)	Not provided	
	Ultra 2	< 10 cm (95%)	Not provided	JPL reference station network and calculations.
	Ultra	< 10 cm (95%)	Not provided	
	Standard 2	< 1 m (95%)	Not provided	Pseudo-range corrections.
	Standard	< 1 m (95%)	Not provided	
TerraStar	TerraStar-C	Not provided	Not provided	Uses ambiguity resolution.
	TerraStar-D	< 10 cm (95%)	Not provided	
	TerraStar-M	< 1m (95%)	Not provided	Pseudo-range corrections.
Novatel	CORRECT (PPP)	4 cm	20-40 min	TerraStar-C corrections.
Hemisphere	Atlas	4 cm	10-40 min	

[4] Not all companies list the accuracy confidence level. Some mention a 1-sigma level (corresponding to 68%), others mention a 95% confidence (corresponding to 2-sigma). However, in some cases it seems that 1-sigma is being mixed up with 95% (i.e. a website states 1-sigma, but a brochure states 95%). The accuracy values shown in this table are the accuracies reported by the companies, and do not refer to values resulting from independent research.

Table 6: Trimble RTX service broadcast augmentation information on different L-band frequencies and baud rates.

Region	**Frequency (MHz)**	**Baud rate**[5]
Western North America (RTXWN)	1557.8615	600
Central North America (RTXCN)	1557.8150	2400
Eastern North America (RTXEN)	1557.8590	600
Latin America (RTXSA)	1539.8325	600
Europe / Africa (RTXEA)	1539.9525	600
Europe	1523.7250	2400
Asia / Pacific	1539.8325	600

[5] The baud rate is comparable to the data rate. However, to convert the baud rate to the data rate (in bits per second, bps), one needs to know the modulation scheme used. Some modulation schemes are designed to submit 2 bits at once, which means that the bit rate equals to twice the baud rate. For Trimble RTX, the baud rate most likely equals the data rate in bps (Leandro et al. 2012).

Table 7: List of the communication satellites utilised by commercial service providers.

Company	**Augmentation/Communication Satellite**
OmniSTAR	ASAT, MSV, AORW, AORE, ESAT, IOR, PORL
Fugro	ASAT, MSV, AORW, AORE, ESAT, IOR, AUSAT, POR
Fugro Starfix.HP	Inmarsat, SpotBeam
NavCom	IND-W (25°E), PAC-E (98°W), IND-E (109°E)
C-Nav	Inmarsat 4-F3, Inmarsat 4-F1, Inmarsat 3-F5, Inmarsat 3-F4, Inmarsat 3-F3, Inmarsat 3-F2, Inmarsat 3-F1
Veripos	Inmarsat 25°E, 98°W, 143.5°E, AORE, AORW, IOR, POR
TerraStar	Inmarsat 25°E, 98°W, 143°E, AORE, AORW, IOR, POR

Table 8: Geostationary communication satellites containing L-band transmission communication between 100°E and 180°W.

Location	Satellite name	Company	Year	Transmission Band
103°E	Express AM3 (Ekspress AM3)	Russian Satellite Communications Company	2005	1 L-band
105°E	Asiastar 1 (Asiastar)	Worldspace Satellite Radio	2000	3 L-band
128°E	COMS 1 (Chollian)	Korea Aerospace Research Institute (KARI)	2010	1 L band
140°E	Express AM5 (Ekspress AM5, EAM5)	Russian Satellite Communications Company	2013	2 L-band
143°E	Inmarsat-4F1 (Inmarsat 4-F1, I4F1, PAC-W)	Inmarsat plc	2005	228 narrow, 19 wide, 1 global L-band beams
164°E	Optus B3 (Aussat B3)	Optus Communications	1994	1 L-band
178°E	Inmarsat-3F3 (Inmarsat 3F3, I3F3, POR)	Inmarsat plc	1996	22 (+11) L-band

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