STATE OF THE MARKET REPORT

ON COMMUNICATION TECHNOLOGIES USED FOR THE MASS-MARKET DELIVERY OF GNSS CORRECTIONS

2022 EDITION

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List of Acronyms

Acronym	Full form
3GPP	3rd Generation Partnership Project
AMQP	Advanced Message Queuing Protocol
BLE	Bluetooth Low Energy
C-IoT	Cellular Internet of Things
CoaP	Constrained Application Protocol
CORS	Continually Operating Reference Station
COTS	Commercial Off-The-Shelf
DGPS	Differential GPS
FAIR	Findable, Accessible, Interoperable and Reusable
HTPP	Hypertext Transfer Protocol
IGS	International GNSS Service
IoT	Internet of Things
LTE	Long-Term Evolution
LPP	Low Power Positioning
MQTT	Message Queuing Telemetry Transport
NPIC	National Positioning Infrastructure Capability
NRTK	Network Real-Time Kinematic
NTRIP	Networked Transport of RTCM via Internet Protocol
OEM	Original Equipment Manufacturer
OSR	Observation Space Representation
PRN	Pseudo Random Noise
PPP	Precise Point Positioning
PPP-AR	Precise Point Positioning with Ambiguity Resolution
RSSI	Received Signal Strength Indicator
RTK	Real-Time Kinematic
SATCOM	Satellite Communications
SouthPAN	Southern Positioning Augmentation Network
SPARTN	Safe Position Augmentation for Real Time Navigation
SSR	State Space Representation
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
UWB	Ultra-Wideband
VRS	Virtual Reference Station
Wi-Max	Worldwide Interoperability for Microwave Access
WPS	Wi-Fi Positioning System

Executive Summary

This study was produced by FrontierSI and Positioning Insights for Geoscience Australia as part of their Positioning Australia program. The objective of this report is to review how Precise Positioning using Global Navigation Satellite System (GNSS) is currently delivered and to identify technologies that can increase adoption of mass market users.

This report is presented in three parts. The first is a review of ***Communication Technologies, Standards and Protocols*** currently available in Australia. The second summarises existing ***Positioning Service Providers***. The third identifies ***Future Directions and Benefits***. The findings of the report are presented as recommendations to the Positioning Australia program.

Precise positioning using GNSS has only been available for specialised applications. using specialised equipment. Recent positioning technologies can achieve centimetre positioning accuracies at a fraction of the cost of traditional solutions. This precise positioning capability is enabled by improved GNSS signals and GNSS corrections such as Real Time Kinematic (RTK) and precise point positioning (PPP). The increased availability of this technology opens new mass-market applications that bring wider benefits to Australian industries.

The Positioning Australia program is ensuring that consistent, fit-for-purpose data and services are available to government, business, and academia. These services enable existing industries to improve productivity, efficiency, safety, and knowledge. Additionally, positioning services support new industry applications like Intelligent Transport Systems, Location-Based Services, Internet-of-Things and more. to accelerate the industry adoption and uptake of precise positioning, it is essential that the positioning data, and services are Findable, Accessible, Interoperable and Reusable (FAIR).

This report proposes three Future Directions for focused engagement: ***Communication Technology***, ***Communication Protocols***, and ***Data Standards***. Engagement with industry and public groups should specifically consider six Opportunity areas: ***FAIR Principles***, ***Telecommunications Regulations***, ***Integrity***, ***Encryption***, ***Data Licencing***, and ***Outreach***.

Finally, seven recommendations for support of communication technologies are presented to Positioning Australia.

Recommendation 1: Review and engage with organisations developing industry standards relevant to precise GNSS positioning services.

Recommendation 2: Support the ecosystem of GNSS services delivered through various communication channels like satellite L-Band and 5G.

Recommendation 3: Support industry standard protocols like NTRIP, and new protocols like MQTT.

Recommendation 4: Support minimum of two SSR standards, with at least one being independent and open source.

Recommendation 5: Engage with the relevant Industry and Standards organisations regarding standards for NPIC.

Recommendation 6: Engage with OEMs and service providers to support the delivery of precise GNSS positioning services in mass-market applications.

Recommendation 7: Collaborate and align with 3GPP and other telecommunications Industry and Standards organisations working on precise GNSS positioning services.

1. Introduction

The precise positioning landscape is changing. Whilst the concept of delivering GNSS corrections is not new and has been around for over two decades, the way the corrections are transmitted, the types of corrections, standards, protocols, the end users and the user equipment are changing rapidly. Traditionally the users would be setting up their own base stations and delivering Real-Time Kinematic (RTK) corrections via UHF radio. In the maritime environment, Differential GPS (DGPS) corrections were delivered via geostationary communications satellites. With the establishment of Continually Operating Reference Station (CORS) networks and Network RTK technology, mobile internet has become the preferred method of delivering GNSS corrections to the users for land-based applications.

Based on internet radio streaming protocols and HTTP/1.1 standards, the Network Transport of RTCM via Internet Protocol (NTRIP) has been the standard data transmission protocol to disseminate GNSS data and correction streams. NTRIP continues to be the preferred method of GNSS corrections delivery today for areas with mobile internet coverage. In areas that lack internet coverage, users need to revert to either setting up their own base station and using UHF modems or use a commercial satellite-delivered corrections services.

GNSS corrections are typically delivered to users via satellite or over the Internet. For mobile applications requiring the highest precision, corrections must be delivered using IP sessions over a mobile data plan. Such technology requires two-way communication, reducing the ability to scale and increasing costs for both the users and the correction providers. With the introduction of 5G and modern telecommunication standards, such as 3GPP, the ability to deliver this information over terrestrial broadcast signals becomes a possibility.

Whilst NTRIP remains the preferred way of transmitting high-precision GNSS corrections, it is primarily aimed at a niche market of users which is mainly constrained to geospatial, construction and agriculture industries. The receivers that can use these corrections often need to be dual-frequency, cost thousands of dollars, require large antennas as well as professional hardware and software to interact with them. The reason these survey-grade receivers are so expensive, is because they are based on L1 and L2 frequencies. L2 was not an open signal originally and receiver manufacturers needed to spend considerable amounts of R&D in order to be able to use it in civil applications. The techniques of using L2 were patented, which means that any L2 capable receiver will automatically be high in price.

However, this is beginning to change and there are a number of factors responsible for this change. Firstly, GPS modernisation and the advent of a new open civil L5 frequency signal, as well as Galileo reaching near full operational capability, meaning there are now a considerable number of satellites transmitting on L5/$E5_a$ frequency. This means that new L1/L5 capable receivers can be manufactured, which will have similar characteristics of L1/L2 receivers without the extra cost associated with L2 frequency. Receivers are also becoming smaller and lighter, they are designed for different applications in different user sectors. Instead of being a niche, they are becoming mass market with every mobile phone, car and drone becoming potential users of high precision applications.

This can be demonstrated with some of the recent dual-frequency GNSS chipsets coming on to the market. Traditional consumer-grade manufacturers are delving into the high precision space, whilst high-precision manufacturers are starting to produce smaller chipsets targeted at mass markets, whilst maintaining the performance of the more expensive and bulkier GNSS boards that are aimed at high-precision markets. Examples of that trend are shown in Figure 1 with three GNSS chipsets from u-blox, Septentrio and Broadcomm. U-blox and Broadcomm were always targeted at the consumer market with single frequency products until Broadcomm released the BCM4755 dual-frequency model in 2017 and u-blox released the F9P model in 2019. Broadcomm's products are especially targeted at mobile phones, whilst u-blox is aimed at various other applications including cars, drones and robotics. Septentrio on the other hand has always been a high-precision GNSS manufacturer until it released the Mosaic module, also in 2019, which is targeted at similar mass market applications as the u-blox F9P module.

Looking specifically at the mobile phone market, a considerable amount of research has gone into mobile phone positioning over the last decade. Several mobile phone manufacturers, such as Xiaomi, Huawei and Samsung have implemented the Broadcomm dual-frequency module in their phones. Additionally, Google has opened access to raw GNSS measurements courtesy of its Android platform, which effectively means that a mobile phone can be used as a professional GNSS receiver, even though the antenna is still a limiting factor to achieving high-precision results.

Figure 1. ublox F9P (left), Septentrio Mosaic (centre), and Broadcomm BCM4755 (right) GNSS chipsets.

All these developments have brought additional challenges in the way that GNSS corrections are transmitted and received. NTRIP has served the surveying community well over time and is continuing to be the protocol of choice for high precision applications. Satellite-delivered corrections can also be delivered using manufacturer specific standards; however, these methods will not be suitable for mass market applications with potentially millions of users. New ways of delivering data need to be considered. These might come from standard Internet of Things (IoT) protocols as well as the new mobile phone data standards such as 3rd Generation Partnership Project (3GPP), which has provisions for State Space Representation (SSR) corrections.

When it comes to the last point, **precise positioning information** can mean any of the terms described in Table 1. In the context of this report, GNSS Correction Information is of primary concern, as the other classes of precise positioning information do not explicitly feature GNSS information.

Information set	Description	Considered in this report
GNSS Corrections	Affords a positioning performance of at least sub-metre accuracy and better (to the centimetre level). This **correction information** can be streamed in 'real-time' over a communication channel. Examples of correction techniques are DGPS, RTK, Network RTK, VRS, PPP, PPP-RTK amongst others.	**Yes**
3D GNSS-derived Coordinates	Whether as Latitude-Longitude-Height (geodetic) or East-North-Up (grid) coordinates; determined using 'real-time' corrections or 'post-processing' where the required precise positioning performance is achieved after the data collection event (sometimes known as PPK (post-processed kinematic) amongst others).	No
Precise GNSS position solutions and metadata	Often streamed from real-time GNSS devices to other devices or to the internet.	No
File-based GNSS and related products	Such as RINEX, SINEX, precise orbit and clock products in SP3, ionosphere information in IONEX files, NMEA log files, and so on.	No
Additional precise geodetic information	Such as elevations, geoid information, datum information, timestamps and so on.	No

Table 1. Precise Positioning Information Types.

2. Current Communications Technologies, Standards and Protocols

To deliver GNSS information in real-time, four components are necessary: transmission protocol, data standard, communications link and software to decode the data. In this section, we summarise each of these components in detail, namely:

- **Communication technologies** that are used to transfer the data.
- **Transmission Protocols** used to handle the data transfer.

- **Data Standards** used in precise positioning.
- **Software** used in precise positioning activities.

The GNSS signals that are to be transmitted/disseminated as per the topic of this report, are in the 1.2-1.6 GHz frequency range (see Figure 2 and Figure 3 below).

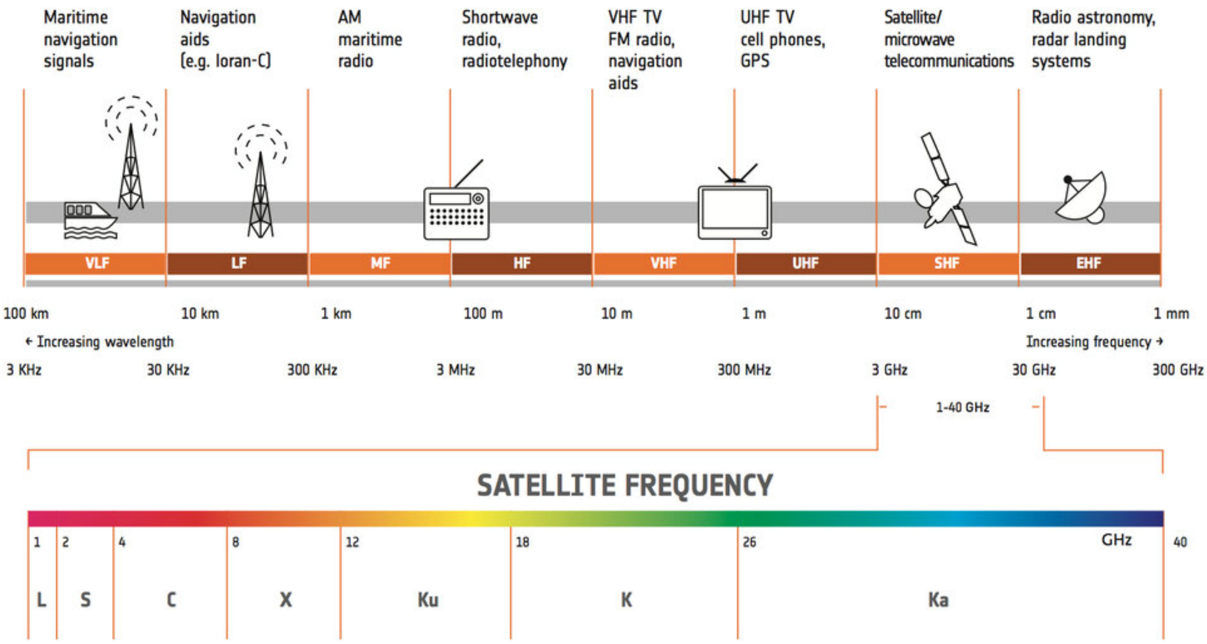

Figure 2. Satellite frequency bands.[1]

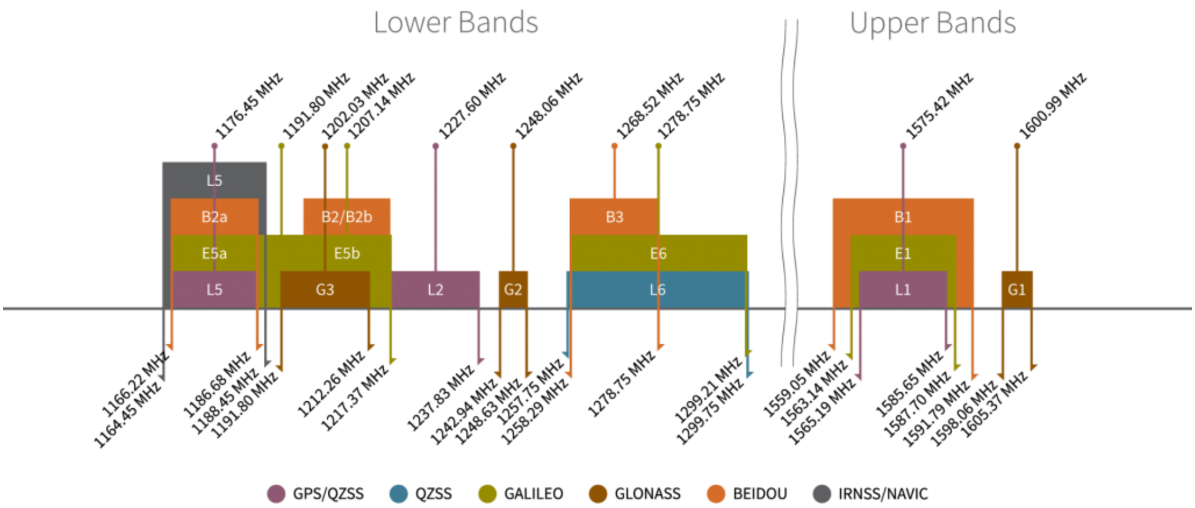

Figure 3. GNSS Signal Frequencies and Types.[2]

2.1. Communication Technologies

GNSS data can be transmitted using several ways, most common of which include mobile internet, satellite and UHF radio, however various other technologies such as Bluetooth and Wi-Fi are also emerging as additional ways to transfer GNSS data.

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[1] https://www.esa.int/Applications/Telecommunications_Integrated_Applications/Satellite_frequency_bands
[2] https://www.tallysman.com/gnss-constellations-radio-frequencies-and-signals/

2.1.1. Cellular Technologies

Cellular technologies have gone through several iterations which are summarised in this section. A new generation of cellular standards has been developed approximately once every decade since 1G systems were introduced in 1979. Each generation is characterised by new frequency bands, higher data rates and not-backward-compatible transmission of technology. Table 2 below summarises the various cellular standards starting from the 3rd Generation (3G).

Cellular Technology	Definition
3G	3rd Generation of wireless mobile telecommunications technology which was introduced in 2001 and superseded 2.5G GPRS and 2.75G EDGE with information transfer rates of at least 14 Mbps.
4G	4th Generation of cellular network technology launched in 2010. The main difference between 3G and 4G are access methodology, data transfer rate, transmission terminology and security. 4G had speeds of up to 100Mbps. 4G introduced several new technologies including 3GPP, LTE and Wi-Max.
5G	5th Generation technology standard for broadband cellular networks which began deploying worldwide in 2019. 5G can be implemented in low-band, mid-band or high-band millimetre-wave 24 GHz up to 54 GHz. Low-band 5G uses 600–900 MHz frequency range; mid-band 5G uses microwaves of 2.3–4.7 GHz, allowing speeds of 100–900 Mbit/s; and high-band 5G uses frequencies of 24–47 GHz. The industry consortium setting standards for 5G is the 3rd Generation Partnership Project (3GPP). It defines any system using 5G NR (5G New Radio) software as "5G".
UWB	Ultra-wideband is a technology for transmitting information across a wide bandwidth (>500 MHz). While not directly connected to 5G, UWB is an important enabling technology for greater data throughput and better location precision for high-speed wireless network applications. UWB is useful for real-time location systems, and its precision capabilities and low power make it well-suited for radio-frequency-sensitive environments.
EDGE	Edge computing in telecoms provides execution resources for applications with networking close to the end-users, typically within or at the boundary of operator networks. The main benefits edge solutions provide include low latency, high bandwidth, device processing and data offload as well as trusted computing and storage (Ericsson, 2021). In simple terms, edge computing moves some portion of storage and compute resources out of the central data centre closer to the source of the data itself.
6G	6th Generation standard is currently under development. Like its predecessors, 6G networks will probably be broadband cellular networks, in which the service area is divided into small geographical areas called cells. 6G networks are expected to be even more diverse than their predecessors and are likely to support applications beyond current mobile use scenarios, such as virtual and augmented reality (VR/AR), ubiquitous instant communications, pervasive intelligence and the Internet of Things (IoT).

Table 2. Communications Technologies – Cellular

2.1.2. Radio Technologies

Various radio technologies have been used to transmit and receive GNSS data. These are summarised in Table 3 below.

Radio Technology	Definition
UHF	Ultra-high frequency (UHF) is the ITU designation for radio frequencies in the range between 300 MegaHertz (MHz) and 3 GHz, also known as the decimetre band as the wavelengths range from one meter to one tenth of a meter (one decimetre).
VHF	Very High Frequency (VHF) is the ITU designation for the range of radio frequency electromagnetic waves (radio waves) from 30 to 300 MHz, with corresponding wavelengths of ten meters to one meter.
LoRa / LoRaWAN	LoRa (Long Range) is a proprietary low-power wide-area network modulation technique and is based on spread-spectrum modulation techniques derived from chirp spread spectrum (CSS) technology. Sometimes referred to as LoRaWAN (Long Range Wide Area Network).
SigFox	Designed to support IoT devices and applications, Sigfox is a specific interpretation of radio signal transmissions within the ISM radio band (868 MHz in Europe and 902 MHz in the US). It uses a wide-reaching Ultra Narrowband (UNB) signal that passes freely through solid objects such as buildings and rocks, and can be used to easily cover large areas.

Table 3. Communications Technologies – Radio

2.1.3. Satellite Technologies

Satellite delivery is another common way to deliver GNSS corrections to a variety of users and markets. Commercial services started delivering DGPS corrections for vessels working offshore. Later services evolved into various types of PPP and PPP-RTK corrections. Satellite-Based Augmentation Systems (SBAS) like the Wide Area Augmentation System (WAAS) in North America, the European Geostationary Navigation Overlay Service (EGNOS) in Europe and the Southern Positioning Augmentation Network (SouthPAN) in Australia and New Zealand are public augmentation systems targeted at civil aviation but with applications in many other industry sectors. Most corrections are delivered via L-band frequencies meaning they are directly compatible with commercial off-the-shelf (COTS) GNSS receivers and antennae. However, commercial services are typically delivered in proprietary formats and are constrained to specific manufacturer hardware. The details on satellite-based GNSS corrections are included in Table 4.

Satellite Technology	Definition
L-band	The L-band frequency spectrum (1-2 GHz) with its wavelength of 30-15cm is typically used for satellite transmissions, such as GNSS, radio, telecommunications, and aircraft surveillance. Commercial services (Omnistar, TerraStar, and others) and public services (WAAS, EGNOS, SouthPAN and others) make use of L-band.

Table 4. Communications Technologies – Satellite

In this context, satellite delivery is understood as a dedicated communication link that broadcasts GNSS corrections. There is the possibility of using satellite Internet (Starlink or Intelsat Ku-band services) to access GNSS corrections over IP. For example, vessels and aircraft with an existing satellite Internet connection can reuse this channel to access GNSS corrections. Whilst this is technically possible, dedicated L-Band services are safer, more reliable, and economical than satellite Internet.

2.1.4. Wireless Technologies

Wireless technologies have not been used traditionally for GNSS corrections transfer, but they're starting to be used more and more, as the technologies mature, become more stable and provide increased range. Table 5 below shows the details of the various wireless technologies that can be used to transport GNSS data.

Wireless Technology	Definition
Bluetooth	Bluetooth is a short-range wireless technology standard that is used for exchanging data between fixed and mobile devices over short distances using UHF radio waves. Bluetooth was developed by industry leaders Intel, Nokia and Ericsson in 1996 in order to transmit data wirelessly between various devices that are within short range of each other. Since then, the technology has undergone a number of upgrades. With release 5.0, Bluetooth Low Energy (BLE) was introduced, which has a long range mode allowing devices to achieve connectivity for distances over a kilometre. Bluetooth technology can also be used to determine the physical location of devices. It works by using the received signal strength indicator (RSSI) measurements to estimate the distance between Bluetooth devices. Just by using RSSI, positioning systems can achieve meter-level accuracy, however, by adding a direction finding feature, these systems can achieve greater accuracy — down to centimetre-level (Bluetooth, 2021).
Wi-Fi	Wi-Fi is a wireless network technology, based on the IEEE 802.11 family of standards, which can be used to connect various devices to the internet using local are networking. The data is exchanged using radio waves that are transmitted in frequencies 2.4GHz or 5GHz. These frequencies are considerably higher than those used for mobile phones, allowing Wi-Fi to carry more data. Since it is based on radio ranging signals, Wi-Fi can also be used for geolocating devices. Wi-Fi Positioning System (WPS) uses a number of Wi-Fi hotspots in the same area to locate a device relative to these hotspots. Wi-Fi positioning has proved popular in indoor locations where GNSS signals are not accessible. WPS also uses RSSI as well as fingerprinting, which is a technique that divides an indoor space into small grids, and collecting RSSI values in each grid cell, which is called a radio map. Fingerprinting compares this radio map with the Wi-Fi signal intensity received from an arbitrary point to presume the grid having the most similar pattern as the user's position. Sub-metre accuracy can be achieved using this method (Lee at al., 2019).
Zigbee	Zigbee is an IEEE 802.15.4-based specification for a suite of high-level communication protocols used to create personal area networks with small, low-power digital radios, such as for home automation, medical device data collection, and other low-power low-bandwidth needs, designed for small scale projects which need wireless connection. Hence, Zigbee is a low-power, low data rate, and close proximity (i.e. personal area) wireless ad hoc network. The technology defined by the Zigbee specification is intended to be simpler and less expensive than other wireless private area networks (WPANs), such as Bluetooth or more general wireless networking such as Wi-Fi.

Table 5. Communications Technologies – Wireless

Figure 4 below shows two examples of Bluetooth and Wi-Fi being used as the communication means between the base and the rover.

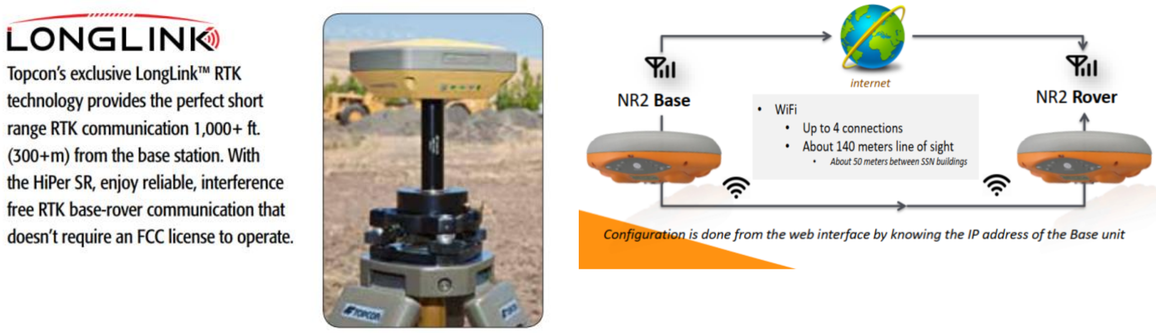

Figure 4. Examples of Bluetooth[3] and Wi-Fi[4] Communications between GNSS Receivers.

Figure 5 below presents an overview of the current communications technologies in use, based on responses to a 2021 Industry Engagement campaign carried out by Geoscience Australia and FrontierSI as part of the Positioning Australia Industry Engagement project. Over 70% of the surveyed precise positioning users reported utilising some form of terrestrial mobile technology, while over 50% of respondents are using satellite communications, presumably in areas of no mobile coverage. Terrestrial Radio transceivers and Terrestrial wired connections were less common responses, but were clearly represented nonetheless.

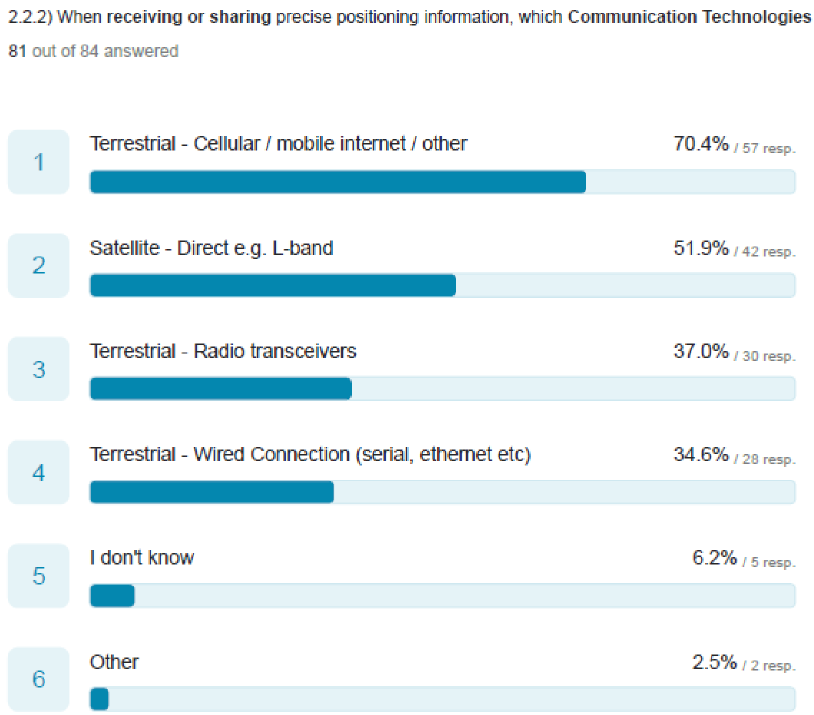

Figure 5. Excerpt from Positioning Australia Industry Engagement campaign responses (FrontierSI, 2021).

2.2. Communications Protocols

Data transmission protocols govern how the data is transferred from the reference to the rover receivers. Networked Transfer of RTCM via Internet Protocol (NTRIP) has been the de facto standard for transferring data via internet. NTRIP is a generic, non-proprietary protocol based on Hypertext Transfer Protocol (HTTP)/1.1 and

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[3] https://www.topconpositioning.com/gnss/gnss-receivers/hiper-sr
[4] https://www.septentrio.com/en/products/gnss-receivers/smart-antennas/altus-nr3

uses TCP (Transmission Control Protocol) as the transport layer. Contrary to its name, it can disseminate any kind of differential data over the internet, not just RTCM. The advantage of using TCP as a transport layer (in contrast to User Datagram Protocol (UDP)) is that it establishes a reliable connection between two IP addresses. If a loss of connection occurs, it will be automatically recognized by the TCP-sockets and this occurrence can be used to trigger software events such as an automated reconnection.

NTRIP has served the precise GNSS community well over time, however that community was largely restricted to surveying, construction and agriculture industries, where users had dedicated professional receivers with NTRIP client capabilities. However, as the precise positioning market expands into consumer and IoT applications, NTRIP is unlikely to scale and be able to deal with the projected increase of users and hence new ways of data transmission need to be found.

Modern data transmission protocols need to improve on NTRIP in a number of areas in order to satisfy the modern mass-market applications. In particular, the focus is on the provision of precise positioning information to service providers and system integrators where the majority of the workloads are handled. Additionally, service providers and system integrators need to manage the ever-expanding user requirements from the current applications, as well as the emerging applications. Overall, the transmission protocols need to satisfy the following requirements:

- Utilise open standards;
- Be interoperable with and supported by modern applications;
- Have a highly scalable, reliable, and secure system architecture;
- Provide additional benefits to existing and future real-time GNSS applications through features such as:
    - Buffering of data during telecommunication outages,
    - Interoperability with other systems,
    - Reduction and optimisation of data transmission bandwidth.

Geoscience Australia commissioned a scoping study in 2020 (Wang, 2020) to examine the various IoT protocols to see whether they could be suitable for transmission of GNSS corrections. Seven protocols were reviewed including HTTP, CoAP, MQTT, AMQP, Websocket, Kafka and 3GPP LPP. For technical details of each protocol the reader is referred to Wang (2020), and the overall performance of the protocols for GNSS data transmission is summarised in Appendix A.

Overall, it was found that MQTT 5 released in 2019 is the most flexible and versatile data communication protocol available to address the future precise positioning requirements and recommended for the future GNSS precise positioning sector. MQTT 3.1.1 released in 2014 has been criticised for the overhead, lack of reasoning and security over other IoT protocols (Wang, 2020). The MQTT 5 addressed these criticisms and enhanced a number of features including new AUTH packet for additional security methods; topic alias to reduce data transmission overhead; better error and reason codes; enhancement for scalability; and capability discovery and request-response.

MQTT comes with three levels of Quality of Service (QoS) defined below:

- QoS0 – At most once,
- QoS1 – At least once,
- QoS2 – Exactly once.

A unified MQTT protocol based on GNSS data delivery service can be established to serve the needs of future data submission, data processing and service management, and data delivery. This finding is confirmed by the industry developments with u-blox, who is one of leaders of precision mass market GNSS chipsets opting to use MQTT as the protocol of choice instead of the more traditional NTRIP. Several issues need to be taken into the account when transmitting terrestrial GNSS corrections to users, including:

- End user market, number of users and their accuracy requirements,
- Type of positioning correction service required – DGNSS, RTK, NRTK, PPP, PPP-AR,
- Whether the services are offered for free or commercially – has implications on authentication and authorisation functionalities,
- Data formats – NMEA, RTCM, various proprietary formats from different vendors,
- Transmission protocols – NTRIP, MQTT, 3GPP LPP,
- What type of precise positioning information to transmit.

Other findings from the project included:

- HTTP & Websocket are designed for web services and applications and as such are supported by major browsers. They have significant overheads, but useful for service management and monitoring purposes.

- MQTT / AMQP / CoAP and Kafka are highly scalable protocols with software implementation supporting distributed / clustering architecture.
- Kafka is more of a software platform than a protocol. It covers streaming, processing, and storage components.
- AMQP and Kafka requires reliable and high throughput network connection. Both are unsuitable for resource constrained devices.
- MQTT and CoAP are both light weighted protocols and used by IoT devices in many applications.
- CoAP is based on UDP lossy connection. QoS has been added as part of the application layer protocol specification, however, is limited to confirmable message or non-confirmable message. The current standard is based on Request and Response model, the publish and subscribe mode is in draft. It is suitable for slow-varying/static information inquiry, notification, or command type of messages, rather than GNSS observation/correction delivery.
- MQTT based on TCP has the most software implementations and community support. It also has the most protocol specified features that may be utilized to improving the service operation and management. The new version 5 provides additional benefits that bring MQTT close to AMQP with enhanced security, reduce overhead, improve scalability, and heaps of other functionalities useful for IoT operation.
- 3GPP has the potential in playing a key role in the real-time GNSS data delivery to end-users within the coverage of cellular services.

The findings from Wang (2020) are summarised in Table 6 below.

Key Performance Indicator	**Most promising protocol**		**< - >**	**Least promising protocol**	
Latency					
Over LAN	CoAP	MQTT QoS0	AMQP	Websocket	HTTP/REST
Over Mobile network	MQTT QoS0	CoAP	Websocket	MQTT QoS1	
Required bandwidth	CoAP	MQTT	AMQP		HTTP/REST
Throughput	MQTT		CoAP	AMQP	
Reliability	MQTT	AMQP	CoAP	Websocket	HTTP/REST
Security	AMQP / MQTT 5	HTTP	CoAP		MQTT 3.x
Developer's preference	MQTT	HTTP/REST	Websocket	CoAP	AMQP

Table 6. IoT protocol transmission performance summary (Wang, 2020).

2.3. GNSS Data Standards

The format of the data and information being communicated, e.g. RTCM Version 3 RTK GNSS messages, International GNSS Service (IGS) precise clock and orbit products can be based on in two types of standards – open and proprietary.

- Open data format standards – commonly open as their standard definition is purposefully within the public domain. Access to open data can either be free (where standards are freely available without license), or licensed (where the standards body typically charges for copies of the standard's definition).
- Closed or proprietary data format standards – closed or private formats, typically by private/commercial organisations as a means of ensuring competitive advantage.

Historically, two formats have been developed for transfer of GNSS data, namely NMEA 0183 and RTCM SC-104 developed by National Marine Electronics Association and Radio Technical Commission for Maritime Services Special Committee 104 respectively. In the early days of GNSS differential services were mainly used in the maritime sector, hence both formats have been developed by maritime organisations. However, as the use of GNSS have spread widely to other sectors, so did the use of these two formats, which quickly spread to all other domains, except aviation, which developed its own standards by the Radio Technical Commission for Aeronautics (RTCA). Both NMEA and RTCM remain de-facto standards for all GNSS receivers to this day, even though they have undergone various version upgrades. The difference between them is that NMEA provides only basic PNT attributes such as timestamped coordinates, whereas RTCM provides full set of raw measurement messages including observations, corrections, biases and more.

Apart from NMEA and RTCM, different GNSS manufacturers have developed their own proprietary standards for transmitting precise GNSS information either as the incumbent standards were either incomplete or of insufficient flexibility to contain the information needed necessary, or an official standard had not even been defined yet.

There is also a competitive aspect that must be considered, whereby having a closed or proprietary format allows for additional information to be transmitted to/from a specific brand affording one or more differentiators to be exploited for competitive advantage. An example is the inclusion of prediction ionospheric information from a local base station for the benefit of any dual-frequency rovers using those messages.

In terms of precise GNSS positioning, there are a handful of proprietary data standards which are well-established across numerous sectors. Note that there are many more proprietary/manufacturer standards out there, however only the most popular / prevalent ones have been included here.

Another important aspect that needs to be considered when transmitting differential GNSS corrections is in which way to represent the states of the GNSS error components. There are two possible options available, which are:

- OSR = Observation Space Representation
- SSR = State Space Representation

In the OSR approach, network corrections are computed in the observation domain, meaning individual errors are modelled for each observation between a satellite and a receiver. GNSS data from the reference stations is used to compute network corrections and these are then applied to the rover using conventional algorithms. The corrections are transmitted to the rover as a lump sum of all the individual errors for each satellite-receiver observation. The rover uses this information to solve ambiguities and compute its position.

In the SSR approach, each individual error component affecting GNSS observations is determined separately providing information about the complete 'state' of the system. Each error component has a functional and an optional stochastic description. Both OSR and SSR approaches are illustrated in Figure 6 and Table 7 below.

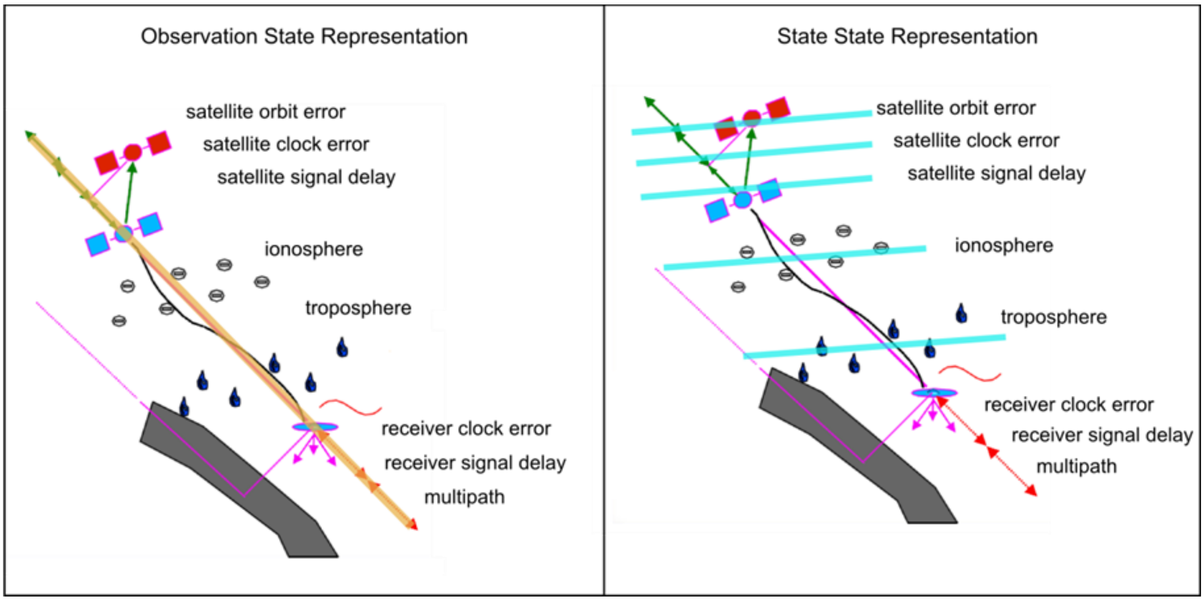

Figure 6 – Diagram illustrating the Observation and State Space Representations (Wübbena, 2008).

Characteristic	OSR	SSR
Bandwidth	High bandwidth requirements. A bandwidth-inefficient format of transmitting all available GNSS corrections (and components) at high data rates and typically supported by duplex communication means.	Low bandwidth requirements. A bandwidth-efficient format to deliver GNSS corrections to mass-market applications at scale, making it suitable for automotive and mobile customers

Error Sources	Grouped	Individual error sources are described as 'states'
Compatibility / Interoperability	Supports most receivers and legacy equipment	Very limited interoperability by niche providers, increasingly by mass-market manufacturers
Coverage	Local to base stations in the area	Wide regional or global coverage
Applications	Small subset of professional users in surveying, construction, agriculture, and similar sectors.	Wide user group including mass market, consumer, automotive, maritime, and other applications.

Table 7. OSR and SSR differences.

The traditional approach of GNSS corrections stemmed initially from the differential code pseudorange corrections developed for GPS in the late 1980s to satisfy maritime positioning requirements, and hence were based on OSR approach. However, more recently SSR has gained more popularity due to its enhanced coverage and more complete modelling of the various GNSS biases. That lead to new data standards being developed targeting SSR corrections, and also traditional standards such as RTCM expanding to also include SSR messages. A selection of the most popular open and proprietary standards are described in Table 8 below.

STANDARDS	ACCESS	PRIMARY SECTORS	OSR / SSR	COMMENTS
RTCA	Open – licensed	Aviation	OSR	Aviation standard
RTCM	Open – licensed	Survey, Maritime, Construction, Agriculture, etc.	OSR	
NMEA	Open - Licensed	Maritime, Survey, Construction, Agriculture, etc.	OSR	
3GPP	Open - free	Mass market	OSR	Telecommunications standard
Trimble RT27/CMR+	Proprietary	Surveying, Engineering, Agriculture, Automotive	OSR	Manufacturer
Ublox ubx	Open - free	Automotive, IoT, mass market, etc	OSR	Manufacturer
Septentrio SBF	Open – free	Robotics, UAV, construction, survey	OSR	Manufacturer
Leica LB2	Proprietary	Survey, construction, agriculture	OSR	Manufacturer
Topcon TPS	Proprietary	Construction, survey, agriculture	OSR	Maufacturer
Javad JPS	Proprietary	Surveying, construction	OSR	Manufacturer
IGS SSR	Open – free	Research, Scientfic	SSR	RTCM Message 4076
Compact SSR	Open – free	Research, Scientfic,	SSR	RTCM Message 4073
SPARTN	Open – free	Automotive, mass market, IoT	SSR	
SSRZ	Open - free	Scientific (including Geodetic, Earth Sciences, Geophysical and Astronomical)	SSR	

Table 8. Open and Proprietary Data Standards for GNSS data.

SSR formats represent the future for mass-market, automotive, and various other positioning sectors. Currently there are four SSR standards that are being actively developed. These include IGS SSR, compact SSR, SPARTN and SSRZ. The comparison of these four standards is shown below.

SSR	Multi-stage/scalability		RTCM-SSR	IGS-SSR	Compact SSR	SPARTN	SSRZ
RTCM framing			yes	yes	yes	no	optional
SV clock	high rate clock		available	available	available	available	available
	low rate clock		available	available			available
SV orbit			available	available	available	available	available
SV code bias			available	available	available	available	available
SV phase bias			Prop/tested	available	available	available	available
Ionosphere	global	VTEC	Prop/tested	available		available	available
	global	STEC	under discussion	under discussion			available
	regional	STEC			available	available	available
	Residual	gridded/ station			available	available	available
Troposphere	global		under discussion	under discussion			in preparation
	regional					available	available
	residual	gridded/ station			available	available	available

Table 9. Comparison of the various SSR standards (Stürze et al., 2020).

IGS SSR, compact SSR and SSRZ are all open standards that are well equipped for future usage by the industry, however at the moment they lack industry support. SPARTN on the other hand is already compatible with two of the leading GNSS chip manufacturers, namely u-blox and Septentrio. Which standard to adopt is a key question for anyone developing various GNSS products and services.

2.4. Industry and Standards Groups

In this section, eleven key Industry Sectors have been selected as highlighted by the Australian Department of Industry. It is worth noting that Standards Australia has responsibility for each of these industry sectors where it relates to their Australian operations. Standards Australia has a number of committees addressing geospatial industry themes, such as IT-004 Geographic Information/Geomatics, and IT-023 Transport Information and Control Systems.

For each industry sectors, the most relevant and applicable Industry or Standards Groups have been identified, with focus on those with a strong or growing interest in precise positioning capabilities. Table 10 presents the relevant International Groups; Table 11 presents the relevant Australian Groups and Table 12presents the relationship to each sector.

GROUP	DESCRIPTION	PUBLICATIONS
RTCM	The Radio Technical Commission for Maritime Services (RTCM) are involved on maritime radio navigation and radio communication policy, regulatory, and standards development. RTCM Special Committees have developed the most widely used format for GNSS correction data.	• RTCM 10403.3, Differential GNSS (Global Navigation Satellite Systems) Services-Version 3 + Amendment 3
RTCA	The Radio Technical Commission for Aeronautics (RTCA) is the premier Public-Private Partnership venue for developing consensus among diverse, competing interests on critical aviation modernization issues.	• Minimum Operational Performance Standards for Global Positioning System / Satellite-Based Augmentation System Airborne Equipment. DO-229E, SC-159.
3GPP	The 3rd Generation Partnership Project (3GPP) develops Mobile Broadband Standards with specifications for cellular telecommunications technologies	• 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Study on positioning use cases; Stage 1 (Release 16) • LTE Positioning Protocol (LPP) TS 37.355
SAE International	The Society for Automotive Engineers (SAE International) are responsible for AE standards and have created J3016™ – the gold standard for benchmarking self-driving systems, which were recently updated (cf. Figure 7)	• Requirements for a terrestrial based positioning, navigation, and timing (PNT) system to improve navigation solutions and ensure critical infrastructure security, SAE6857
ICAO	ICAO supports international diplomacy and cooperation in air transport; Its core function is to maintain an administrative and expert bureaucracy supporting diplomatic interactions and researching new air transport policy and standardization innovations through the ICAO Assembly, or the ICAO Council.	• Standards and Recommended Practices (SARPs), Volume 1 – Annex 10, Amendments 1-81 • Performance-based navigation (PBN) manual, No 9613 AN/937, 3rd edn.
IMO	The International Maritime Organization (IMO) is the United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships.	• MSC.401(95), Performance Standards for Multi-System Shipborne Radionavigation Receivers • MSC.1/Circ.1575, Guidelines for shipborne position, navigation and timing (PNT) data processing
IHO	The International Hydrographic Organization (IHO) is an intergovernmental organization that works to ensure all the world's seas, oceans and navigable waters are surveyed and charted. It issues survey best practices, provides guidelines to maximize the use of hydrographic survey data and develops hydrographic capabilities in Member States.	• S-100 IHO Universal Hydrographic Data Model • S-101 Electronic Navigational Chart (ENC)

IMCA	The International Marine Contractors Association (IMCA) is a leading international trade association for the marine contracting industry. It is a not for profit organisation with members representing the majority of worldwide marine contractors in the oil and gas and renewable energy industries	• Guidance on Satellite-Based Positioning systems for Offshore Applications, International Marine Contractors Association, Rev. 0.1.
IALA	The International Association of marine aids to navigation and Lighthouse Authorities (IALA) is a non-profit, international technical association. The work of the committees is aimed at developing common best practices through the publication of IALA Standards, Recommendations, Guidelines and Model courses.	• IALA Guideline G1129 The Retransmission of SBAS Corrections Using MF-Radio Beacon and AIS, Edition 2.0
IGS	The International GNSS Service (IGS) ensures open access, high-quality GNSS data products. These products enable access to the definitive global reference frame for scientific, educational, and commercial applications.	• RINEX v. 4.00 • SSR v1.0
ISO	The International Organization for Standardization (ISO) is an independent, non-governmental international organization with a membership of 167 national standards bodies. Through its members, it brings together experts to share knowledge and develop voluntary, consensus-based, market relevant International Standards that support innovation and provide solutions to global challenges. Standards are developed by technical committees (TC) and sub committees (SC) among which are: • ISO/TC 211 - Geographic information/Geomatics • ISO/TC 20 - Aircraft and space vehicles • ISO/TC 20/SC 16 - Unmanned aircraft systems • ISO/TC 23/SC 19 - Agricultural electronics • ISO/TC 127 - Earth-moving machinery • ISO/TC 204 – Intelligent Transport Systems	• ISO 17123-8:2015 - Optics and optical instruments — Field procedures for testing geodetic and surveying instruments — Part 8: GNSS field measurement systems in real-time kinematic (RTK) • ISO 12188-1:2010 - Tractors and machinery for agriculture and forestry — Test procedures for positioning and guidance systems in agriculture — Part 1: Dynamic testing of satellite-based positioning devices • ISO/TR 22086-1:2019 - Intelligent transport systems (ITS) — Network based precise positioning infrastructure for land transportation — Part 1: General information and use case definitions • ISO 17757:2019 - Earth-moving machinery and mining — Autonomous and semi-autonomous machine system safety • ISO 19156:2011 - Geographic information — Observations and measurements • ISO 19157-1 - Geographic information — Data quality — Part 1: General requirements • ISO/TS 19157-2:2016 - Geographic information — Data quality — Part 2: XML schema implementation

CENELEC	CENELEC, the European Committee for Electrotechnical Standardization, is an association that brings together the National Electrotechnical Committees of 34 European countries. CENELEC prepares voluntary standards in the electrotechnical field, which help facilitate trade between countries, create new markets, cut compliance costs and support the development of a Single European Market	• Railway applications - Communication, signalling and processing systems - Software for railway control and protection systems, EN 5012 • Railway Applications - The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS) - Part 1: Generic RAMS Process, EN 50126-1
OGC	The Open Geospatial Consortium (OGC) is an international consortium of more than 500 businesses, government agencies, research organizations, and universities driven to make geospatial (location) information and services FAIR - Findable, Accessible, Interoperable, and Reusable.	• 19-008r4 - OGC GeoTIFF Standard • 07-036 - OpenGIS Geography Markup Language (GML) Encoding Standard • 12-007r2 - OGC KML • 06-042 - OpenGIS Web Map Service (WMS) Implementation Specification
NASPSG Foundation	The National Alliance for Public Safety GIS (NAPSG) Foundation is a 501(c)(3) nonprofit organization that was formed in 2005 to overcome the challenges faced by Federal, tribal, state, and local public safety agencies in the adoption and use of GIS as a tool to protect their citizens.	• Implementation Guidance: Information Sharing Standards for Crisis Management Mutual Aid Technology • i-Axis Best Practices Guide to Indoor Mapping, Tracking, and Navigation v2

Table 10 International Industry and Standards Groups

GROUP	DESCRIPTION	PUBLICATIONS
Standards Australia	Standards Australia is a standards organisation established in 1922 and is recognised through a Memorandum of Understanding with the Australian government as the primary non-government standards development body in Australia. International standards are adopted to the national collection of standards by Standards Australia are typically preferred by sectors making a conscious decision on using standards.	• AS/NZS ISO 19115 - ANZLIC Metadata Profile Version 1.1 (implemented using ISO/TS 19139:2007, Geographic information – Metadata – XML schema implementation) • AS1199.0-2003 Sampling procedures for inspection by attributes • AS/NZS 4819:2011 Rural and Urban Addressing • Open Geospatial Consortium (OGC) Web Map Service (WMS) Implementation Specification 1.3.0 (OGC Document No. 06-042) • AS5488-2013 Classification of Subsurface Utility Information (SUI)
ICSM	The Intergovernmental Committee on Surveying and Mapping's (ICSM) core function is to coordinate and promote the development and maintenance of key national spatial data including geodetic, topographic, cadastral, street addressing, tides & sea level, and geographical names.	• Special Publication 10, The Australian Geodetic Datum Technical Manual • Guideline for Adjustment and Evaluation of Survey Control v2.2 • ICSM Guidelines for Digital Elevation Data
ANZLIC	The Spatial Information Council (ANZLIC) is the peak government body in Australia and New Zealand responsible for spatial information. ANZLIC develop policies and strategies to promote accessibility and usability of spatial information, advocating for the resolution of national level issues and providing a link between government and industry, academia and the general public.	• ANZLIC Metadata Profile Guidelines VERSION: 1.2. AS/NZS ISO 19115:2005 Geographic information—Metadata.
CASA	The Civil Aviation Safety Authority (CASA) is the Australian national authority for the regulation of civil aviation. Although distinct from the government, it reports to the Federal Minister for Infrastructure and Transport.	• CNS/ATM resource kit – Chapter 3: Global navigation satellite systems (GNSS) • AC 21-36 v2.3 - Global navigation satellite systems (GNSS) equipment Airworthiness guidelines • AC 91-05 v1.0 - Performance-based navigation
Airservices Australia	Airservices Australia is a government-owned organisation responsible for the safety of its airspace, the safe and efficient management of Australia's skies and the provision of aviation rescue fire fighting services at Australia's busiest airports.	• H03/21 - Change to Instrument Flight Procedure Approach Chart Identification from RNAV to RNP

RISSB	The Rail Industry Safety and Standards Board (RISSB) RISSB is the only accredited standards development organisation for the rail industry in Australia and provides good practice Standards, Codes of Practice, Guidelines and Rules.	• AS 7460 Remotely Piloted Aicraft Systems (Drones) – Operational Requirements
ACRI	The Australasian Centre for Rail Innovation (ACRI) undertakes targeted, applied research and strategic analysis to solve issues raised by the rail industry to support and ensure continued improvement in productivity and sustainability to underpin the competitive position of the Australasian Rail Industry.	
EMV	Emergency Management Victoria (EMV) leads emergency management in Victoria by maximising the ability of the emergency management sector to work together and to strengthen the capacity of communities to plan for, withstand, respond to and recover from emergencies.	• Emergency Management Performance Standards 2019 (version 3)
AIMS	The Australian Institute of Mine Surveyors (AIMS) provides professional representation to government, industry and educational organisations on mine surveying issues around Australia.	• Survey and Drafting Directions for Mining Surveyors 2020 version 2.0
TMR	The Department of Transport and Main Roads, known often as TMR, is a department of the Queensland Government, formed in April 2009 with the merger of the Queensland Transport and the Department of Main Roads. The department provides manuals, guidelines, specifications and other technical information relating to road infrastructure and its operation	• Transport and main roads specifications: MRTS04 general earthworks • Transport and Main Roads SpecificationsMRS05: Unbound Pavements • Transport and Main Roads Specifications:MRS07A Insitu Stabilised Subgrades using Quicklime or Hydrated Lime • Transport and Main Roads Specifications:MRS07C Insitu Stabilised Pavements using Foamed Bitumen
Austroads	Austroads is the collective of the Australian and New Zealand transport agencies, and provides high-quality, practical and impartial advice, information, tools and services to deliver efficient, reliable and safe mobility.	• Vehicle positioning for C-ITS in Australia (Background document), report No. AP-R431/13
Roads Australia	Roads Australia is the peak body for roads within an integrated transport system, representing membership across all of Australia's transport agencies, road, owners, contractors, consultants, technology and material suppliers, and industry groups.	
TCA	The Transport Certification Australia (TCA) is the Australian entity responsible for providing assurance in the use of telematics and related intelligent technologies.	

Table 11 Australian Industry and Standards Groups

INDUSTRY	RELEVANT INDUSTRY AND STANDARDS GROUPS	
	INTERNATIONAL	NATIONAL
Agriculture	ISO, RTCM	Standards Australia
Aviation	ISO, RTCM, ICAO	Standards Australia, CASA, Airservices Australia
Consumer	ISO, RTCM, 3GPP	Standards Australia
Construction	ISO, RTCM	Standards Australia
Emergency Response	ISO, NASPSG Foundation	Standards Australia, EMV
Governmental	ISO, OGC	Standards Australia
Maritime	ISO, RTCM, RTCA, IMO, IHO, IMCA, IALA	Standards Australia
Rail	ISO, RTCM, CENELEC	Standards Australia, RISSB, ACRI
Resources	ISO, RTCM	Standards Australia, AIMS
Road/Automotive	ISO, RTCM, SAE International	Standards Australia, TMR, Austroads, Roads Australia, TCA
Science, Research & Environmental	ISO, RTCM, OGC	Standards Australia
Spatial & Surveying	ISO, RTCM, IGS, OGC	Standards Australia, ICSM, ANZLIC
Utilities	ISO, RTCM	Standards Australia

Table 12 Relevant Standards and Industry Bodies for each sector

There are numerous other organisations and partnerships working on the dissemination of precise positioning information, or the development of standards relevant to precise positioning. Several of these groups produce standards which are applicable to multiple industries.

ISO is a far-reaching organisation with many technical committees, such as TC20 and TC211, featuring 3D positioning and location within their standards; TC20 around aircraft and space systems. ISO/TC211 has a specific focus on Geographic information/Geomatics producing the 19100 series of standards with many of them relevant for GNSS (cf. Positioning Australia PA1003 Report). Some of the ISO standards such as those around ISO Unmanned aircraft systems over multiple sectors. ISO 19116:2019 is applicable to Geographic information and Positioning services across many sectors of industry.

In the automotive industry, SAE International is a prominent global driver for positioning needs around advanced driver aided solutions (ADAS) for connected and autonomous vehicles (CAV) including driverless vehicles as in Figure 7. SAE International, which has created J3016™ – the gold standard for benchmarking self-driving systems

– has recently updated its six levels of driving automation.

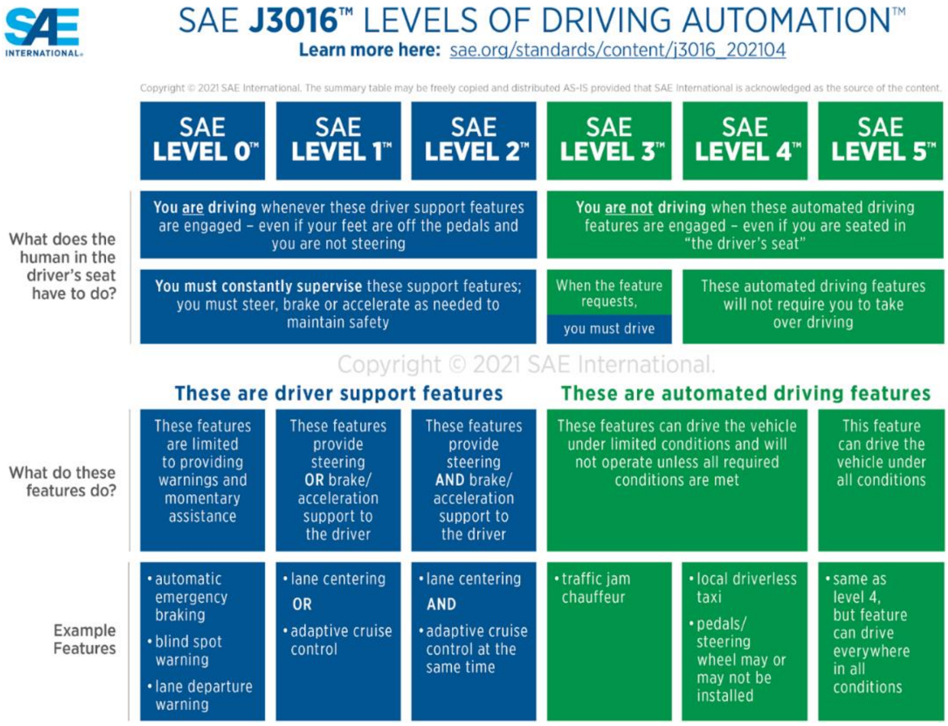

Figure 7. SAE International, which has created J3016™ – the gold standard for benchmarking self-driving systems – has recently updated its six levels of driving automation.

The 3rd Generation Partnership Project (3GPP) brings together seven telecommunications standard development organizations to produce the release specifications that define 3GPP technologies. 3GPP specifications address radio access, core network and service capabilities, providing a complete system description for mobile telecommunications. The 3GPP specifications also provide methods of non-radio access to the network, allowing interoperability with non-3GPP networks. Individual Ministries, Operators, Manufacturers, Associations, and various private companies contribute to 3GPP as 'Individual Members' in the project, collectively addressing shared technical challenges and related scheduling. Through 3GPP Release 15, 16 and 17, 3GPP standards are enabling a step change in 5G capabilities for the precise positioning of mobile devices. 3GPP standards have defined open, interoperable and scalable OSR and SSR representations of GNSS assistance data that can be transmitted over the 5G network, unlocking the potential for 3–5-centimetre real-time accuracies. While Positioning, Navigation & Timing (PNT) forms only a portion of the focus of the 3GPP consortium, many of their releases have provided new capabilities in this area, such as: Release 18 – including Positioning Evolution (TSG RAN)[5], SA1 Services[6] , UAV over 5G[7], Low Power Positioning (LPP), and C-IOT (Cellular IoT).

Open Mobile Alliance (OMA) and its SpecWorks initiative[8] host a Location Working Group (LOC WG). The LOC WG develops specifications to ensure the interoperability of Location Services on an end-to-end basis and provides technical expertise and consultancy on Location Services for other working groups across OMA SpecWorks. LOC WG has collaborated with network operators to deliver a variety of reliable location enabled services; currently focused on extending location services into areas considered difficult to serve (i.e., Indoor Location) and to support the latest technologies such as Wi-Fi positioning, image recognition based positioning, and IOT sensors. OMA has produced the Secure Plane User Location (SUPL) – together with u-blox, et al. Support for the OMA SUPL 1.0 protocol in WCDMA (UMTS) mobile handsets will help drive the deployment of services based on accurate and ubiquitous A-GPS technology -- such as satellite navigation, location-enhanced gaming, personal productivity tools and friend finders -- to add a new level of value to the mobile wireless experience. Another notable OMA initiative is the Mobile Location Services Mobile Location Protocol (MLS-MLP). MLS-MLP is an application-level protocol for

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5 https://www.3gpp.org/ftp/Inbox/Marcoms/Relase_18_features_tsg94_v09.pdf
6 https://www.3gpp.org/Specifications-groups/sa-plenary/51-sa1-services
7 https://www.3gpp.org/technologies/keywords-acronyms/2090-unmanned-aerial-systems-over-5g
8 Location Working Group – OMA SpecWorks

positioning mobile stations (mobile phones, wireless personal digital assistants, etc.) independent of underlying network technology.

The Secure Position Augmentation for Real Time Navigation (SPARTN) format was designed by Sapcorda Services in collaboration with member companies of the Sapcorda joint venture, which has evolved based upon collaboration and interoperability testing in industry. SPARTN is an open standard to provide the data necessary to support high precision positioning applications using GNSS processing techniques in a secure manner. The current version V.2.0.1[9] format is available free of charge and is supported by receiver offerings from prominent OEMs u-Blox and Septentrio.

The Organization for the Advancement of Structured Information Standards (OASIS[10]), are a notable Timing Standards body, seeking to advance capabilities across cybersecurity, blockchain, IoT, emergency management, cloud computing, and legal data exchange. OASIS mission is to advance the fair, transparent development of open-source software and standards through the power of global collaboration and community.

The 5G Automotive Association (5GAA) is an international, multidisciplinary organisation of companies from the automotive, and telecommunications industries, collaborating on end-to-end solutions to address future mobility and transportation services. 5GAA has grown since its launch in 2016 to a global footprint in the automotive, technology and telecommunications industries. This includes automotive manufacturers, equipment suppliers, chipset/communication system providers, mobile operators and infrastructure vendors.

The Open Geospatial Consortium (OGC) SensorThings API is an open, unified way to interconnect spatially enabled data from Internet of Things (IoT) devices, with applications over the Web. The OGC SensorThings API encompasses "Sensing", a standard method to manage and retrieve observations and metadata from IoT sensor systems, and "Tasking", a standard way to parameterize IoT devices, such as individual sensors and actuators, mobile and wearable devices, or even unmanned systems such as drones, satellites, or connected and autonomous vehicles.

There are an increasing number of commercial companies, such as Navmatix, who are now offering an MQTT broker for IoT traffic and data streams (including GNSS RTK and NRTK corrections)[11]. As MQTT implementations continue to be developed for GNSS use cases, standardisation will be necessary to ensure interoperability between service operators and their downstream users.

Recommendation 1: Review and engage with organisations developing industry standards relevant to precise GNSS positioning services.

2.5. Market Feedback on Current Obtainability of Required Performance Levels

This section summarises the public responses to the 2021 Industry Engagement campaign carried out by Geoscience Australia and FrontierSI as part of the Positioning Australia Industry Engagement project, specifically feedback provided on the current obtainability of required performance levels using data standards, technologies, software packages, and protocols currently available within the market – both Australia and overseas.

Figure 8 shows the responses to one such survey question, which asked users whether they are able to achieve their self-reported requirements for Precise Positioning performance. In general, there was a positive response, with 75% of respondents indicating that the levels of performance obtained using the current methodologies were sufficient.

[9] https://www.spartnformat.org/download/
[10] OASIS Open Org
[11] https://www.navmatix.com/services/

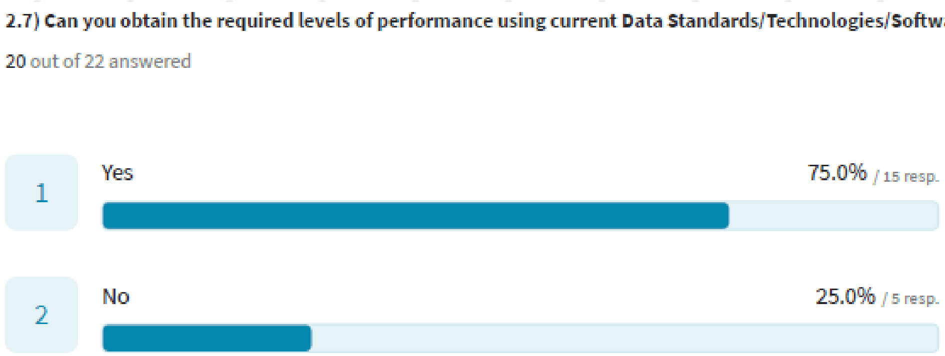

Figure 8. Excerpt from Positioning Australia Industry Engagement campaign responses (FrontierSI, 2021).

"No" Respondents may indicate users with performance requirements at levels that were not achievable with the current standards, technologies, or protocols. In some instances, a "No" response may indicate that some respondents were not aware of the capabilities of existing services on the market, either as free or subscriptions offerings. "No" Respondents were subsequently asked to elaborate on their challenges to provide more context.

A number of responses were filtered during review stages, including requests for 'RTK performance for free over the entire country'. These responses were flagged, and prompted internal discussions about the rationale and feasibility of this capability. It was noted that Australia and New Zealand upcoming SBAS service, SouthPAN, will have a satellite-delivered PPP service which will have free-to-air coverage all over Australia and will assist with approaching the requested levels of performance and availability.

The engagement campaign also sought to understand the variety of different software used in industry, academia and government in relation to precise positioning. Responses were segmented into "common" responses, which were familiar to the project team, and "unexpected" responses, which were notable, interesting, or otherwise worth discussing. These responses are summarised in Figure 9 below.

Q7: When receiving or sharing precise positioning information, which Software(s) are used?	
Q7 Common	Q7 Unexpected
QASTOR	SOCET GXP (BAe Systems) https://www.geospatialexploitationproducts.com/content/socet-gxp
QGIS	Geocortex - plugin for ESRI ArcGIS https://www.geocortex.com/
R, Python, Matlab	R s (software?)
Trimble	DJI RTK
Leica (including GNSS Spider)	Data over Radio
HydroMagic	M-Consulting proprietary http://mconsulting.com.au/
ESRI - ArcGIS	EPOS.P8 ?
GMV	Effigis https://effigis.com/en/
Javad Software	Smallworld
Septentrio RxTools	Bentley Open Roads
Ezsurv	mapbox https://www.mapbox.com/
MapInfo	AgDNA, Farmworks, AFS or PLM Mapping
AutoCAD	ROS (Robot Operating System) https://www.ros.org/
Bernese GNSS Software	Harris Radio (Defense, Part of L3 Corporation) https://www.l3harris.com/all-capabilities/tactical-multiband-radios
In-house developed software (Fugro | Sensahub)	Navcast (Mobile services) https://www.navcast.com/
RTKLIB	
BKG Client, BNC BKG	
WayPoint Grafnet	
Emlid, emlid reach view	
Carlson SurvCE, SURV-PC	
Navsim	
Google Earth	Q7 Comments:
My John Deere	Very little specific mention of Mobile Platforms / applications
12d CAD	

Figure 9. Current Software Used by Respondents of the Positioning Australia Industry Engagement campaign (FrontierSI, 2021).

When asked about the upcoming trends around precise positioning, the following responses were provided by respondents of the Positioning Australia Industry Engagement campaign. Again, responses were segmented into "common" responses, and "unexpected" responses. Some responses were filtered during review stages due to unverifiable relevance, such as "quantum". The responses are summarised in Figure 10 below.

Q10 : Are there any upcoming technologies, protocols, software, data standards you have heard about, which you might consider to use for the receipt and/or transmission of precise positioning information in the future?	
Q10 Common	Q10 Unexpected
SBAS (DFMC)	Movement of the Earth / 4D Positioning
FOSS	STANAG standards (NATO standards)
MQTT	SensorThings API
3GPP	OGC API
5G	TSO-C146 Gamma class
"IoT"	Visual Positioning
"No"	CPro? Terrastar? (commercial services from Veripos | Hexagon)
SSR and IGS SSR	Authentication
GVX??	quantum
GeodesyML	Visual Positioning
Galileo HAS	Third frequency
	software based receivers
	OMA
	open for options = basically anything?
	Too many to list'
	xFill (Trimble for Prec Ag markets)

Figure 10. Upcoming Trends noted by the Respondents of the Positioning Australia Industry Engagement campaign (FrontierSI, 2021).

2.6. Chapter Summary

In summary, GNSS positioning and differential correction delivery are both changing rapidly. Until recently high precision GNSS was a domain of a few specialised industries including surveying, construction, maritime and agriculture being the main ones. Specialised receivers are being used in these sectors and the corrections we delivered via NTRIP protocol in areas with internet coverage and typically OSR method (RTK or NRTK) being used. In places without internet coverage, such as in maritime environment, PPP corrections are typically being used and are delivered via satellite broadcast.

This landscape is changing rapidly, with high precision GNSS coming to mass markets including mobile phones, handheld devices, drones, cars and robotics applications. With this change, the positioning methods, data standards and communication protocols need to change in order to adapt to the growing number of devices, extended geographical coverage, increasing accuracy demands and more.

It is anticipated that SSR will be the dominant positioning method in the future due to its extended coverage, ability to model individual errors and efficient bandwidth requirements, enabling it to stream corrections to increased number of users. It is also anticipated that IoT protocols will take over NTRIP also due to their ability to stream data to virtually unlimited number of users in efficient manner. MQTT stands out as a frontrunner from the various IoT protocols due to a number of advantages listed in Section 2.2, with major manufacturers such as u-blox beginning to adopt it as their primary means of data delivery over NTRIP.

A number of SSR formats are also being developed at the moment and it remains to be seen as to which one will become predominant in the future, but any GNSS correction provider needs to monitor the development of these carefully and make informed decisions as to which format to adopt for their needs.

3. Positioning Service Providers

At present, there are a considerable number of positioning service providers (being different from the actual GNSS constellation operators), with the majority having a primary focus on geospatial applications, although new providers are starting to appear with focus on new markets such as automotive, mass markets and IoT. This section reviews the various providers and is split into governmental and commercial providers, each playing a distinct role in the spatial ecosystem.

Governmental services are typically for single-base RTK streams, using NTRIP-RTCM, and are provided conditional to specific terms; the services are provided free of charge, and the services are provided "as is" without any training or technical support, it is left to the users to work out how they wish to use the service.

Commercial services add value through a multitude of premium paid services and customised RTK solutions, and distinguish their offerings through their additional benefits, such as:

- Nearest base RTK streams (as based on an incoming rover NMEA-GGA) for different geographic regions
- Network RTK streams, such as VRS and MAC, for different geographic regions
- Proprietary correction stream formats, as well as custom formats
- Custom support (and maintenance) of customer CORS sites for private or open usage (where a customer shares their GNSS CORS with the provided for all to benefit)
- Extended Customer Support services including 24/7 support line, training services and troubleshooting, and in some cases service level agreements around response and resolution times.
- Corrections through L-band services, local radio (typically UHF) and spread-spectrum radio.

The following sections provide an overview positioning service providers that operate in Australia; beginning with Australian organisations, and then global organisations.

3.1. Governmental Positioning Service Providers in Australia

Table 13 lists the Governmental positioning service providers in Australia.

NAME	TECHNOLOGIES	PROTOCOLS	STANDARDS	SOFTWARE
Geoscience Australia[12]	Internet accessible RTK correction streams and data files	NTRIP for streams HTTP/S for file products	Open: RTCM v3	GINAN
CORSNet-NSW[13]	Internet accessible RTK correction streams and data files	NTRIP for streams HTTP/S for file products	Open: RTCM v3	Trimble Pivot
QLD[14]	Handled by Geoscience Australia	Handled by Geoscience Australia	Handled by Geoscience Australia	Unknown
VICPOS (VIC)[15]	Internet-accessible RTK correction streams and data files	NTRIP for streams HTTP/S for file products	Open: RTCM v3	Trimble Pivot

Table 13. Governmental Precise Positioning Providers in Australia.

3.2. Commercial GNSS Correction Service Providers – Australia

Commercial services add value through a multitude of premium services and customised RTK solutions as described on the previous page. They are generally provided by the value-added resellers (VARs), which are subdivide in two categories or tiers. Tier 1 VARs offer various national subscription-based services such as Networked Real Time corrections, Single Base solutions and GNSS RINEX data available for download. Tier 2 VARs can provide

[12] https://gnss.ga.gov.au/
[13] https://www.spatial.nsw.gov.au/surveying/corsnet-nsw
[14] https://www.business.qld.gov.au/industries/building-property-development/titles-property-surveying/surveying
[15] http://gnss.vicpos.com.au/Login.aspx

subscriptions to the Tier 1 VAR services in a specific sector such as construction, surveying, or agriculture, along with in-depth knowledge of GNSS equipment. Table 14 provides the list of Tier 1 VARs in Australia along with their various features.

NAME	SERVICES	PROTOCOLS	STANDARDS	COVERAGE
Trimble VRSNow[16]	Network RTK, VRS	NTRIP	RTCM v3, Trimble CMR	Australia wide
Hexagon SmartNet[17]	Network RTK, VRS	NTRIP	RTCM v3, Trimble CMR	Australia wide
AllDayRTK[18]	Network RTK, VRS	NTRIP	RTCM v3, Trimble CMR	Australia wide Offering MiRTK[19]
CodyRTK	Network RTK	NTRIP	RTCM v3	Australia wide
MondoPin	Network RTK	NTRIP	RTCM v3	Selected regions in VIC, NSW, QLD
RTK NetWest	Network RTK	NTRIP	RTCM v3	Selected regions in WA

Table 14. Commercial Precise Positioning Providers in Australia.

3.3. Global Commercial GNSS Correction Service Providers

Globally, there is a considerable number of providers of precision GNSS correction services, spanning national and regional governments, multi-nationals through to private companies and start-ups. Some of the more known services are listed in Table 15. A reliable resource for https://www.usegalileo.eu//EN/inner.html#data=surveying

Brand	Service	Provision	Coverage	Comments
Trimble VRSNow	NRTK	Internet	Global	Land-based
Trimble RTX	PPP/DGNSS	Satellite	Global	Land-based (partnership with Fugro)
Fugro Seastar	PPP/DGNSS	Satellite	Global	Marine
Hexagon SmartNet	NRTK	Internet	Global	Land-based
Hexagon Veripos	PPP/DGNSS	Satellite	Global	Marine
Hexagon TerraStar	PPP/DGNSS	Satellite	Global	Marine
TopNet Live	NRTK	Internet	Global	Land-based
Hemisphere Atlas	PPP/DGNSS	Satellite	Global	Marine
QXWZ	PPP/DGNSS	Satellite	Global	Land-based
Teria	PPP-RTK, NRTK	Satellite, internet	Planned globally	Land-based, automotive
Geoflex	PPP-RTK, NRTK	Satellite, internet	Global	Land-based, marine, automotive
GMV	PPP, SBAS	Satellite, internet	Global	Land-based, marine, automotive

[16] https://positioningservices.trimble.com/services/vrs/vrs-now/
[17] https://hxgnsmartnet.com/en-au
[18] https://www.alldayrtk.com.au/
[19] https://www.positionpartners.com.au/product/mirtk/

C-NAV	PPP/DGNSS	Satellite	Global	Marine
SwiftNav Skylark	PPP-RTK	Internet	Planned globally	Automotive, mass-market
u-blox PointPerfect	PPP-RTK	Satellite, internet	Planned globally	Automotive, mass-market Based on the SPARTN format and MQTT
DDK Positioning	PPP-RTK	Satellite	Global	Land-based, marine, automotive Uses Iridium for comms
StarGate	RTK	Internet	Planned globally	Land-based, single-based RTK only
RXNetworks	PPP-RTK, DGNSS	Internet	Planned globally	Land-based, Telecommunications

Table 15. Global Precise Positioning Services.

3.4. Non-GNSS / Alternate PNT Positioning Services

There are numerous companies and start-ups involved with high-accuracy 2D and 3D positioning using alternate (non-GNSS) methodologies and techniques – some using satellites, and others using terrestrial technologies. These organisations include, but are not limited to those in Table 16 below.

COMPANY	TECHNOLOGY	PROTOCOLS / STANDARDS	COMMENTS
Cohda Wireless	Terrestrial	Using DSRC and others	Primarily for automotive
Echo Ridge	Satellite-based	Unknown	Based on Globalstar network
FocalPoint	Terrestrial	Unknown	Will be incorporated into u-blox chipsets
INMARSAT	Satellite-based	Unknown	Primarily for maritime and resilient PNT applications
Locata Corporation	Terrestrial	Locata ICD	Public ICD is out of date
Ligado	Terrestrial / Satellite-based	Unknown	Partnership with Point One
oneWeb	Satellite-based	Unknown	
Satelles STL	Satellite-based	Unknown	Based on Iridium network
Xona	Satellite-based	Unknown	

Table 16. Global Precise Positioning Providers.

3.5. Telecommunications Positioning Service Providers

As precise positioning services get closer and closer to mass markets, especially mobile phones, IoT devices, drones, and autonomous cars, we see a more important role for telecommunication service providers to deliver the precise positioning corrections to these mass-market users. In this section, we summarise those organisations involved in the telecommunications industry sector that are already starting to offer precise positioning services around the world.

PROJECT	COUNTRY	TELCO	PNT PROVIDER	SERVICE	COMMENTS
Bharti Airtel - OneWeb	United Kingdom	Bharti Airtel	Unknown	Unknown	BA is the third-largest mobile operator in the world with over 425 million customers. Will act

					as the testing ground for all OneWeb products, services, and applications.
China Mobile	China	China Mobile	ComNav	RTK	2,000+ CORS
Qianxun SI	China				2,300 + CORS
Deutsche Telekom & Swift[20]	Germany	Deutsche Telekom	Swift Navigation	SSR corrections via Skylark Service	Telekom's comprehensive communications infrastructure via its new Precise Positioning product offering.
NTT DoCoMo[21]	Japan	NTT DoCoMo	Lighthouse Technology & Consulting	RTK	1,300 CORS using GSI and NTT sites, to provide RTK corrections.
ALES Corporation[22]	Japan	Softbank Group	Enabler	RTK	Custom 3,300 site cell tower network across Japan, each containing a customised Septentrio Ax-SB receiver.
Verizon[23]	United States	Verizon	HERE Technologies	RTK via Hyper Precise Location (HPL) service	ThingSpace IoT portfolio with focus on ADAS
Vodafone (Europe)[24]	Europe	Vodafone	SAPCORDA	RTK	TaaS 10cm positioning from PPP-RTK
Vodafone (Europe)[25]	Europe	Vodafone	Porshe, HERE Technologies	RTK over 5G using MQTT	Focus on road safety
MTS	Russia	MTS	Septentrio, ComNav, Javad	RTK	Starting to roll out 1200 nationwide RTK network across Russia

Table 17. Case Studies of Precise Positioning Services offered in conjunction with Telecommunications Providers.

3.6. Timing Services

Typically, the time is transferred via GNSS is done using either a Precision Time Protocol (PTP), Network Time Protocol (NTP) server, or White Rabbit network. PTP provides sub µs accuracy as compared to millisecond of NTP and is considered to be the technology for the future, however at the moment the protocol suffers from a single point of failure which somewhat limits its use at the moment (GSA, 2020). Nevertheless, it is becoming more and more common in keeping geospatial sensors (such as cameras and LiDAR equipment) synchronized on GNSS / UTC time.

It replaces old fashioned NMEA and PPS signal (Pulse Per Second) as a simple Ethernet cable is required to get a very accurate timing (<1µs). Some high-end GNSS+IMU devices support PTP-server functionality such that as soon as a valid

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[20] https://www.telekom.com/en/media/media-information/archive/swift-navigation-and-deutsche-telekom-announce-partnership-595688#:~:text=Swift%20Navigation%2C%20a%20San%20Francisco-based%20tech%20firm%20redefining,one%20of%20the%20world%27s%20leading%20integrated%20telecommunications%20companies
[21] https://www.nttdocomo.co.jp/biz/service/highprecision_gnss_positioning/
[22] https://www.gpsworld.com/softbank-goes-hard-on-autonomous-positioning-in-japan/
[23] https://www.rrmediagroup.com/News/NewsDetails/newsID/19972
[24] Vodafone Satellite-Based Positioning Tech Can Track Vehicles Within Inches - Inside Autonomous Vehicles
[25] https://www.geospatialworld.net/news/here-vodafone-and-porsche-partner-on-real-time-warning-system/?utm_source=GW+Subscribers&utm_campaign=eb3e3c1dce-gw_weekly_asia_05_july_2021&utm_medium=email&utm_term=0_3b0a203c48-eb3e3c1dce-139617129

GNSS signal is received, a very precise time information can be broadcasted or transmitted across the local ethernet network present on a mobile mapping system for example. All compatible equipment can then time stamp and synchronize data to an absolute GNSS/UTC time.

White Rabbit is an ultra-accurate IEEE 1588 (PTP) implementation capable of providing sub-nanosecond accuracy. This makes it more accurate than traditional PTP methods over wide area networks. A two-way exchange of the PTP synchronisation messages allows precise adjustment of clock phase and offset. The link delay is known precisely via accurate hardware timestamps and the calculation of delay asymmetry. White Rabbit is open-source, with hardware, designs and source code all publicly available from the open hardware repository.

Precision timing is an important feature of various alternative / resilient PNT solutions that are coming on to the market today. Miniaturised optical clocks that can be used on LEO satellites and cubesats hold the key to many different PNT applications now and in the future. For more details on the various timing services please see SmartSat (2021).

4. Future Direction and Benefit of these Technologies to Australia

In this section, guidance and advice is provided to GA and other stakeholders of a future NPIC V2.0 for Australia. The recommended engagement strategies are proposed to address some of the potential challenges, limitations, considerations, and opportunities in. For each entry, an increasing level of engagement status will be stated from one of the following four classes.

- **Watch** – maintain a watching brief of this technology,
- **Participate** – be involved through participation in studies, evaluations etc,
- **Collaborate** – work together with main parties to develop and evaluate technologies,
- **Influence** – take a leadership role in proactively shaping this technology to best suit Geoscience Australia's needs.

4.1. Summary of Findings

This section presents findings and recommendations based on the materials referenced in this report and a number of case studies from developed nations (EU, US, Japan and China). Most technological developments are focused on three key areas: communication technologies, communication protocols and data standards. These engagement areas are where PA should presently focus their efforts to benefit PNT in Australia.

The engagement areas have been summarised in the Table 18 Table 20 below, along with the appropriate level of engagement from Geoscience Australia, whereby an increasing level of 'engagement' goes from: Watch -> Participate -> Collaborate -> Influence.

4.1.1. Communication Technology

The various communication technologies are summarised in Table 18 below.

COMMUNICATION TECHNOLOGY	ENGAGEMENT RECOMMENDATION	COMMENTS
5G	*Collaborate*	5G presents the key technology to deliver precise GNSS corrections to mass market users. Additionally, 5G has an independent means of positioning using location-based beamforming, which is currently being developed and felt to be a future game-changer.
6G	*Watch*	Next generation telecommunications technology, which will replace 5G in the future.
L-band	*Influence*	Actively influence through SouthPAN activities
Wi-Fi	*Watch*	Whilst Wi-Fi maybe outside of Positioning Australia scope, it has a large potential for local positioning systems and indoor navigation, so is advisable to watch how it evolves over time.

Table 18. Recommendations around Communication Technology.

Cellular mobile internet will be dominant, with satellite communications growing significantly into the second most common communications approach. It is felt that the short-range communications (wireless and wired) will still prevail, most likely in niche applications requiring local-area coverage, wherein a decentralised approach is not a hindrance. Specialist applications may also turn to other communication signals/bands from satellites.

L-band and 5G represent key technologies for Geoscience Australia's Positioning Australia program. L-band will be actively utilised through the SouthPAN program via provision of SBAS and PPP services, however other opportunities also exist in the space including provision of Emergency Warning Messages (EWS) via L-band. 5G on the other hand will be the key technology to deliver precise GNSS corrections to mass-market industries and users.

Recommendation 2: Support the ecosystem of GNSS services delivered through various communication channels like satellite L-Band and 5G.

4.1.2. Communication Protocols

Table 19 presents the two key communication protocols that are currently being used to transmit GNSS data.

COMMUNICATION PROTOCOLS	ENGAGEMENT RECOMMENDATION	COMMENTS
NTRIP	*Collaborate*	While NTRIP is the current/incumbent protocol-cum-standard for the dissemination of real-time GNSS corrections and is suitable for the majority of existing niche applications (such as surveying, construction and agriculture), it is clearly not capable of supporting mass-market applications. However, NTRIP should be supported for the foreseeable future to ensure that legacy users can continue to access precise positioning services from PA.
MQTT	*Influence*	MQTT is already established within the IoT sectors as the most applicable protocol for the distribution of positioning information and metadata. The investment into MQTT development and productization by u-blox is a strong signal to the market that MQTT has significant benefits / advantages.

Table 19. Recommendations around Communication Protocols.

Whilst NTRIP has served the surveying community well over the last two decades, it has its limitations and will not be suitable to be used for mass market applications with millions of real-time users. MQTT on the other hand has the necessary characteristics to support mass market applications and hence should be the focus of Geoscience Australia's strategy for the future.

Recommendation 3: Support industry standard protocols like NTRIP, and new protocols like MQTT.

4.1.3. Data Standards

Table 20 shows the various data standards that are used in GNSS and the various recommendations for each one.

DATA STANDARDS	ENGAGEMENT RECOMMENDATION	COMMENTS
RTCM	*Influence*	Influencing this data standard is key / critical for supporting NPIC and SouthPAN
RTCA	*Influence*	Influencing this data standard is key / critical for supporting SouthPAN

NMEA	*Influence*	Influencing this data standard is key / critical for supporting NPIC and SouthPAN
3GPP	*Collaborate*	3GPP presents the data standard for mass market users in the future
IGS SSR	*Influence*	Influencing this open data standard is key / critical for supporting Geoscience Australia's Ginan development
Compact SSR	*Influence*	This standard is a compact form of IGS SSR, hence it would be of equal importance to support it for Ginan development
SPARTN	*Collaborate*	Collaborating with this vendor data standard is important for supporting Geoscience Australia's end user base
SSRZ	*Participate*	Participating with this vendor data standard is important for supporting Geoscience Australia's end user base

Table 20. Recommendations around Data Standards.

To support existing user groups, it is important for Geoscience Australia to continue supporting the current standards such as RTCM, RTCA and NMEA for the current and future services, whilst developing the new generation services and make a slow transition towards these in due course.

SSR formats represent the future for mass-market, automotive, and various other positioning sectors. The introduction of band-width efficient message standards will be favourable not only for the end users and integrators, but also Geoscience Australia in terms of reducing its infrastructure data costs. Currently, there are two independent (IGS SSR and Compact SSR) and two vendor standards (SPARTN and SSRZ) being developed.

IGS SSR, compact SSR and SSRZ are all open standards that are well-equipped for future usage by the industry, however at the moment they lack industry support. SPARTN on the other hand is already compatible with two of the leading GNSS chip manufacturers, namely u-blox and Septentrio. Which standard to adopt is a key question for anyone developing various GNSS products and services. Whilst both the SPARTN and SSRZ formats are fast becoming adopted (or at least their marketing materials suggest so), Geoscience Australia should be wary of supporting only vendor-based standards, for several reasons:

- Such vendor-based standards could easily become closed / premium standards should their creators be acquired or cease operating, and
- 'Community' standards such as IGS-SSR are inherently more open, and may become the de-facto standard in the future.

Recommendation 4: Support minimum of two SSR standards, with at least one being independent and open source.

Recommendation 5: Engage with the relevant Industry and Standards organisations regarding standards for NPIC.

Recommendation 6: Engage with OEMs and service providers to support the delivery of precise GNSS positioning services in mass-market applications.

Recommendation 7: Collaborate and align with 3GPP and other telecommunications Industry and Standards organisations working on precise GNSS positioning services.

4.2. Challenges, Considerations and Opportunities

In addition to the three engagement areas addressed in Section 4.1, our research found that the future direction of PNT is concentrated in the six technologies described below. These are extensions of the communication and standards discussed previously and offer opportunities for future developments in PNT. There are a number of challenges, considerations and opportunities for the evolution of NPIC beyond the above technology, data standards and communication protocols. These are summarised in this section.

4.2.1. FAIR Principles for Technologies, Protocols and Standards

Whichever options are selected by Geoscience Australia for NPIC, adherence to FAIR principles should remain a priority. This includes open standards, ideally internationally recognised ones that GNSS manufacturers and service providers can support and integrate. Given currently there are no Australian-based GNSS manufacturing capabilities, the need to support international standards is mandatory. The challenges, considerations and opportunities for FAIR principles are summarised in Table 21 below.

FAIR Principles	Description
Challenges	Ensuring that NPIC V2.0 and its products, deliverables and services adhere to FAIR principles.
	In light of FAIR, it will be necessary to continue to support legacy messages, standards and protocols for an acceptable amount of time. This would include RTCM corrections over NTRIP, and without authentication (e.g NTRIP-TLS).
Considerations	Distribution of messages (positioning and corrections) that support the ability to handle dynamic datum information.
Opportunities	Collaboration with the OGC around the promotion of Positioning Australia and development of future standards.

Table 21. Challenges, considerations, and opportunities around FAIR Principles.

4.2.2. Telecommunications Regulations

Telecommunication regulations will dictate what kind of data can be transferred using this technology. For example, Release 18 of the 3GPP standard has provision for SSR messages, allowing to transmit these corrections via 5G. As such it is vitally important to follow the development of regulations to understand the impact it can have on positioning technologies. The challenges, considerations and opportunities for telecommunications regulations are summarised in Table 22 below.

Telecommunications Regulations	Description
Challenges	Telecommunication is a new domain for GNSS and as such an adoption curve will be required.
Considerations	How to make the most of what the telecommunications standards have to offer for precise positioning.
Opportunities	Take advantage of the various developments in the telecommunications standards to transmit GNSS correction data.

Table 22. Challenges, considerations and opportunities around Telecommunication Regulations.

4.2.3. Reliability and Integrity

Reliability and integrity are equally important to the actual corrections themselves. Whilst SouthPAN services come with inherent integrity information, Geoscience Australia should consider how to implement these procedures for NPIC data. The challenges, considerations and opportunities for reliability and integrity are summarised in Table 23 below.

Reliability and Integrity	Description
Challenges	How to ensure that the data streams supplied by Geoscience Australia are reliable?
	Provide users with sector relevant comprehensive metadata so that they can assess reliability and fit-for-purpose of data and services to their application
Considerations	How to transmit additional integrity messages with the correction data.
Opportunities	To find new ways of computing and sharing integrity information to users.

Table 23. Challenges, considerations and opportunities around Reliability and Integrity.

4.2.4. Encryption and Authentication

Encryption and authentication, be it through a basic Password and Username / Mobile Number, Transport Layer Security (TLS), advanced encryption keys or something different, is something that needs to be considered for the future of positioning corrections delivery by Geoscience Australia. The challenges, considerations and opportunities for Encryption & Authentication are summarised in Table 24 below.

Encryption and Authentication	Description
Challenges	Incorporating Encryption and Authentication information would be challenging as this is a new area.
	Multiple federal stakeholders may benefit from additional information, e.g., PTP in support of timing services for federal authorities and industry.
Considerations	Is there a demand to provide encrypted data? And from which industry sectors?
	Evaluate and assess whether these existing Galileo features have any relevance to NPIC: PRS (Public Regulated Signals) OSNMA messages (Galileo Open Service Navigation Messages Authentication)
	Quantum encryption is a methodology / technology that should be watched, especially as federal government is investing heavily in this.[26]
Opportunities	NPIC broadcast additional information alongside the conventional GNSS precise positioning messages.
	SouthPAN could supply additional value-add messages and information such as, but not limited to: • System Integrity • Authentication • Timing Services At the moment authentication is listed as a future enhancement of SouthPAN.
	Facilitating the output of precision GNSS correction messages using the government communications networks, for the specific purpose of federal

[26] https://www.pmc.gov.au/resource-centre/domestic-policy/quantum-communications-incl-quantum-key-distribution

	departments such as emergency response et al. E.g. can Terrestrial Trunked Radio (TETRA) networks support RTK Corrections?

Table 24. Challenges, considerations and opportunities around Encryption and Authentication.

4.2.5. Data Licensing and Service Level Agreements

With an increase in the number of innovative (non-geodetic) organisations who may wish to access the data streams from Geoscience Australia, it will be necessary to design and implement a framework supporting different tiers of usage, such as different tiers of usage, for example Federal, Defence, Science & Academic, Industry etc.

New companies have the opportunity to offer subscription services to GNSS users for various market sectors. These companies are accessing the downstream data from Geoscience Australia and repackaging it for different markets and users. Given the likely importance of reliable and highly available data streams, what are the repercussions of this open public data?

The challenges, considerations and opportunities for Data Licensing and Service Level Agreements are summarised in Table 25 below.

Data Sharing and SLA	Description
Challenges	Ensuring consistent licensing / sharing model(s) exists for the various service level providers.
	Providing reassurance to industry that Positioning Australia's data sharing services will be reliable, robust and adheres to FAIR.
Considerations	Does or will Geoscience Australia have any liability for the data it provides for the various stakeholders.
Opportunities	To promote innovation and economic growth by providing precision correction data under an open license.
	Investigate any possible accreditation / compliance opportunities (such as ISO/ICAO etc) for NPIC data products and services

Table 25. Challenges, considerations and opportunities around Data Sharing and SLA.

4.2.6. Marketing and Outreach

Marketing and outreach activities should not be overlooked as they correlate directly to the successful adoption and uptake of technology. Outreach institutions like EUSPA, GNSS Asia and MultiGNSS Asia are examples of the outreach carried out by Galileo, QZSS and other system providers. In a similar way, marketing for Positioning Australia services needs to be done consistently across the various sectors by attending the various events around the country, running workshops, and publishing regular newsletters, as well as providing clear engagement points and pathways to handle industry feedback and concerns.

The challenges, considerations and opportunities for Marketing and Outreach are summarised in Table 26.

Marketing and Outreach	Description
Challenges	Outreach to the various stakeholders including federal agencies, industry and international bodies needs to be carried out
	Communication of capabilities, intentions and developments needs to be done consistently
Considerations	Strengthening the marketing activities and market reach around Positioning Australia activities
	Creating an Outreach Strategy that successfully engages the key industry sectors within Australia, as well as the international GNSS community

Opportunities	Positioning Australia should be further developed as a 'brand within a brand'. A suitable tagline could be 'Powered by Positioning Australia' or 'Positioning Australia Inside'.

Table 26. Challenges, considerations and opportunities around Marketing and Outreach.

4.3. Summary of Recommendations

This report has outlined seven recommendations to Geoscience Australia, intended to assist with the future development of NPIC services. These recommendations are as follows:

Recommendation 1:

Review and engage with organisations developing industry standards relevant to precise GNSS positioning services.

Recommendation 2:

Support the ecosystem of GNSS services delivered through various communication channels like satellite L-Band and 5G.

Recommendation 3:

Support industry standard protocols like NTRIP, and new protocols like MQTT.

Recommendation 4:

Support minimum of two SSR standards, with at least one being independent and open source.

Recommendation 5:

Engage with the relevant Industry and Standards organisations regarding standards for NPIC.

Recommendation 6:

Engage with OEMs and service providers to support the delivery of precise GNSS positioning services in mass-market applications.

Recommendation 7:

Collaborate and align with 3GPP and other telecommunications Industry and Standards organisations working on precise GNSS positioning services.

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6. Appendices

6.1. Appendix A – IoT Protocol Transmission Performance Summary (Wang, 2020)

Protocol	HTTP (2.0)	CoAP	MQTT	AMQP	Websocket	Kafka	3GPP LPP
Standard	IETF	IETF	OASIS	OASIS	IETF	Apache Software Foundation	3GPP
Architecture	Client / Server	Request / Response or Client / Server	Client / Broker	Client / Broker	Client / Server	Client / Broker	Client / Server
Abstraction	Request / Response	Request / Response or Client / Server	Publish / Subscribe	Publish / Subscribe	Request / Response	Publish / Subscribe	Request / Response and Broadcast
Header Size	Undefined	4 Bytes	2 Bytes	8 Bytes	TBD	Undefined	TBD
Message pattern	Large and Undefined (depends on the web server or the programming tech	Small and Undefined (normally small to fit in single IP datagram)	Small and Undefined (up to 256 MB maximum size)	TBD	TBD	TBD	Vary, defined by the Information Element (IE) in the standard
Semantics/Methods	Get, Post, Head, Put, Patch, Options, Connect, Delete	Get, Post, Put, Delete	Connect, Disconnect, Publish, Subscribe, Unsubscribe, Close	Open, Begin, Attach, Transfer, Flow, Disposition, Detach, End, Close	TBD	TBD	TBD
QoS/Reliability	Limited (via Transport Protocol - TCP)	Confirmable Message or Non-confirmable Message	QoS 0 - At most once QoS 1 - At least once QoS 2 - Exactly once	3Levels	TBD	TBD	Via LPP acknowledgement request and/or indicator
Transport Protocol	TCP	UDP	TCP (MQTT-SN can use UDP)	TCP	TCP	TCP	LTE
Security	TLS/SSL	DTLS/IPSEC	TLS/SSL, AUTH packet for SASL framework or OAuth / re-authentication	TLS/SSL	TLS/SSL	TLS/SSL	Authentication and Key Agreement (AKA) protocol
Software support	High	High	High	High	High	N/A	Manufacture and equipment providers

Table 27. Comparison of modern data transmission protocols.

6.2. Appendix B – GNSS Positioning Hardware Providers (chipsets, modules, receivers, systems)

There are numerous organisations developing, manufacturing and distributing GNSS receivers and components, including chipsets, modules and systems. They can be classified as Professional or Consumer level systems. The providers listed below all offer precise positioning services that make use of augmented positioning information, either through cellular internet, L-band SBAS systems or a combination of both.

Professional

Professional GNSS hardware providers include, but are not limited to:

- Bad Elf – bad-elf.com/
- CHC Navigation – www.chcnav.com/products/gnss-systems
- ComNav Technology – m.comnavtech.com
- EOS Positioning Systems – eos-gnss.com
- Furuno – www.furuno.com
- Garmin – www.garmin.com
- Hexagon – www.hexagon.com including NovAtel www.novatel.ca and Leica Geosystems www.leica-geosystems.com
- Hi-Target – en.hitarget.com.cn
- Honeywell – www.honeywell.com
- Javad GNSS – www.javad.com/
- Juniper Systems – junipersys.com/
- Kongsberg – www.kongsberg.com
- Satlab – www.satlab.se
- Septentrio – www.septentrio.com
- South – en.southgnss.com
- STMicroelectronics – www.st.com/content/st_com/en.html
- Swift Navigation – www.swiftnav.com/about-us
- Tersus GNSS – www.tersus-gnss.com/
- Topcon Positioning Systems – www.topconps.com
- Trimble | Ashtech | Spectra Precision – www.trimble.com
- Unicore – en.unicorecomm.com/
- Unistrong (Beijing Unistrong Science & Technology) – www.unistrong.com/ including Hemisphere GNSS www.hemispheregnss.com and Stonex www.stonex.com

Consumer

Consumer-grade GNSS hardware providers include, but are not limited to (in alphabetical order):

- Broadcom – www.broadcom.com/products/wireless/gnss-gps-socs
- LOCOSYS – www.locosystech.com/
- Qualcomm Technologies – https://www.qualcomm.com/products/automotive/positioning-solutions
- Quectel - https://www.quectel.com/
- Skytraq Technology – www.skytraq.com.tw/products/products.html
- u-blox – www.u-blox.com/en/positioning-chips-and-modules