PPP-RTK market and technology report

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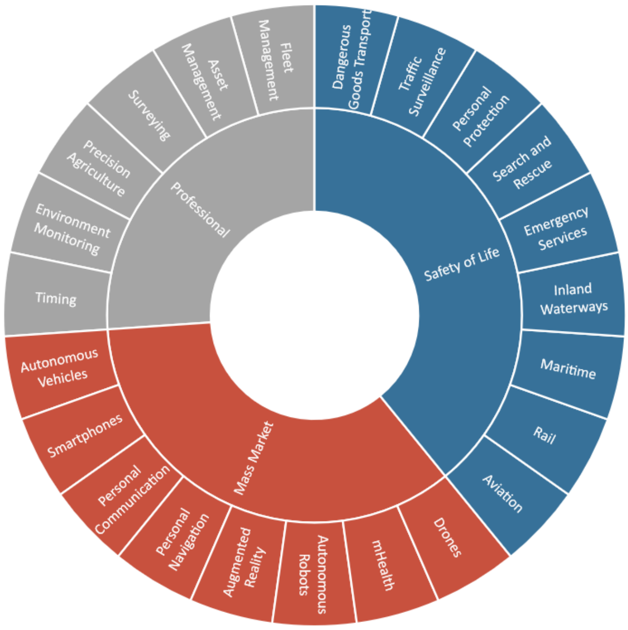
EXECUTIVE SUMMARY

Whilst GNSS offers fantastic benefits to the modern world and has enabled many applications across multiple industries, often the standalone accuracy provided is not sufficient for professional applications such as **Precision Agriculture** and **Surveying**. Errors must be eliminated from the location data to achieve high accuracy positioning; multiple technologies such as **PPP (Precise Point Positioning)**, **RTK (Real Time Kinematic)** and more recently the hybridisation of the two, **PPP-RTK,** have been developed to achieve this.

A review of these technologies was undertaken to determine their suitability to mass-market applications. RTK is held back by its requirement for bi-directional communication, limiting the number of users the network could support. PPP has long convergence times which typically don't align with mass-market user requirements. PPP-RTK eliminates both issues and looks to be a promising technology for the mass-market. Multiple **innovative concepts** have already been developed for PPP-RTK, highlighting its potential. To understand the defining features and characteristics of these models, a literature review was undertaken. Multiple research papers and discussions with experts found that these innovative concepts are **mathematically equivalent,** these are therefore expected to deliver equal results.

Exhibit 1: Examples of High-Accuracy GNSS Applications



Interviews were held with 15 industry experts to obtain a comprehensive understanding of the market and to interpret how it is expected to develop, as well as to discuss the feasibility of applying high-accuracy signal augmentation technologies to **smartphones** and **automotive** applications. Most of the experts interviewed believe that there would be a benefit of achieving high-accuracy positioning for both applications, but that the **low-quality antennas** currently make them **incapable of achieving the expected accuracies**. In coming years, as mass-market antennas develop, both smartphones and automotive hardware are expected to be able to achieve high-accuracy positioning.

Given the highly developed nature of the European market, the deployment of PPP-RTK is expected to see success once its benefits have been clearly demonstrated in real-world applications. The introduction of **Galileo High Accuracy Service (HAS)** is expected to be well received by most of the industry, but it will be a direct competitor to some solutions provided by current service providers. As such, it is thought that Galileo HAS will have a greater impact on mass-market applications rather than professional or safety of life applications already served by commercial service providers.

To enable PPP-RTK to be applied on a global scale, the data format must first be standardised. The

Radio Technical Commission for Maritime Services (**RTCM) standard** has been widely accepted for Observation Space Representation (OSR) data, and the standardisation process for State Space Representation (SSR) for PPP-RTK is ongoing. It is believed that **delays** within the standardisation procedure are being caused by private entities who have their own interests in the adoption of a specific data format, due to having already deployed hardware or services using their own **proprietary data format**.

The inadequate quality of antennas currently available for mass-market hardware and the delays within the RTCM standardisation process are currently acting as barriers to the adoption of PPP-RTK to mass-market applications. **Mass-market antennas** suitable for high-accuracy applications should be focus of development activities by industry.

Abbreviations and Acronyms

Acronym	Description
A-PPP	Array-Aided Precise Point Positioning
AR	Augmented Reality
BIM	Building Information Modelling
CAGR	Compound Annual Growth Rate
CLAS	Centimetre Level Augmentation Service
CORS	Continually Operating Reference Station
CSSR	Compact State Space Representation
DAB+	Digital Audio Broadcasting
EGNSS	European Global Navigation Satellite System
FKP	Flächen–Korrektur–Parameter (Area Correction Parameters)
FLAMINGO H2020	Fulfilling enhanced Location Accuracy in the Mass-market Initial GalileO services Horizon 2020
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPS	Global Positioning System
HAS	High Accuracy Service
HMI	Hazardously Misleading Information
INS	Inertial Navigation System
LBS	Location Based Services
LDBV	Landesamt für Digitalisierung, Breiband and Vermessung
MAC	Master Auxiliary Concept
NRTK	Network Real-Time Kinematic
OS	Open Service
OSR	Observation Space Representation
PPM	Parts Per Million
PPP	Precise Point Positioning
PPP-AR	Precise Point Positioning with Ambiguity Resolution
PPP-AR	Precise Point Positioning Ambiguity Resolution
PPP-RTK	Precise Point Positioning – Real-Time Kinematic
PRS	Pseudo Reference Station
QZSS	Quasi-Zenith Satellite System
RMS	Root Mean Square
RS	Reference Station
RTCM	Radio Technical Commission for Maritime Services
RTK	Real-Time Kinematic
SOL	Safety Of Life
SSR	State Space Representation
VRS	Virtual Reference Station

1. INTRODUCTION

1.1 Background and context of the study

The main goal of this study is to assess the innovative concepts around Real-Time Kinematic (RTK) and Precise Point Positioning (PPP), with focus on their hybrid variations (e.g. PPP-RTK), relevant on-going standardisation activities, new players in the market, opportunities and limitations, as well as to perform an analysis on the PPP-RTK actual functioning, and associated pros and cons for this concept to be used in mass market applications, including automotive platforms.

1.2 Document Scope and Objectives

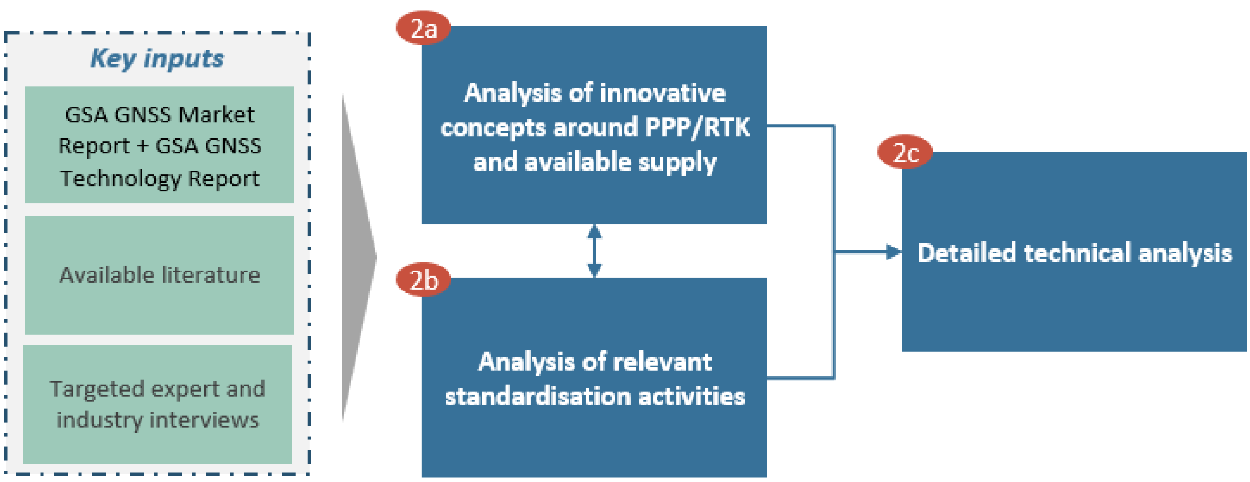
1.2.1 Objective

This document aims to provide an overview of the key technologies in the high-accuracy market and analyse the key innovative concepts surrounding PPP-RTK. The commercially available products will be highlighted, as well as the planned developments of the companies providing them. The opportunities and limitations of the European market will be showcased, in conjunction with the ongoing standardisation activities.

1.2.2 Scope

This document is aimed at providing the findings of the study tasks (Exhibit 2). The scope of these tasks covers a detailed analysis of the technological advancements within PPP, RTK and the hybridised PPP-RTK, a review of the GNSS signal augmentation market, and a review of the relevant standardisation activities. Interviews were held with industry experts who provided insights on the outlook of the market and technology trends; the key outcomes of these discussions are included either at the end of each relevant section or referred to across the document, as deemed necessary.

Exhibit 2: Scope and focus of this document



1.3 Study inputs

1.3.1 Stakeholder Consultation

1.3.1.1 Aim of consultation

Key members of the GNSS industry were invited to support this study through interviews. The aim of this consultation was to validate the literature review as well as to ensure an accurate understanding of the technologies. These interviews were undertaken with nine industry experts from a variety of field of expertise.

1.3.1.2 Scope of interviews

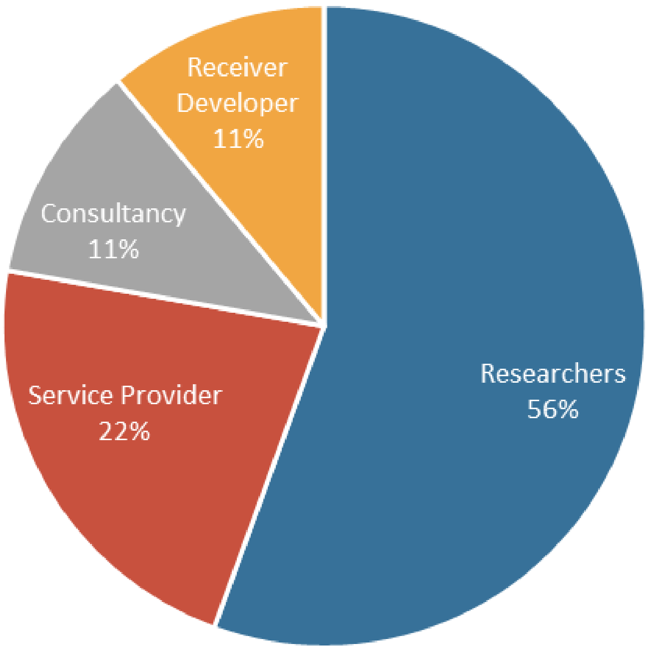
The interviews discussed the status of the current European market regarding high-accuracy positioning services, the details of PPP-RTK technology and its application to mass-market applications, as well as the impact that Galileo High Accuracy Service (HAS) might have upon the high-accuracy positioning market.

Each interviewee was informed that any and all information obtained through the interviews would be anonymised and that no information obtained from them would be directly quoted within this study. The minutes of these interviews are not to be shared with any other party outside of the GSA without obtaining approval of the interviewee.

1.3.1.3 Stakeholder Expertise

To ensure that an accurate representation of the current market situation was obtained, interviews were held with a variety of key industry stakeholders whose associations are shown in Exhibit 3.

Exhibit 3: Associations of Interviewed Stakeholders



A more detailed breakdown of the expertise represented by the stakeholders is shown in Exhibit 4.

Exhibit 4: Breakdown of interviewees and relevant expertise

Label	Category	Expertise
Researcher A	Research expert	Navigation, Geomatics, Surveying
Researcher B	Research expert	Geodesy, Navigation and Position Fixing, Surveying, Satellite-based positioning
Researcher C	Research expert	GNSS, signal augmentation technologies, PPP-RTK, GNSS LAMBDA method,
Researcher D	Research and market expert	Geodesy, Geomatics, satellite-based positioning,
Researcher E	Independent consultant and researcher	Chipset development, automotive applications, software and hardware development.
Company A	Receiver developer	Receivers, signals, autonomous vehicles
Company B	Service provider	RTK, NRTK, smartphones, hardware development, sensor fusion
Company C	Consultancy	Satellite-based positioning, CORS networks, data formats
Regional Authority A	Service provider	PPP-RTK. Automotive, regional systems

1.3.2 Reference sources

The following table lists the key documents / sources used as references for the study. The links to these documents are provided in Annex B.

Reference ID	Title and date	Authors
[RD.01]	GNSS User Technology Report 2018	GSA
[RD.02]	Review and Principles of PPP-RTK Methods	P.J.G Teunissen Amir Khodabandeh
[RD.03]	GNSS Precise Point Positioning	Suelynn Choy
[RD.04]	Trimble RTX, an Innovative New Approach for Network RTK	Xiaoming Chen et al
[RD.05]	Report on Surveying User Needs and Requirements	GSA
[RD.06]	Global PPP with Ambiguity Resolution providing improved accuracy and instant position coverage	David Russel
[RD.07]	An Introduction to GNSS	NovAtel Inc.
[RD.08]	Global Navigation Satellite Systems – Signal, Theory and Applications: Chapter 7 – Precise Real-Time Positioning Using Network RTK	Ahmed El-Mowafy
[RD.09]	Geo++ SSR Brochure	Geo++
[RD.10]	The Path to High GNSS Accuracy	Galileo GNSS
[RD.11]	PPP-RTK Precise Point Positioning Using State Representation in RTK Networks	Wübbena et al. (GEO++)
[RD.12]	Geo++ SSR + RTCM – Current Status	Gerhard Wübbena Martin Schmitz Jannes Wübbena
[RD.13]	Quasi-Zenith Satellite System Interface Specification Centimetre Level Augmentation Service	Cabinet Office, Government of Japan

Reference ID	Title and date	Authors
[RD.14]	Investing in GPS Guidance Systems?	Gordon Groover Robert Grisso Department of Agriculture and Applied Economics
[RD.15]	PPP with Ambiguity Resolution (AR) using RTCM-SSR	Gerhard Wübbena Martin Schmitz Andreas Bagge
[RD.16]	A Comparison of Three PPP Integer Ambiguity Resolution Methods	Junho Shi, Yang Gao
[RD.17]	Using GNSS Raw Measurements on Android Devices	Gaetano Galluzzo et al.
[RD.18]	Comparison of Common Representation Techniques	Geo++
[RD.19]	SSR assist for smartphones with PPP-RTK processing	Koki Asari Masayuki Saito Hisao Amitani
[RD.20]	Precise RTK Positioning with GNSS, INS, Barometer and Vision	Patrick Henkel Alexander Blum Christoph Gunther
[RD.21]	Global autonomous mobile robots market	QYResearch
[RD.22]	Safety robotic lawnmower with precise and low-cost L1-only RTK GPS positioning	Jean-Marie Codol Michele Poncelet Andre Monin Michel Devy
[RD.23]	Applications of GPS Technologies to Field Sports	Robert Aughey
[RD.24]	Wearable Fitness Tracker Market	P&S Intelligence
[RD.25]	Using Global Localisation to improve navigation	Google AI
[RD.26]	Mining and Construction	Septentrio
[RD.27]	Real-Time GPS PPP-RTK Experiments for Mining Applications using Quasi-Zenith Satellite System Augmentation Signal	Luis Elneser Suelynn Choy Ken Harima James Millner
[RD.28]	Precision Agriculture Market Analysis	Hexa Reports
[RD.29]	Precise GNSS Positioning for Mass-market Applications	Yang Gao
[RD.30]	Towards PPP-RTK: Ambiguity resolution in real-time precise point positioning	J. Geng F. Teferle X. Meng A. Dodson
[RD.31]	Centimetre Level Augmentation Service Overview	Cabinet Office Japan
[RD.32]	Enabling RTK-like positioning offshore using the global VERIPOS GNSS network	Pieter Toor
[RD.33]	Reference Station Network Information Distribution	Hans-Juergen Euler
[RD.34]	A-PPP: Array-Aided Precise Point Positioning with Global Navigation Satellite Systems	P. Teunissen
[RD.35]	Activities for Utilisation of CLAS from QZSS and Proposal for Cooperative Work for SOL Applications	Hiroshi Koyama

Reference ID	Title and date	Authors
[RD.36]	A Novel Un-differenced PPP-RTK Concept	Baocheng Zhang Peter Teunissen Dennis Odijk
[RD.37]	PPP-RTK: Results of CORS network-based PPP with integer ambiguity resolution	Baocheng Zhang Peter Teunissen Dennis Odijk
[RD.38]	Integer Ambiguity Resolution on Undifferenced GPS Phase Measurements and its Application to PPP and Satellite Precise Orbit Determination	D. Laurichesse F. Mercier J. Berthias P. Broca L. Cerri
[RD.39]	Resolution of GPS Carrier-Phase Ambiguities in Precise Point Positioning with Daily Observations	M. Ge G. Gendt M. Rothacher C. Shi J. Liu
[RD.40]	Top 3 Positioning Challenges in Autonomous Marine Navigation	Septentrio
[RD.41]	Rethinking Maps for Self-Driving	Lyft Level 5
[RD.42]	Opening of PPP Services	Geoflex
[RD.43]	FLAMINGO Unveils High-Accuracy Solution for Smartphones	GSA
[RD.44]	2019 Trimble RTX Satellite Broadcast Frequency Coverage Map	Trimble
[RD.45]	PPP-RTK & Open Standards Symposium	GIM International
[RD.46]	Compact SSR Messages with Integrity Information for Satellite Based PPP-RTK Service	Rui Hirokawa Yuki Sato Seigo Fujita Masakuzu Miya
[RD.47]	Galileo High Accuracy Service and its importance for mobility applications	EC
[RD.48]	Galileo: user-tailored positioning and timing services made in Europe	GSA
[RD.49]	FLAMINGO: Encapsulation of High Accuracy Positioning Service for Smartphones and IoT	NSL
[RD.50]	Smartphone (PPP-RTK) – first results and challenges	Geo++
[RD.51]	Bridging between RTK and PPP-RTK to Develop New Survey Period	Satellite positioning research and application center
[RD.52]	Comparative analysis of positioning accuracy of GNSS receivers of Samsung Galaxy smartphones in marine dynamic measurements	C. Specht, P.S. Dabrowski, J. Pawelski, M. Specht, T. Szot
[RD.53]	GNSS Positioning using Android Smartphone	Paolo Dabove, Vincenzo Di Pietra, Shady Hatem and Marco Piras
[RD.54]	Handbook of Global Navigation Satellite Systems - Annex A: Data Formats	Oliver Montenbruck, Ken MacLeod
[RD.55]	RTCM State Space Representation Messages, Status and Plans	Geo++

Reference ID	Title and date	Authors
[RD.56]	IGS White Paper on Satellite and Operations Information for Generation of Precise GNSS Orbit and Clock Products	IGS Multi-GNSS Working Group
[RD.57]	Multi-GNSS PPP-RT: From Large- to Small-Scale Networks	Nandakumaran Nadarajah, Amir Khodabandeh, Kan Wang, Mazher Choudhury and Peter J. G. Teunissen
[RD.58]	Single-frequency PPP-RTK: Theory and experimental results	Dennis Odijk, P. Teunissen, Amir Khodabandeh
[RD.59]	Recent Activity of International Standardization for High-Accuracy GNSS Correction Service	Mitsubishi Electric Corporation
[RD.60]	FUGRO Marinestar G4+ PPP-RTK Developments	Hydro International
[RD.61]	Real-Time PPP using open CORS Networks and RTCM Standards	Andrea Stuerze, Wolfgang Sohne, Georg Weber
[RD.62]	RTCM Background and SC-134 Evolution	RTCM
[RD.63]	Location based services: ongoing evolution and research agenda	Haosheng Huang Georg Gartners Jukka Krisp Martin Raubal Nico Van de Weghe
[RD.64]	Report on location-based services user needs and requirements	GSA
[RD.65]	CORSnet – NSW: Towards statewide CORS infrastructure for New South Wales, Australia	Volker Janssen Thomas Yan
[RD.66]	ETSI TS 136 355 V15.0.0 LTE: Evolved universal terrestrial access; LTE Positioning Protocol	3GPP
[RD.67]	EGNOS and Galileo for Aviation	GSA
[RD.68]	E-GNSS Applications in Rail	GSA

2. Technical Analysis

2.1 Overview

Standalone GNSS signals enable the calculation of the receiver's position, however given the extreme distances and speeds of satellites, errors cause these positions to have limited accuracy (~4m). Emerging applications such as drones, augmented reality and autonomous vehicles are driving the demand for high accuracy (<1m) and high precision real-time positioning in the mass-market. Where accuracy relates to the difference between the ground truth location and the received position, and precision relates to the error bands of the received position. Adoption of high accuracy positioning within the mass-market is also being supported by other factors, such as availability of multi-constellation and dual-frequency chipsets, access to raw GNSS measurements in Android 7+ and falling prices of both receivers/chipsets and augmentation services. On the other hand, significant challenges remain in obtaining high-accuracy (cm/dm level) position data using low-cost GNSS receivers due to their tendency to obtain poor quality measurements.

To achieve real-time high accuracy positioning using GNSS, several signal augmentation techniques such as RTK, PPP and hybrid variations (e.g. PPP-RTK) have been developed. These technologies can deliver cm/dm level accuracy, but have traditionally been implemented using sophisticated, high-performance antennas which are not available in mass-market devices such as smartphones [RD.17]. Given the potential benefit of bringing high accuracy and precision positioning to mass-market devices, there is a need to review the current market situation of these services.

High-accuracy positioning capabilities have previously been limited to highly specialised applications such as surveying and agriculture. As these applications are typically undertaken within a defined area, RTK signal augmentation can be used. RTK is the gold standard for high-accuracy applications and is based on the use of carrier measurements and the transmission of corrections from a base station (whose location is precisely known) to the rover (a potentially moving receiver, whose position is being determined), so that the main positioning errors can be eliminated. An RTK base station typically covers a service area of 30 - 50 km and requires a real-time communication channel to connect the base station and rover. The achievable accuracy of RTK is up to 1 cm + 1 part per million (ppm) accuracy. Depending on the method of implementation, data may be transmitted over cellular radio links or another wireless medium [RD.07]. It is worth noting that conventional RTK transmits corrections using the Observation Space Representation (OSR) approach [RD.9] which groups the errors together, providing the total correction measurements rather than for the individual parameters. Therefore, all parameters are updated at the same frequency, irrespective of their time sensitivity. The OSR approach requires a two-way communication channel for each user and has high bandwidth requirements, which limit its scalability. It is expected that current mobile communication networks would not be able to sustain this level of communication were it to be adopted *en masse*, making RTK poorly suited for mass-market applications such as within smartphones, IoT and the automotive industry [RD.10].

PPP, which has become an attractive alternative to RTK, is a signal augmentation technique that removes GNSS system errors to provide high accuracy positioning using only a single receiver. PPP solutions rely on GNSS satellite clock and orbit corrections, generated from a network of global Continuously Operating Reference Stations (CORS). Once the corrections are calculated, they are delivered to the user via satellite or the internet resulting in dm-level or better real-time positioning without the need for a local base station [RD.07]. PPP solutions typically require a convergence period of 5-30 min to resolve any local biases such as the atmospheric conditions, multipath and satellite geometry.

To overcome the long convergence times of PPP, several innovative concepts have been developed. The most promising of which is PPP-RTK, which extends the PPP concept by also providing corrections for atmospheric errors (caused by disturbances in the ionosphere and troposphere) which are calculated using a CORS network [RD.2]. PPP-RTK also has some infrastructure requirements, although lesser than NRTK; however, if the user exceeds the range of the CORS network the service degrades to mimic standard PPP. The inclusion of atmospheric error corrections enables convergence times to be reduced to less than 60s, as well as accuracy on par with conventional RTK techniques. Unfortunately, as PPP-RTK is reliant on the presence of NRTK for fast initialisation, its greatest assets of global coverage and infrastructure independence are partially degraded.

Unlike RTK, the PPP and PPP-RTK techniques utilise State Space Representation (SSR), which was established by Wübbena G. (Geo++) [RD.11]. SSR broadcasts a single stream of correction data (one-way communication) to all rovers within a serviced area, providing a significant benefit over OSR techniques. SSR represents and separates the individual error components, which minimizes the required bandwidth amongst providing other advantages, such as enabling the use of single frequency rovers [RD.11]. SSR represents the state-of-the-art in high accuracy GNSS positioning, capable of meeting stringent requirements in terms of bandwidth, flexibility, scalability, performance, coverage and handover that satisfy the needs of the mass-market.

Exhibit 5: Summary of Available Signal Augmentation Technologies [RD.09]

	RTK	Network RTK			Phase based PPP	Code based PPP	PPP-RTK
	RS	FKP	MAC	VRS/PRS			
Errors corrected	Orbit error, Clock error, Bias, Ionospheric delay, Tropospheric delay				Orbit error, Clock error, Bias, Iono/Tropospheric delay (PPP-RTK)		
Approach	OSR (Observation State Representation)				SSR (State Space Representation)		
Accuracy	cm				< dm	~3dm	< dm
Mean convergence time	< 5s				20 min	< 1s	< 5s – 1 min
Largest service area	Local	Regional			Global	Global	Global
Double frequency	Yes				Yes	No	Yes
Required bandwidth	Medium	Medium	High	Medium	Low	Low	Low -Medium

CORS network density requirement (km)	20 - 50	70 – 100	70 – 100	70 – 100	1000’s	1000’s	100’s

Technological advancements in GNSS signal augmentation services are opening the door to many new and innovative high-accuracy applications. These developments will place greater demands on both service providers and hardware developers. The traditional signal augmentation technologies of PPP and RTK have been surpassed, and service providers are looking to increasingly innovative adaptations and hybrid technologies. These retain the principle concepts of the traditional technologies and can include additional data to improve convergence times or to maintain accurate positioning during signal outages.

2.2 Real-Time Kinematic (RTK)

RTK can provide very high accuracy positioning over a short range. It involves a CORS transmitting its raw measurements or observation corrections to a rover receiver via a direct (two-way) communication channel. This enables the rover to resolve the ambiguities of the differenced carrier phase data and to estimate the coordinates of the rover position. RTK is severely limited by the short coverage range (30 – 50 km), which is caused by the degradation of the distance-dependent biases such as orbit error and ionospheric and tropospheric signal refraction. Within close proximities of the base station (10 – 20 km), RTK provides near instant, high accuracy positioning of up to 1 cm + 1 ppm; however, as a direct communication channel is required between the rover and the base station, bandwidth limitations prevent large numbers of users utilising the same base station, making RTK ill-suited to mass market applications [RD.07].

RTK is the most popular GNSS signal augmentation technology for many industries such as surveying and agriculture and is particularly prevalent in regions with well-developed CORS networks like central Europe. Its popularity has led to it being further modified than PPP and PPP-RTK. The developments upon the traditional RTK technology address its greatest weakness; the restrictive range of its reference stations.

2.2.1 Network RTK

Network RTK (NRTK) was one of the earliest adaptations of RTK and enables the rover to connect to any CORS within an interconnected network of stations. **As the rover is no longer limited to the range of a single CORS, the coverage area of the RTK solution can be drastically improved**. NRTK provides multiple benefits over traditional RTK [RD.33]:

- Signal does not degrade as the distance between the receiver and the reference station increases as the rover can connect to a different CORS if it is closer, retaining a high quality connection.
- Significantly improved RTK coverage in well-developed areas.

- Reduces initial cost to user as no infrastructure installation is required.
- Service subscriptions are easier for businesses to manage.

As the coverage area of NRTK is dependent on the number of available CORS, **it is particularly successful within regions which have a high density of permanent base stations**, such as central Europe.

For the rover to be able to connect to different base stations within the network, a common processing technique must be applied across all base stations. The standardisation across the network of CORS prevents the rover from having to re-initialise the ambiguity fixing filters each time they connect to a different base station [RD.33]. To simplify this task, multiple standards have been developed; however, the Radio Technical Commission for Maritime Services (RTCM) standard is the most widely recognised.

2.2.2 Virtual Reference Station

A Virtual Reference Station (VRS) is an imaginary, unoccupied reference station which is modelled only a few meters from the RTK user. This interpolates the data of several CORS and delivers higher-accuracy corrections for the rover. **VRS provides multiple benefits such as enabling a greater distance between the CORS and the rover, shorter initialisation times and higher signal reliability**. If a CORS were to temporarily fail, correction data can still be computed from the surrounding CORS [RD.4].

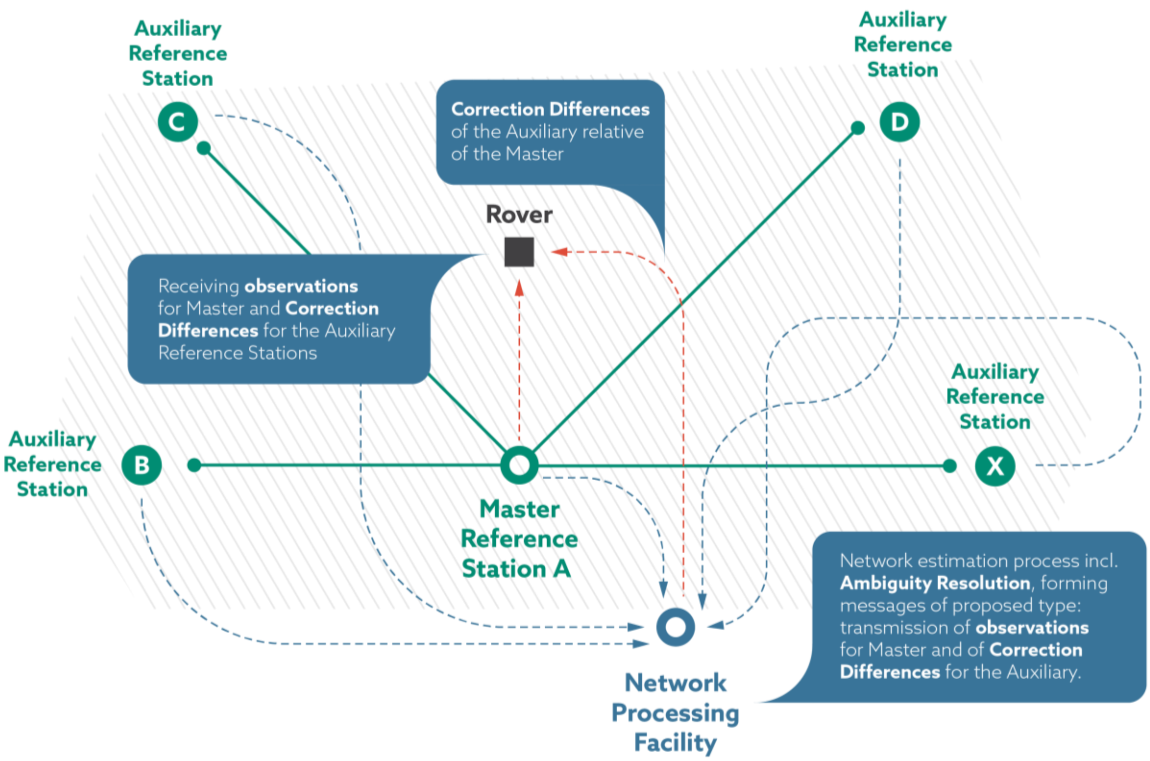
VRS requires bi-directional communication to allow the VRS server to generate data streams for specific rovers in a standardised data format [RD.4]. The requirement for bi-directional communication prevents the broadcasting of corrections and increases the necessary bandwidth to operate the system. **This prevents the technology from being suitable for mass-market applications as it would quickly overload current mobile networks**.

2.2.3 Network RTK Master-Auxiliary Concept

Expanding upon the VRS technology, the RTCM SC104 committee standardised a broadcast NRTK data format, often referred to as the Master-Auxiliary Concept (MAC). This technique uses one “Master” reference station and its raw data stream such as RTCM V3.0 message type 1004 and reduced information of other “Auxiliary” reference stations in the vicinity of the rover. The rover receiver estimates the bias around its position, using correction data with respect to at least five CORS. This technique places a greater computational load on the rover, as it shifts calculations away from the control centre [RD.4].

As MAC is based on a broadcast data format it does not require a bi-directional communication link; however, the technology is limited by the number of CORS that can be included within the data stream and additional computational requirements placed upon the rover. The limited number of CORS stations that can be incorporated within the network restricts the serviceable area of the technology, making it **poorly suited to mass-market applications**.

Exhibit 6: Network-RTK Using MAC Concept [RD.33]



2.2.4 Sensor Fusion with RTK

In addition to incorporating more CORS into the base RTK technology, researchers have been looking to sensor fusion to improve positioning integrity. The use of Inertial Navigation Systems (INS) in tandem with RTK is becoming widely implemented and has even been incorporated into mass-market products such as autonomous lawn mowers and is widely expected to be necessary for automotive applications. **The combination of INS and RTK drastically increases the reliability of the positioning and helps maintain accuracy during periods when the GNSS signal is lost**.

The concept of increasing the number of data sources by incorporating additional sensors continues to advance, with recent developments incorporating barometers and optical scene recognition to improve acquisition time and accuracy [RD.20].

2.3 Precise Point Positioning (PPP)

PPP is a signal augmentation technique that eliminates GNSS system errors to provide high accuracy positioning using only a single receiver. PPP solutions rely on GNSS satellite clock and orbit corrections which are generated from a global network of CORS. These corrections are delivered to the user via satellite or through the internet, **resulting in dm-level or better real-time positioning with no local ground infrastructure requirements**. PPP solutions typically require a convergence period of 5-30 min to resolve any local biases such as the atmospheric conditions, multipath and satellite geometry.

The primarily limitation of PPP is that it does not resolve the ambiguities of the carrier phase errors, and instead uses an estimation of these. This leads to a long initialisation time, which requires full re-initialisation if the signal is lost.

2.3.1 PPP-Ambiguity Resolution

While the initial convergence times for PPP and PPP with Ambiguity Resolution (PPP-AR) are similar, **PPP-AR provides a significant improvement to the re-initialisation time after the signal is lost**. This reduction is achieved by solving the carrier phase ambiguities within the receiver, this requires additional observation specific biases to be determined and broadcast.

PPP-AR uses a global network of CORS (much like NRTK) to estimate the code and phase biases in addition to the orbit and clock corrections which are then broadcast to users by communication satellites. The user's receiver then decodes and applies these corrections with specialised positioning algorithms to provide improved performance. **PPP-AR has two key benefits over regular PPP, which are rapid recovery after the loss of GNSS data and a higher standard accuracy** [RD.06], [RD.32].

2.3.2 Array-Aided PPP

Array-Aided PPP (A-PPP) uses GNSS data from multiple antennas in a known formation to realise real-time precise orientation and improved positioning of a stationary or moving platform. It achieves this as the known array geometry in the platform frame enables successful integer carrier phase ambiguity resolution, thereby realising a two-order of magnitude improvement in the between-antenna GNSS pseudoranges. These very precise pseudo-ranges are then used to determine the platform's earth fixed orientation, thus effectively making the platform a 3D direction finder. At the same time, the precision of the absolute pseudo-ranges and carrier phases are improved by exploiting the correlation that exists between these data and the very precise between-antenna pseudo-ranges. **This improvement enables enhanced platform parameter estimation. Additionally, integrity improves, since with the known array geometry, redundancy increases, thus allowing improved error detection and multipath mitigation** [RD.34]. As this technology requires the use of multiple antennas in a known formation, it is not practical to achieve this in mass-market devices.

2.4 Precise Point Positioning – Real-Time Kinematic (PPP-RTK)

Researchers and service providers are hybridising PPP and RTK in an attempt to obtain the benefits of both technologies. **The concept of PPP-RTK is to augment PPP estimations with precise un-differenced atmospheric corrections and satellite clock corrections from a network of CORS, so that instantaneous ambiguity fixing is achievable for users within the network** [RD.8], **these resolved integer ambiguities lead to shorter convergence times** [RD.57]. PPP-RTK utilises a map of atmospheric errors generated by a network of CORS, the quality of this map determines the ambiguity resolution capability of the service. This map is most accurate at the location of each CORS (where the data is generated) and as the distance between the rover and the CORS increases the quality of the map degrades, leading to longer convergence times. If ambiguity resolution is not possible (e.g. because the rover has exceeded the range of the CORS network) there is a smooth transition to standard PPP, as the ambiguity-float PPP-RTK solution exactly corresponds to the standard PPP solution [RD.58]. It should be noted that while degraded PPP-RTK reverts to standard PPP, the positioning algorithms of PPP are not interchangeable with those of RTK or PPP-RTK.

As SSR corrections are derived from the redundant CORS within the network, the station dependant errors (such as multipath) are reduced [RD.11]. Combined with the short convergence times, ability to broadcast corrections, graceful degradation of the service and lower bandwidth requirements, **this makes PPP-RTK a highly promising solution for mass-market applications.**

Exhibit 7: High level view of main benefits and drawbacks of PPP-RTK compared to PPP and RTK only

Solution	Benefits	Drawbacks
PPP	Has no local ground infrastructure requirements Global	Long convergence times Lower accuracy
RTK	High accuracy (2cm) Near-instant convergence times	Highly reliant upon local ground infrastructure Short range of transmissions
PPP-RTK	Fast convergence times High accuracy Lower density CORS network than NRTK Degrades to standard PPP	Reliant upon local ground infrastructure

Alongside the precise satellite clocks, orbits and phase biases, PPP-RTK makes use of local/regional/national CORS networks to provide users with ionospheric and tropospheric delay corrections, allowing them to perform integer resolution of ambiguities and **achieve centimetre-level accuracy in significantly reduced time**. The convergence time is typically in the range of 1-10 minutes however, in ideal circumstances can be achieved in seconds.

The performance of a PPP-RTK system is dependent on how much data can be provided to the receiver and how quickly it can be delivered. The quantity and frequency of data that can be broadcast is limited by the available bandwidth and the data packet size, requiring these factors to be balanced. A reduction in the quantity of data would reduce the accuracy of the service and increase convergence times, whilst reducing the frequency of data updates may introduce latency issues to the service. Other factors such as the proximity to a CORS station can also impact the convergence time of a PPP-RTK solution due to the ionospheric disturbance model degrading as the distance from the CORS increases. As the model degrades, the ambiguity resolution becomes worse, and convergence times increase.

Exhibit 8 presents an overview on how the inclusion of additional data, constellations and frequencies can impact both the accuracy and convergence time of the solution.

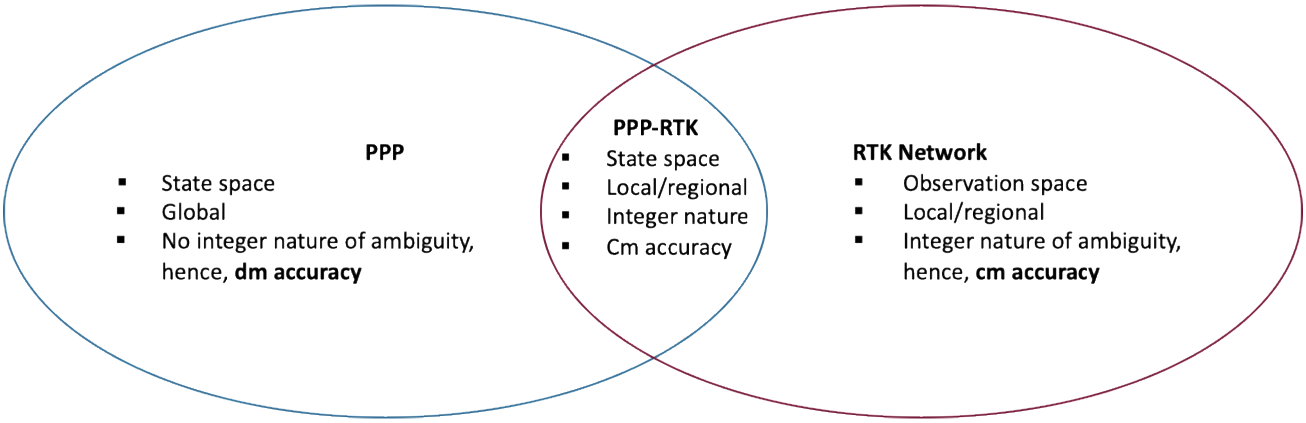
Exhibit 8: Comparison of PPP Technologies [RD.42]

Service	Technology	Accuracy (cm)	Convergence Time (minutes)
Multi-GNSS single frequency PPP	RT-PPP-L1	80	30
Single Frequency PPP, Multi-GNSS + Ion, SBAS	RT-PPP-L1 “Fast and Precise”	50	1

Multi-GNSS dual – frequency PPP with floating ambiguities	RT-PPP-L1/L2	10	30
Multi-GNSS dual – frequency PPP with fix ambiguities	PPP-IAR	4	30
Multi-GNSS tri-frequency PPP with fix ambiguities	PPP-RTK	2-4	5

PPP-RTK is the synthesis of the positive characteristics of both PPP and RTK concepts (Exhibit 9), whose individual strategies have already been well proven.

Exhibit 9: Synthesis of PPP and RTK Networking [RD.11]



A few drawbacks remain which prevent PPP-RTK from being widely adopted. PPP-RTK requires the same localised infrastructure as NRTK, limiting very high-accuracy positioning to areas within range of base stations. As the technology is still relatively new it has not yet been widely adopted by signal augmentation service providers, leading to a less competitively priced market. This market situation is exacerbated by the current lack of standardised data formats, highlighting the early development stage of the technology. Despite these challenges, there are several PPP-RTK services already available in the market and multiple innovative concepts remain under development, showcasing the potential of the technology [RD.02]. **These innovative concepts utilise different methodologies for removing errors from the received signals, but are all based on the same principle technology and the equations for resolving ambiguities remain the same**.

2.4.1 Innovative PPP-RTK Concepts

There are multiple emerging concepts within the PPP-RTK technology such as those proposed by Wübbena, Laurichesse and Mercier, Teunissen, etc. These are variations upon the base technology of PPP-RTK and differ slightly in their approach to removing the fractional phase part of the error, such as clock and bias modelling and corrections. An overview of these models is provided in Exhibit 10.

Exhibit 10: Overview of PPP-RTK Innovative Concepts

PPP-RTK Methodology	Defining Features	Example of Use
Common Clock	Both the phase and code equations have the satellite clock parameter in common which is provided externally by a GNSS network.	A Novel Un-differenced PPP-RTK Concept – [RD.36]

Distinct Clock	Utilises different clocks for each observable type	PPP-RTK: Results of CORS Network-Based PPP with Integer Ambiguity Resolution – [RD.37]
Integer Recovery Clock & Decoupled Satellite Clock	These models are equivalent and interchangeable. They work with ionosphere-free combinations. This can simplify the model but reduces the ambiguity resolution capabilities, requiring relatively long observation spans to achieve successful integer ambiguity resolution	Integer Ambiguity Resolution on Undifferenced GPS Phase Measurements and its Application to PPP and Satellite Precise Orbit Determination – [RD.38]
Uncalibrated Phase Delay & Fractional Cycle Basis	These models are also based on ionosphere-free models, and in addition utilise a wide lane transfer function.	Resolution of GPS Carrier-Phase Ambiguities in Precise Point Positioning with Daily Observations – [RD.39]

These models may contain small numerical differences in the computational processes; however, comparisons undertaken by industry experts have found them to be mathematically equivalent [RD.16] and [RD.02]. **As such, the benefits and limitations of each of these concepts are currently thought to be indistinguishable**. It is possible that in real-world applications with non-perfect conditions the performance of these concepts will differ, enabling the best performing technique to be found. No research showing a real-world comparison of these concepts has been found and it has not been possible to identify the most promising of these concepts.

Exhibit 11: Expert opinions on PPP-RTK

It was universally agreed by each expert who had researched the innovative concepts of PPP-RTK that they appeared to be mathematically equivalent, and as such it is not expected that any one of these will outperform the others. It was also found that whilst some companies are developing PPP-RTK services, there is very little information available on how they will implement this, as well as which concept they are using. This makes it difficult to determine which of the concepts is best as there is little to no real-world data. This was further reinforced by several companies who are developing PPP-RTK services declining the invitation for interview, stating that at this time they would prefer to keep the information in-house. Fugro have announced that they are using the uncalibrated phase delay technique for their commercial PPP-RTK service.

The performance of a PPP-RTK system is dependent on how much data can be provided to the receiver and how quickly it can be delivered. The quantity and frequency of data that can be broadcast is limited by the available bandwidth and the data packet size, requiring these factors to be balanced. A reduction in the quantity of data would reduce the accuracy of the service and increase convergence times, whilst reducing the frequency of data updates may introduce latency issues to the service. Other factors such as the proximity to a CORS station can impact the convergence time of a PPP-RTK solution due to the ionospheric disturbance model degrading as the distance from the CORS increases. As the model degrades, the ambiguity resolution becomes worse, and convergence times increase.

Before PPP-RTK can be deployed to the mass-market, there is still significant development required to understand the technicalities of its deployment. Most of the available literature focuses the methodologies of the technologies, and so there is little understanding on how this can be implemented. **Experts did state that the operating environment for mass-market application of augmented signals will be much harder than for professional applications**.

2.5 Comparison of key technologies

The characteristics of these technologies makes them suited to specific applications. PPP provides global coverage of moderate accuracy positioning for an unlimited number of rovers using via broadcast. As PPP is not reliant upon regional CORS networks, it can deliver standardised performance in all regions of the globe. This independence from local infrastructure makes it well suited to sparsely populated areas and marine applications. While the accuracy provided by PPP is significantly better than standalone GNSS, it is not comparable to the accuracies achieved using of RTK. In addition, the long convergence times of PPP may act as a barrier to the technology's adoption within the mass-market.

Conversely RTK provides regional, near-instantaneous high-accuracy positioning. As one of the earliest signal augmentation technologies, RTK is well proven and has been widely adopted within many industries such as agriculture. Capable of providing 2cm accuracy, RTK delivers the highest precision solution available on the market and further developments of the RTK technology have helped to address the range limitations which hindered the original technology. The OSR message format remains a limitation of the technology, requiring a bidirectional communication channel between the CORS and the rover, severely limiting the number of users that can be supported by the network at once. This capacity limitation makes the technology unsuitable for mass-market applications as network bandwidths would rapidly become over-burdened.

Performance Parameter	RTK	PPP
Accuracy	cm	cm - dm
Coverage Area	50 km	Worldwide
Message format	OSR	SSR
Errors removed	Orbit error Clock error Bias Ionospheric delay Tropospheric delay	Orbit error Clock error Bias

By hybridising both PPP and RTK methodologies, PPP-RTK provides global, near-instantaneous, high-accuracy positioning for an unlimited number of users. To achieve high performance, PPP-RTK requires a regional CORS network similar in density to an RTK solution; however, if the user exceeds the range of the CORS network the solution would gracefully degrade to mimic standard PPP. **The**

use of SSR enables PPP-RTK corrections to be broadcast to users, with significantly lower bandwidth requirements than OSR, **enabling an unlimited number of users to connect without disrupting the system. These characteristics make PPP-RTK well suited to mass-market applications**.

PPP and RTK are suited to specific environments. RTK is the preferred technology if there is sufficient CORS infrastructure available, otherwise PPP will be used. There are few examples where this is not the case in the current market. PPP-RTK bridges this gap and enables users to use one service subscription and receiver to undertake any application, with decreased reliance on the available CORS infrastructure.

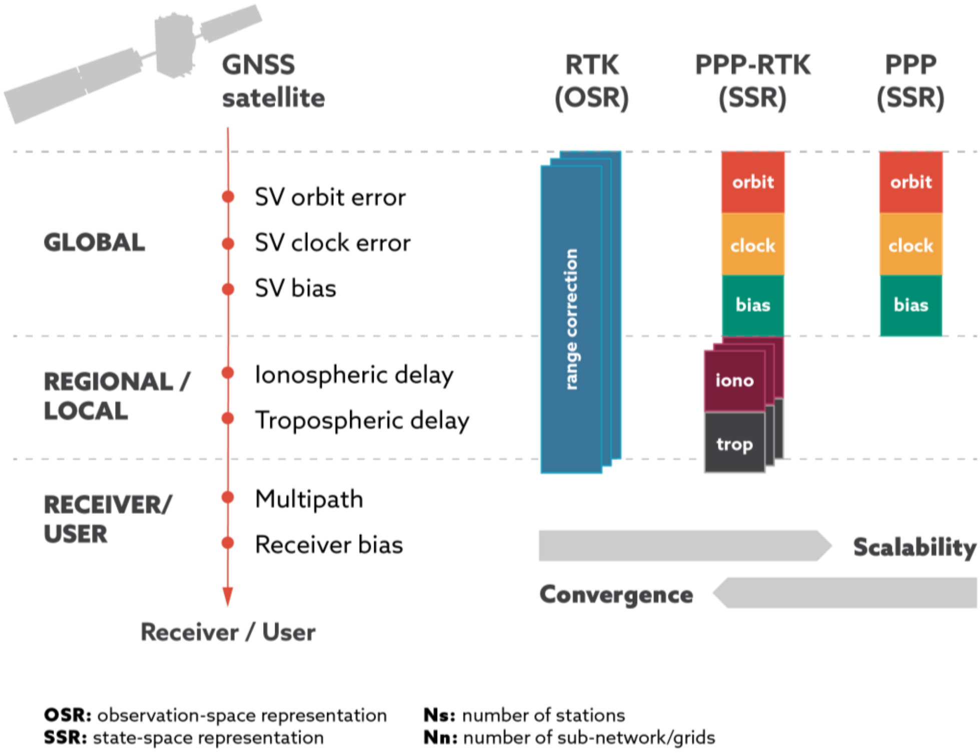
Exhibit 12: Expert opinion on key signal augmentation technologies

Each expert was asked about their opinions on the available signal augmentation technologies, no preference was found for a specific technology. Instead the decision on which technology would be utilised is primarily based on the nature of the application and its geographic location. Regions such as Europe which already have well-established dense CORS networks are well suited to NRTK; however, were the same application to be undertaken offshore then PPP or PPP-RTK would be the only viable options. If NRTK is available, there is generally no reason to use PPP as it delivers longer convergence times and lower accuracy positioning. **Some experts do not believe that PPP-RTK offers a significant improvement over NRTK as they are both reliant upon a CORS network. Within regions with well-established CORS networks, PPP-RTK and NRTK are expected to deliver comparable results.**

It was highlighted by multiple experts that the importance of **"accuracy" is often over-emphasised and that the integrity and availability of the position data must also be considered**. This would enable the user to determine the confidence bands for the location data, a factor that is critical in ensuring that Hazardously Misleading Information (HMI) is not provided to the user.

2.6 Message format

Exhibit 13: Message Format Comparison [RD.59]



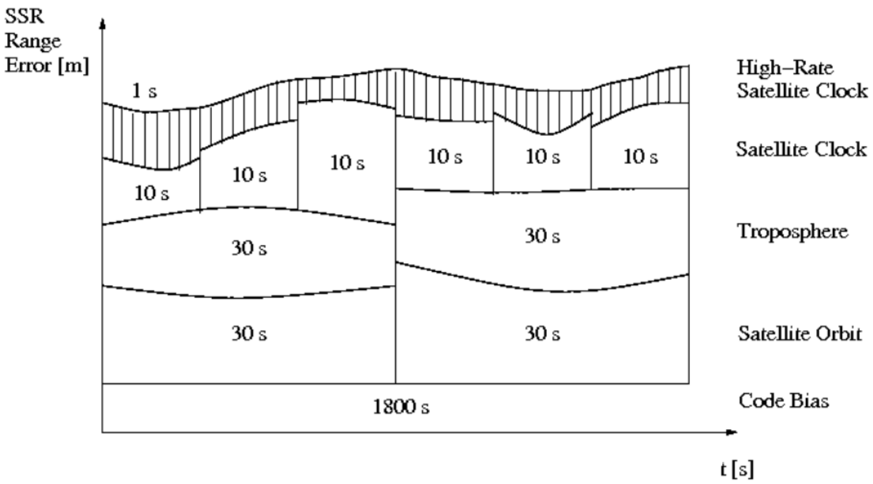
The OSR message format is used within RTK based solutions. The RTCM SC-104 standard offers a harmonised framework for transmitting such corrections to the user independent of the underlying network architecture. Both Global Positioning System (GPS) and GLONASS network-RTK services are supported through dedicated messages. A typical RTK reference station will provide raw observation data in the 1004 (Extended L1&L2 GPS RTK Observables) and 1012 (Extended L1 & L2 GLONASS RTK Observables) messages and send these at a 1 Hz rate. While at the same time, sending its ECEF location using either a 1005 (Stationary RTK Reference Station Antenna Reference Point), 1006 (Stationary RTK Reference Station Antenna Reference Point with Antenna Height) or 1007 (Antenna Descriptor) message every 10 – 30 seconds. Most reference stations do not send broadcast orbital data, called Ephemeris using RTCM messages 1019 (GPS orbits in Kepler format) and 1020 (GLONASS orbits in XYZ dot product format) [RD.54].

SSR represents a new concept for the provision of correction data in PPP and PPP-RTK applications. Rather than providing combined corrections in observation space, the SSR approach separates the errors and provides individual corrections for each error. These corrections include satellite position corrections and satellite clock corrections as well as code biases. Different message types are supported for individual or combined orbit and clock corrections. Furthermore, distinct high rate clock correction messages are available to ensure that satellites with fast changing atomic clocks can be accurately characterised. The SSR concept also foresees the provision of vertical total electron content information for single-frequency users, even though these are not yet part of the RTCM SC-

104 standard. The generic nature of the SSR corrections makes them largely independent from the user location and provides the basis for global PPP applications [RD.54].

When using the OSR approach, the correction update rate will be a compromise between the requirement of the most time-sensitive parameter (such as satellite clock errors) and efforts to minimise transmission bandwidth. Whereas using **SSR enables individual update rates for each parameter to be defined as shown in Exhibit 14 [RD.61] [RD.58]. SSR also provides several further advantages including redundancy in the network, residual errors of an individual reference station are eliminated or significantly reduced and missing observations do not result in missing state space information.** Unfortunately, the use of SSR a greater standardisation effort and more complex rover algorithms. As SSR is an absolute positioning method, additional errors (relativistic corrections, phase wind-up, earth-tides, etc) must be accounted for to ensure consistent modelling with the service provider. **The SSR format offers many advantages over OSR, in both the number of users that can be served and the bandwidth requirements, making SSR a more promising technology which offers higher performance.**

Exhibit 14: RTCM-SSR update interval to ensure the consistency of different SSR parameters [RD.61]



2.7 Galileo HAS Overview

The Galileo HAS will provide users with an enhanced accuracy of approximately 20 cm and is aimed at market applications which require higher performance than those offered by the Galileo Open Service (OS) or other standalone GNSS services. This service is intended to be provided free of charge, with content and format of data publicly and openly available on a global scale. To achieve this, Galileo HAS will use a combination of signals in the E6 band with the E6-B channel being well suited to the transmission of PPP information. It is claimed that the available rate of 448 bps per satellite allows the transmission of satellite orbits and clock data at an adequate update rate to provide accuracy at the centimetre level. The data update rate is especially relevant for satellite clock corrections, which are not as stable in the medium and long term as the orbits. In order to obtain the highest accuracy, corrections must be updated every few seconds, especially for the satellites with less stable clocks [RD.47]. Galileo HAS will allow for the transmission of different parts of corrections from different satellites, enabling the total bandwidth to be highly increased leading to better performance and may reduce the PPP receiver convergence time. The inclusion of CORS infrastructure is also being considered to further reduce the convergence time. It is anticipated that Galileo HAS shall use the RTCM Compact SSR (CSSR) data format, but this format is yet to be standardised [RD.47] [RD.59].

The open and free service provided by Galileo HAS is set to drastically change the current GNSS signal augmentation market. There are no free and open services currently on the market and until recently, the market has seen little disruption. Service providers were previously able to charge high prices due to a lack of competition and high barriers to market entry, but as the market has matured increased competition has driven down service prices. These services are primarily used for professional applications, some of which will require higher accuracies and faster convergence times than standalone PPP can require. Safety of Life (SOL) applications will also require the provision of position integrity, which cannot be achieved through standalone PPP.

As the technical specifications of Galileo HAS have not yet been fully defined, it is difficult to determine the full impact that it will have upon the market. Galileo HAS will directly compete with the commercial high accuracy services currently on the market, and if it can provide comparable or improved performance it is expected to naturally replace them. The inclusion of CORS data in the service would greatly improve the uptake of the solution, as it would then exceed the performance of commercial PPP solutions and could directly compete with commercial RTK solutions.

3. Potential PPP-RTK Based Applications

3.1 Introduction and overview

Precise GNSS positioning using low-cost GNSS sensors faces some significant challenges in order to support mass-market applications. **Existing high-accuracy GNSS techniques based on either NRTK or PPP techniques require high-end receivers and are currently targeted at professional applications** such as surveying, mapping, remote sensing, precision agriculture and marine positioning [RD.29].

Current precise GNSS positioning systems also depend on high frequency real-time corrections for error mitigation. This dependence makes the positioning system sensitive to correction outages as a high update rate means that the users have to maintain continuous wireless connections in order to timely receive the correction data. In real-world applications, correction data may be blocked or attenuated by buildings or trees and loss of correction data could also occur due to poor wireless network connections, causing frequent message packet losses. The loss of correction data in turn will reduce the availability of the positioning system due to performance degradation and re-convergence of the positioning solutions. Increased communication cost and higher power consumption in the devices for users to receive the correction data at a frequency is also problematic for mass-market applications. **Mass-market applications (such as drones, smartphones, etc.) demand careful consideration of the bandwidth, latency and data transfer cost for correction data transmission in the development of a real-time precise positioning system**. Mass-market applications also require rapidly obtainable precise position solutions and therefore long ambiguity convergence and fixing time are not acceptable. UAVs, for example, depend on precise positioning at all the times in order to achieve high performance flight control in complex environments.

In fact, mass-market applications such as autonomous vehicles, UAVs and smartphones are increasingly demanding high accuracy from GNSS integrated with other enabling navigation sensors. This demand is driven by the increasing availability of carrier phase measurements from low-cost GNSS chipsets that have been widely implemented within mass-market systems. For example, Google recently made GNSS raw measurements and carrier phase measurements available from a phone or tablet and Broadcom has announced the launch a mass-market GPS chip that uses L1 and L5 signals to pinpoint a device's accuracy to within 30 cm. Although mass-market antennas are still subject to further improvement due to their high noise ratios, their potential to support precise positioning is undeniable, and it is just a matter of time before they are widely adopted.

Autonomous vehicles are one of the most highly anticipated mass-market applications and most localisation experts agree that for fully autonomous navigation, the vehicle needs to position itself within 20-30cm horizontally. Whilst autonomous vehicles use a wide range of local sensors, it is anticipated that GNSS will complement these sensors. If reliable, high-accuracy, high-precision, high-integrity positioning can be achieved in autonomous vehicles, then GNSS can be used to validate these on-board sensors and enhance navigation.

3.2 Current use: mainly for professional applications

3.2.1 Precision Agriculture

Agriculture is a well-established application for GNSS data, with many tractor manufacturers incorporating GNSS receivers within their models to enable tracking and in some cases automated control. This enhanced control of farming equipment is leading to improvements in crop yields, productivity and a decrease in machine wear, with a 2009 study from Virginia Technology University claiming that an estimated 5% saving could be achieved from the use of GNSS guidance systems on farms [RD.14]. A clear example of how important GNSS data has become to the agriculture is showcased by John Deere establishing a subsidiary dedicated to the provision of GNSS signal augmentation – StarFire (both PPP and RTK services). This is further reinforced in **market research such as that published by Hexa Reports, which states that the precision agriculture is set to grow to $43.4 billion by 2025** [RD.28].

Applications enabled through improved accuracy GNSS:

- Automated ploughing, seeding and crop dusting etc.
- Marking of crop locations within farms
- Potential to track herds + flocks
- Use of UAVs to monitor and work on crops

GNSS augmentation signals can improve the precision of seeding, allowing for crops to be planted closer together to improve the efficiency of land and pesticide use. As RTK is well adopted into the agriculture industry, it is expected that PPP-RTK will initially see a slow uptake as users are reluctant to stop using their tried and tested services. The benefits of PPP-RTK may also be more limited in agriculture, as applications typically occur in pre-defined areas which can be covered by RTK stations. For farms which span large areas, the use of PPP-RTK could reduce infrastructure costs while retaining high accuracies comparable to RTK.

3.2.2 Surveying

Surveying was one of the earliest adopters of high accuracy GNSS services and has been fundamental in defining the user requirements for developing technologies [RD.05]. Surveying requires high accuracy data with low convergence / re-acquisition times, as these parameters are directly linked to the quality of their work and the productivity of their teams. As surveying is undertaken all around the world, there is a need to reduce reliance on the local infrastructure. **PPP-RTK can act as an excellent bridging technology between PPP and RTK by reducing the reliance on local infrastructure whilst also reducing the convergence times.**

3.2.3 Mining

The monolithic scale of open-pit mining requires huge fleets of machinery, creating a significant logistics challenge for operators. GNSS data is often used to enhance these operations; however, **it**

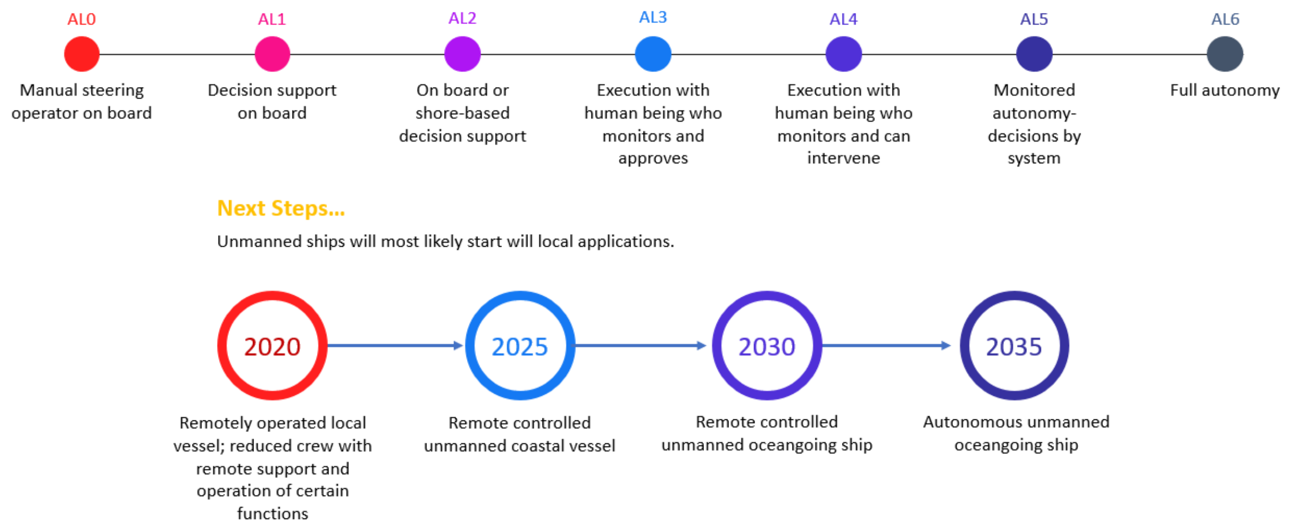
can be difficult to receive a reliable and accurate GNSS signal in some mine locations. These challenges hamper the productivity of mines and can present safety hazards to operators [RD.26]. **The provision of enhanced GNSS signals such as PPP-RTK is set to alleviate these challenges**.

Additionally, the availability of enhanced GNSS data can support the automated control of drills which increase safety and productivity as a single operator in a secure control room can operate and monitor up to five automated drills. Blast holes drilled by the automated drills must be very precise as the horizontal positioning is critical in controlling rock fragmentation size, which is directly related to the wear of rock crushers [RD.07]. **QZSS is using PPP-RTK in the mining industry and investigating how this technology can enhance mine performance** [RD.27]. Given the large areas, complex terrain and obstacles present at many mines, the provision of RTK can be challenging and costly. PPP-RTK can offer a high-quality signal across a broad area with a reduced reliance on local infrastructure, allowing greater flexibility in mine exploration and growth.

3.2.4 Marine

Whilst PPP is currently applied to a wide variety of marine applications such as navigation, seafloor mapping, underwater exploration, dredging, search and rescue operations, offshore drilling and pipeline routing, **it is expected that PPP-RTK will enhance each of these services through improved accuracy and reduced convergence times**. An increase in positioning accuracy can lead to improved fuel and time management reducing carbon footprint of vessels. Whilst autonomous capabilities are typically associated with the automotive industry, it is widely anticipated that marine shipping will also become increasingly automated. Increased positional accuracy will directly support the evolution of marine autonomy shown below.

Exhibit 15: Marine Autonomy Evolution [RD.40]



3.2.5 Geospatial Information Systems

A Geographic Information System (GIS) captures, stores, analyses, manages and presents environmental or resource data that is linked to a specific location. GIS is also used to map attributes and assets for insurance companies and other organisations. To achieve this, data must be collected in tandem with accurate location measurements which are provided via a GNSS receiver and either

PPP or RTK signal augmentation services. **PPP-RTK could improve the productivity of GIS data collectors through improving convergence times compared to PPP and removing the local infrastructure reliance of RTK**.

3.2.6 Aviation

As airports and skies become increasingly congested due to growing air traffic, there is growing pressure on small and regional airports to be safely accessible at all times. To meet these demands, air traffic management has adopted high-accuracy services such as the European Geostationary Navigation Overlay System (EGNOS) to provide enhanced vertical accuracy and integrity. It is expected that the aviation industry will continue to adopt high accuracy services to further improve the safety and efficiency of their air traffic management services [RD.67].

3.2.7 Rail

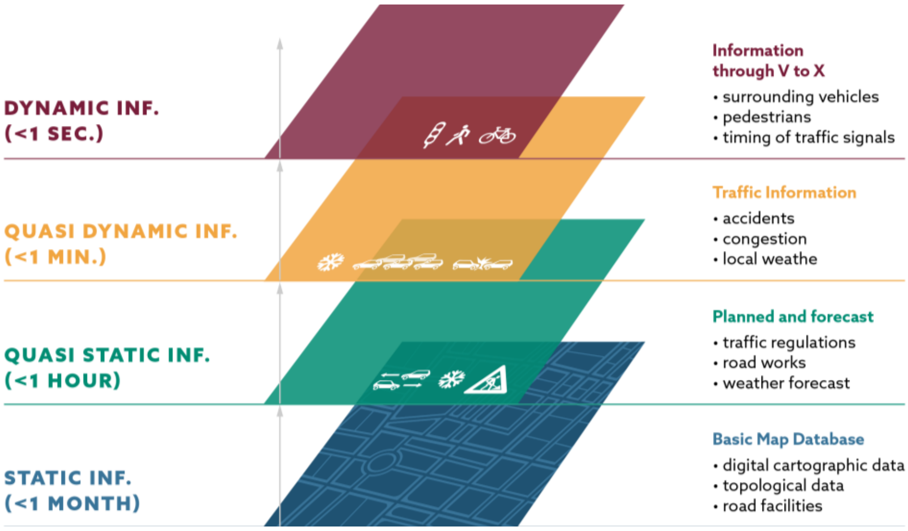
Railway transportation is a critical aspect of mass transportation and must maintain high safety standards within tight time constraints. The introduction of automatic train control systems has improved the efficiency railways, complemented by the use of GNSS to track trains even on low density line networks. High accuracy services improve the safety of signalling applications and can reduce the need for additional sensors on low traffic density lines, reducing maintenance costs [RD.68].

3.3 Future applications: mass-market and others

3.3.1 Common 3D Digital Map Concept

It is envisaged that PPP-RTK could be used to generate a high-accuracy 3D digital map which would support multiple applications [RD.35]. For example, this digital map could act as reference data for disaster planning simulations whilst also supporting infrastructure monitoring and traffic planning. This 3D digital map could operate in much the same manner as the "Digital Twin" concept which has become widely adopted in engineering industries. **The enhanced accuracy of these maps would support personal navigation and, in the future, would improve autonomous vehicles. It is anticipated that an accuracy of 10 – 30 cm would be sufficient for the Common 3D Digital Map Concept** [RD.35].

Exhibit 16: Breakdown of Common 3D Digital Map Concept [RD.35]



3.3.2 Smartphones

Whilst there have been studies on the application of PPP-RTK to smartphones such as that undertaken by Koki Asari et al [RD. 19], it should be noted that in this example an external survey-grade antenna was used. The impact of this on the results is unclear, but it makes it difficult to determine how suitable smartphones are to PPP-RTK. In addition, the same paper concludes that smartphones require significant performance improvements before they can receive a ranging signal that is suitable for PPP-RTK. Additional details on the suitability of PPP-RTK to smartphones can be found in Exhibit 17, where many experts queried the necessity of high accuracy positioning within mass-market devices.

The addition of high-accuracy positioning may enable a wealth of new apps, particularly with the adoption and development of augmented reality (see Section 3.3.5) however the benefits that these will bring remains to be seen. It is currently expected that the majority of these would be entertainment based and that enhanced accuracy is a nice additional feature but is not essential to their development.

GNSS is sometimes seen as a low priority in the design of smartphones, with the antenna buried deep within the phone and shared with other services. The GNSS capability of smartphones is also limited by the presence of radio frequency interference and the need to minimise power consumption. Generally, smartphones are not well suited to the adoption of GNSS [RD.49]. Centimetre level positioning is thought to be possible on smartphones but is very challenging to achieve and would work much better with improved antennas. Decimetre level positioning is much simpler to achieve with current smartphone technology [RD.50].

Exhibit 17: Stakeholder opinions on smartphone applications

Whilst asking about the suitability of smartphones for high accuracy applications, it was questioned by multiple experts whether smartphones required cm-level accuracy. No experts were able to identify applications where cm-level accuracy on smartphones would be the key enabler. However, some did point out that just because smartphones do not require high accuracy does not mean that it would not be widely adopted or potentially required in the future. Others, noted that besides accuracy considerations, the increase in reliability of the signal (due to the incorporation of multi-constellation GNSS) might be beneficial.

One of the companies interviewed had been working on the implementation of RTK to smartphones. **They stated that it is not currently possible to achieve sub-decimetre level accuracy, as ambiguity resolution could not be achieved due to the low-quality antenna and poor signal strength. Were the issues with the antenna to be resolved then this company believes that the computational demands, bandwidth requirements and battery drain of heightened accuracy services would not act as a significant barrier to its adoption to smartphones**. It is believed that smartphones are suitably powerful to support methodologies where the majority of calculations are undertaken on the "rover" unit such as VRS.

It was hypothesised by some experts that in the coming years, PPP-RTK could be implemented on smartphones to achieve cm-level accuracy as GNSS modules continue to are become cheaper and smaller. Whilst the accuracy might be desirable, the convergence time is likely to be a significant barrier to be overcome for the adoption of PPP-RTK in the mass-market as smartphone users expect near-instant results.

Antenna

The antennas used within smartphones are much lower quality than those used in surveying and other professional activities. The experts interviewed gave differing views on how this will impact their ability to achieve PPP-RTK on smartphones. Many experts said that the low-quality antennas are preventing smartphones from being able to achieve high-accuracy positioning, this viewpoint has also been reinforced in the available literature [RD.19]. However, some experts debated this and said that the quality of the antenna does not significantly impact the ability of the smartphone to receive and solve the carrier phase solutions. Whilst the quality of the antenna does impact the accuracy, it is not an insurmountable barrier to the uptake of PPP-RTK on smartphones. This provides an excellent demonstration of the complexity of the problem facing organisations attempting to deploy PPP-RTK and use novel technologies**. It is worth noting that all experts interviewed believed that further smartphone antenna development would enable them to achieve high-accuracy positioning**.

While it is anticipated that future development of smartphone antennas will increase their ability to achieve high accuracy measurements, experimental results have shown that GNSS performance of smartphones has decreased in recent years. Recent experimentation compared the accuracies of GNSS measurements between the Samsung Galaxy S4 (2013) and the Samsung Galaxy S7 (2016), with the S4 achieving an average (2D – root mean squared) horizontal accuracy of 6.59m and the S7 averaging 10.54m [RD.52]. Additional experiments suggest that the use of RTK on smartphones (Huawei P10+ - 2017) does not provide a significant advantage as it is unable to fix the phase ambiguities [RD.53].

Battery

The battery is **not expected to be a critical limiting factor** in the application of PPP-RTK to smartphones. This battery would become a consideration after issues with the antenna are resolved, the battery drain would be similar the that experienced when using the standard GNSS chip in current smartphones.

Computational Demand

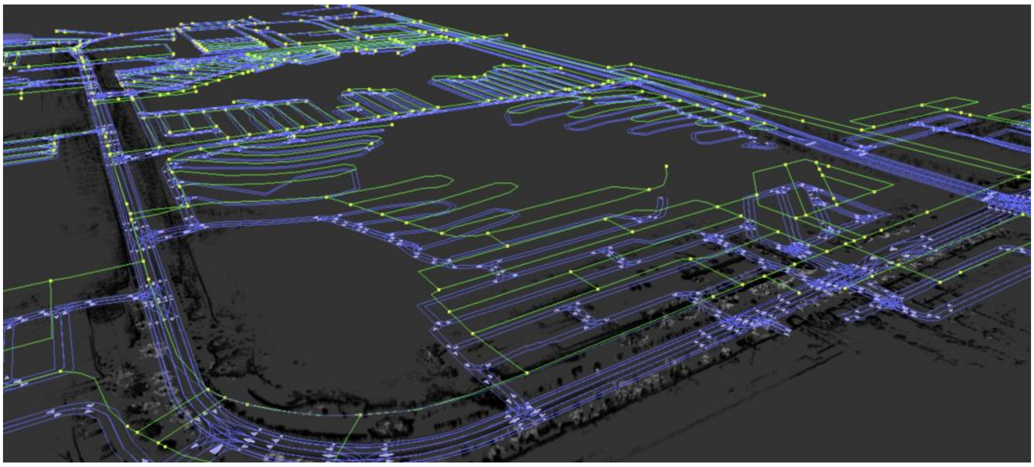
There is little available information on the computational requirements of the innovative PPP-RTK algorithms. As such, it is not currently possible to quantifiably determine the impact that the computational requirements may have upon smartphones and how much of a limitation this will be. Nevertheless, based on the viewpoints of experts, the computational requirements are not expected to be a limitation to the adoption of PPP-RTK on smartphones.

3.3.3 Navigation maps

Mass-market navigation tools such as Google maps have become widely adopted around the world; however, often these have issues with providing an accurate initial user location. Multiple methodologies are being developed to resolve this issue, with Google focusing on the use of machine learning and scene recognition [RD.25]. This solution faces many issues such as the visual environments changing throughout the year. Instead it is envisaged that PPP-RTK could be implemented to provide the high-accuracy initial location, enhancing the user experience.

3.3.4 Automotive

Exhibit 18: High-accuracy routing map for automotive applications [RD.41]



Autonomous vehicles require the combination of highly specialised sensors to navigate without the aid of a human pilot. The inclusion of GNSS will be essential to their ability to navigate through the open-ended environment of the world; however, multiple barriers restrict the use of GNSS to providing complementary data to aid navigation.

Accuracy: Standalone GNSS may not provide high enough accuracy to be used as a primary sensor for autonomous navigation, making the use of signal augmentation services necessary. Given the potential demonstrated by the automotive market, multiple service providers such as Trimble and Novatel are already offering signal augmentation services for the automotive market. Even with the improved performance of RTK, PPP, or PPP-RTK it is not expected that autonomous vehicles will solely rely on GNSS, as other sensors such as LIDAR are able to provide higher accuracy with increased position reliability and integrity. **Instead, GNSS will likely be used to obtain an approximate location, which the other sensors will improve upon**.

Reliability: It is not expected that GNSS will be used as the primary sensor for autonomous navigation of vehicles as it relies on receiving a continuous external signal. Instead, manufacturers are likely to combine data from multiple sensors to ensure a continuous position can be obtained even in areas without GNSS coverage. There are currently no feasible changes that can be made to either vehicles or GNSS services that will ensure that GNSS signals are not lost. Despite these challenges, the occurrences of these dropouts are thought to be infrequent and short-lived making GNSS suitable as a core part of autonomous navigation solutions.

Integrity: Whilst high accuracy can be achieved through GNSS signal augmentation services, there remains a critical barrier to its adoption in automotive applications. While resolving the integer ambiguities required to achieve RTK-level accuracies, it is difficult to determine the accuracy which is being achieved. As such, this can potentially lead to false accuracies being stated, providing HMI to the navigator leading to potentially dangerous manoeuvres / decisions.

Latency: In addition to these limiting factors, the latency of the service could also present a barrier to adoption. QZSS CLAS states that a latency of 10 - 20 seconds could be expected due to the delay between information creation and transmission. This latency could prevent the use of high-accuracy GNSS for high speed applications [RD.31].

Exhibit 19: Stakeholder Opinions on Automotive Applications

Every expert who was questioned about the suitability of PPP-RTK to the automotive industry stated that it would be a critical mass-market application for high-accuracy positioning; however, they also noted that as this is a safety-critical application, it is likely that GNSS signals will be used as a secondary data source. On-board sensors such as LIDAR are expected to remain as the primary sensor used for autonomous navigation.

It is expected that automotive applications (manual or autonomous) will not require cm-level accuracy, **instead an accuracy of 0.5m would be sufficient as long as the convergence time is kept sub-minute**. As automotive applications are a safety-of-life application, it is essential to ensure that vehicle is not provided with HMI. HMI is when the location provided to the vehicle presents a false sense of accuracy, causing trust to be placed in the positioning data which could then lead to potentially dangerous decision making.

As the integrity of the location received is critical, there is a need to know the error margin of the accuracy. **Some experts expect that the automotive industry will follow the example of the aviation industry**, by using float solutions which enable an understanding of the integrity of the accuracy provided.

Antenna

Automotive applications have already been successfully using GNSS to support navigation and several high accuracy services are available to provide both PPP and RTK corrections. Ongoing developments and **EU projects such as PRoPART are supporting the adoption and implementation of high accuracy GNSS within automotive applications and have demonstrated that automotive antennas have not proven to be a limiting factor to the use of these technologies.**

3.3.5 Augmented reality

Recent technological developments are expanding the capabilities and suitability of AR to the mass-market. AR has become a staple of maintenance and inspection activities within multiple industries, providing easy access to plant information and hazard identification. The mutually beneficial advancements of Building Information Modelling (BIM) and AR continues to provide significant benefits to the construction and maintenance industry, demonstrating the potential of the technology.

As the technology becomes more flexible to varying environments it is expected that AR will become more widely adopted within mass-market applications. Whilst the exact nature of these mass-market applications is unknown, it is expected that accurate positioning data will be critical to support environment identification and in-game locations.

For most mass-market AR applications, it is expected that high-accuracy positioning of the user would lead to a smoother and more enjoyable user experience. A specific example of AR for entertainment could be a virtual "laser-tag" game where players tag one another based on the location and orientation of their phone. For this, the accuracy of the players position would be critical to the success of the game. AR headsets (such as the Microsoft HoloLens) are also highly anticipated to disrupt the inspection and maintenance industry, where the use of high accuracy GNSS would improve the marking of defects, improving worker performance and reliability. Once PPP-RTK can be deployed on small mobile devices, AR headsets and AR enabled smartphones would greatly benefit from the improved accuracy; however, the use of low-cost antennas presents the same barriers as for smartphones.

3.3.6 Autonomous Robotics

Robotics is widely reported to be one of the fastest growing market sectors with a predicted Compound Annual Growth Rate (CAGR) of 15.9% per year to 2025 [RD.21]. This explosive growth is being driven be the developing capability of robots to navigate complex environments and understand the context of the situation they are in. Whilst local sensors such as LIDAR are critical to understanding the robot's immediate surrounding, the inclusion of GNSS sensors are necessary for open environment navigation. In addition, GNSS sensors can support environment identification of the robot, by geo-fencing high-hazard or prohibited areas such as airports.

High-accuracy positioning systems have been already been implemented on mass-market robotics such as the ANAVS multi-sensor RTK module, which is advertised for use with autonomous lawnmowers and is further demonstrated in research literature [RD.22].

3.3.7 Sports tracking

Driven by the desire for increasingly advanced activity tracking applications, the personal fitness tracker market expected to exceed $48 billion by 2023 [RD.24]. Whilst many of the casual users of these technologies will be content with the accuracy currently provided by systems such as Fitbit, professional athletic teams also use positioning and timing technologies to track athlete performance, fatigue and strategy effectiveness [RD.23]. **Athletes (such as long-distance cyclists and rally-racing teams) would greatly benefit from the increased accuracy and world-wide coverage that PPP-RTK offers, enhancing their performance analytics**.

3.4 Market and Technology Trends

The market for augmented GNSS services is well established and the technologies have been adopted by a wide variety of industries. Due to the ever-expanding requirements of these individual industries, there have been multiple technological developments within the GNSS signal augmentation markets, such as those described in Section 2.

Given the niche nature of the market, there is little available literature on how the market is expected to develop in the coming years, particularly regarding how the novel technology of PPP-RTK will be incorporated into the market. Based upon the available literature, three core characteristics of the augmented GNSS service market have been identified:

1. Signal augmentation technologies are selected based upon the characteristics of the intended application.
2. The market remains interested in the development and deployment of PPP-RTK, although only a few real-world demonstrations have been found in either mass-market or professional domains.
3. Service providers do not currently view the mass-market as a viable target for their services, it is believed that this is primarily due to the limitations of low-cost receivers.

It is expected that the three core GNSS signal augmentation services shall continue to be used within the market for the foreseeable future. The deployment of PPP-RTK will not necessarily drive users to leave the proven technologies of RTK and PPP. This viewpoint is reflected in the opinions of the stakeholders interviewed (summarised in Exhibit 20). Additionally, it is believed that PPP-RTK will see greater adoption in the professional sectors where increased accuracy can be directly related to enhanced efficiency and operations. Mass-market applications are not currently being targeted by PPP-RTK service providers; likely due to the remaining hardware limitations of mass-market devices.

Exhibit 20: Stakeholder Opinions on PPP-RTK Uptake

When asked about the expected adoption of PPP-RTK within the mass-market, multiple experts foresee it being integrated into professional services more heavily than the mass-market due to various technical limitations of mass-market devices and the technologies. This viewpoint is reinforced by the business plan of an organisation which intends to implement a nation-wide PPP-RTK service. The decision to provide this service came from the request of regional authorities and professional applications, and the service is not intended to be used by the mass-market, although the automotive sector expressed an interest. This service has undertaken multiple trial periods where corrections were broadcast using Digital Audio Broadcasting (DAB+) and the same Compact SSR format as QZSS.

Some experts stated that it is hard to predict the extent of the adoption of PPP-RTK, the industry is conservative and therefore are reluctant to upgrade systems that they know work. Once the advantages of the technology have been clearly demonstrated, then it is expected that there will be a significant increase in adoption.

The chipset and receiver technologies are closely linked to the development of the service providers, with some receiver manufacturers directly supporting the development of PPP-RTK. Efforts are also being made to ensure backward compatibility of newer signal augmentation services with older receiver models. In addition to the enhancement of chipsets and receivers, it is also worth noting that many hardware developers are incorporating interesting complementary technologies (such as accelerometers, barometers, LIDAR and map matching) to improve performance and provide enhanced services, especially in demanding environments such as autonomous vehicles.

Exhibit 21: Stakeholder Opinions on Expected Chipset Developments

Receiver manufacturers are directly supporting the development of PPP-RTK and are working to ensure that GNSS corrections are as simple as possible to use, to achieve this they are often also active in developing the signal processing software. For professional services it is expected that these receivers will continue to expand their functionality, whereas for mass-market applications it is believed that dual frequency should be sufficient, however multi-GNSS is likely to be incorporated to improve reliability. Some experts did believe that if smartphone chipsets continue to include multiple frequencies and multiple constellations, then companies which provide standalone receivers may be impacted.

4. COMPETITIVE LANDSCAPE

4.1 Introduction

The market for high accuracy GNSS applications has been rapidly evolving in recent years and has reached a high level of maturity in the professional field, ranging from mapping & surveying, GIS, mining, maritime, precision agriculture and construction. Current service providers offer SBAS, RTK, DGNSS (based on satellite/ground monitoring station) and PPP solutions, and continually expand their offering with innovative concepts such as PPP-RTK. Currently, these services are entirely focused on professional applications as hardware limitations prevent mass-market receivers from using high-accuracy services.

European
Global Navigation
Satellite Systems
Agency

4.2 Precise Point Positioning

The following provides an overview of some key players offering PPP solutions to date. It is not meant to be exhaustive.

Company	Service Name	Product	Stated Performance	Convergence Time	Supported Constellations	Country
Trimble	Omnistar	XP	8-10 cm	< 45 min	GPS	US
		G2	8-10 cm	< 20 min	GPS + GLONASS	
Fugro	Starfix / Seastar	XP	10 cm		GPS	Netherlands
		G2	10 cm		GPS + GLONASS	
		G2+	3 cm		GPS + GLONASS	
		G4	5-10 cm		GPS + GLONASS + BeiDou + Galileo	
		XP2	20 cm		GPS + GLONASS	
Hemisphere	Atlas	Basic / H100	50 cm	< 2 min	GPS + GLONASS + BeiDou + Galileo	US
		H30	30 cm	< 5 min	GPS + GLONASS + BeiDou + Galileo	
		H10	8 cm	< 40 min	GPS + GLONASS + BeiDou + Galileo	
John Deere	Starfire	SF2	5 cm		GPS + GLONASS	US
Oceaneering International	C-Nav	C1	5 cm		GPS	US
		C2	5 cm		GPS + GLONASS	
Hexagon AB	Veripos	Apex	< 5 cm		GPS	Sweden
		Apex²	< 5 cm		GPS + GLONASS	
		Apex⁵	< 5 cm		GPS + GLONASS + BeiDou + Galileo + QZSS	
		Ultra	10 cm		GPS	
		Ultra²	10 cm		GPS + GLONASS	
	TerraStar	TerraStar D	10 cm		GPS + GLONASS	
		TerraStar L	50 cm	< 5 min	GPS + GLONASS	
		TerraStar C	5 cm	30-45 min	GPS + GLONASS	
		TerraStar C Pro	3 cm	< 18 min	GPS + GLONASS + Galileo + BeiDou	
TopNET global	TopNET live	TopNET live	4-10 cm	20 – 30 min	GPS + GLONASS	US
Rokubun	Rokubun	JASON	40 cm			Spain
Septentrio	Secorx	Secorx-60			GPS + GLONASS	Belgium
		Secorx-C			GPS + GLONASS	
		Secorx-D	10 cm		GPS + GLONASS	

NovAtel	Waypoint	GrafNav	< 5 cm		GPS + GLONASS + Galileo + BeiDou + QZSS	Canada
GMV	Magic	MagicPPP	< 10 cm	30 min	GPS + GLONASS + Galileo + BeiDou + QZSS	Spain

4.3 Real-Time Kinematic

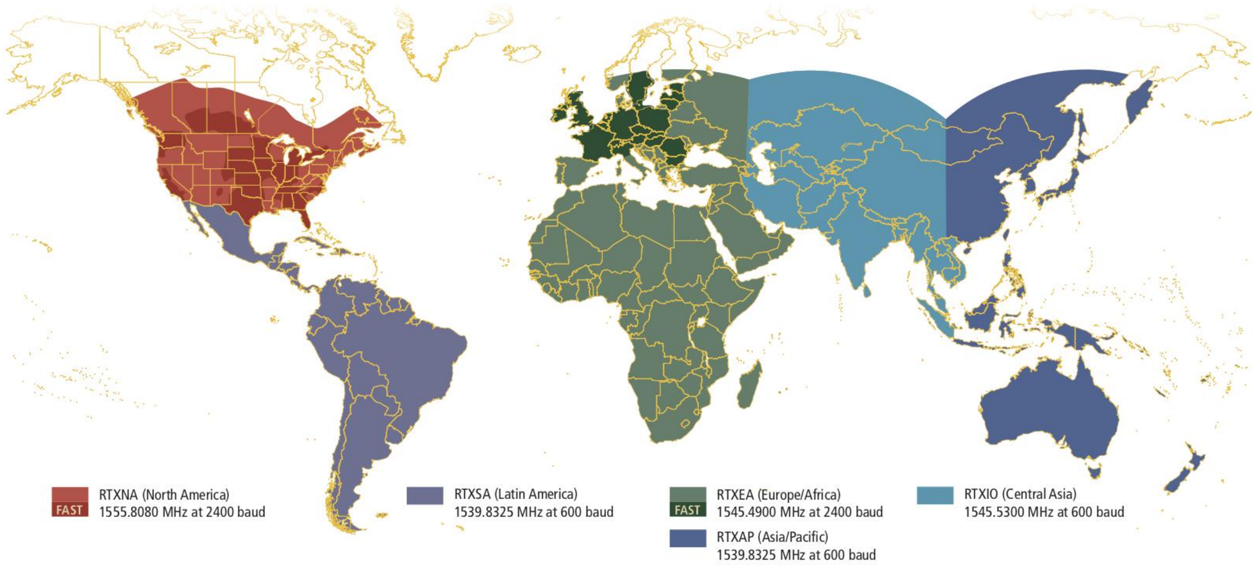
There are many RTK providers, each country in Europe has more or less at least 3. The following table summarises some example s of players and offered solutions.

Company	Service Name	Product	Stated Performance	Convergence Time	Supported Constellations	Country
Trimble	VRS Now	VRS Now	< 2 cm	Instant	GPS + GLONASS + BeiDou + Galileo + QZSS	US
Ordnance Survey Limited	OS Net	OS Net	5 cm	< 60 min		US
Advanced Navigation	Kinematica	Kinematica	2 cm		GPS + GLONASS + Galileo + BeiDou	Australia
SBG Systems SAS	Qinertia	Ellipse	2 cm		GPS + GLONASS + Galileo + BeiDou	France
		Ekinox	2 cm		GPS + GLONASS + Galileo + BeiDou	
		Apogee	1 cm		GPS + GLONASS + Galileo + BeiDou	
Trimble	Axio-Net	Axio-Net RTK	2 cm		GPS + GLONASS	US
Swift Navigation	Swift Navigation	Piksi Multi	2 cm	< 1 min	GPS + GLONASS + Galileo + BeiDou	US
		Duro Inertial	10 cm	< 10 seconds	GPS + GLONASS + Galileo + BeiDou	
Metro Vancouver GNSS Service	Metro Vancouver GNSS Service	Metro Vancouver GNSS Service			GPS + GLONASS	Canada
u-blox	ZED-F9P	ZED-F9P	10 cm	< 30 seconds	GPS + GLONASS + Galileo + BeiDou	Switzerland
NovAtel	CORRECT	CORRECT with RTK	1 cm		GPS + GLONASS + BeiDou	Canada
FixPosition	FixPosition	FixPosition	1 cm	5 seconds	GPS	Switzerland

4.4 Precise Point Positioning – Real-Time Kinematic

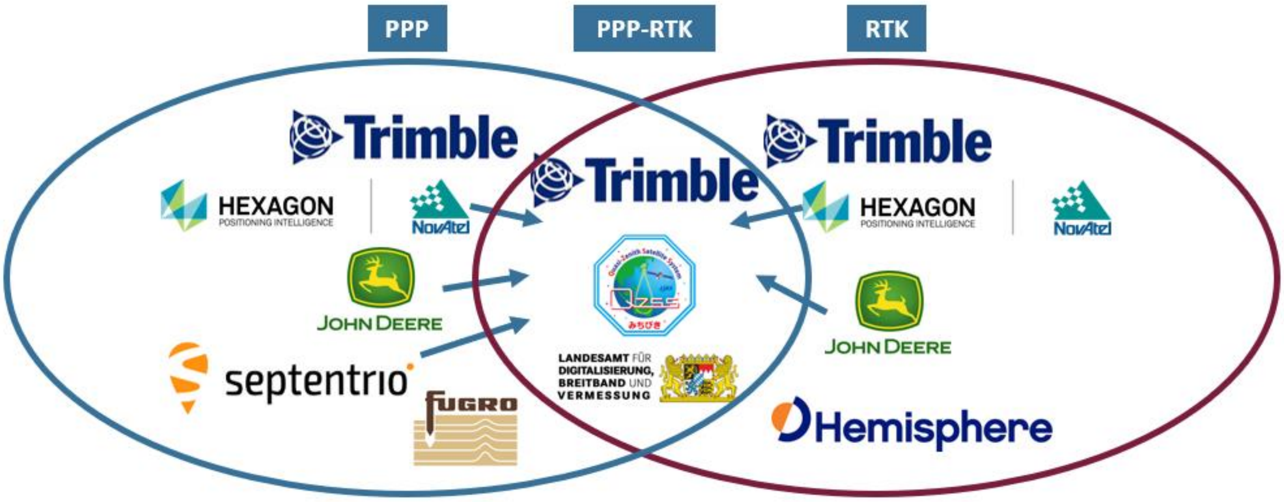
Global PPP-RTK remains in the development and early-application stages; however, there are a couple of notable regional deployments of the technology. Some regional authorities have developed their own signal augmentation services, such as the Japanese Quasi-Zenith Satellite System Centimetre-Level Accuracy Service (QZSS CLAS) (operational since 2018) and the Bavarian State Office for Survey and Geoinformation (undertaking trial operations) have begun offering PPP-RTK services. Additionally, commercial companies are beginning to offer PPP-RTK services, such as the service provided by Trimble which is available in some regions across North America and Central Europe (shown as “FAST” regions in Exhibit 22).

Exhibit 22: Trimble RTX Satellite Broadcast Frequency Coverage Map



If these applications prove to be successful and effectively demonstrate the benefits of PPP-RTK, then it can be expected that additional PPP-RTK services will come to the market. Exhibit 23 presents the current market offerings from key service providers and the anticipated developments in their offerings.

Exhibit 23: Current and Future Outlook on Service Providers



4.4.1 FLAMINGO H2020

Fulfilling enhanced Location Accuracy in the Mass-market through Initial Galileo services Horizon 2020 (FLAMINGO H2020) is an EU Funded project which has developed an enhanced location accuracy solution for the mass-market. FLAMINGO is aimed at developers of mass market applications delivering the best available accuracy for the device and environment. It is implemented via a service which itself is enabled through a programmers Application Programming Interface (API). Styled on Google's Geolocation API, the FLAMINGO API provides a familiar interface and conceals the complexities of GNSS positioning to the end users.

Behind the scenes, FLAMINGO is utilising multi-constellation and multi-frequency (when available) GNSS from Smartphone and IoT devices along with different GNSS and positioning services dependent on the location and densification of the ground network providing the required RTCM data services. These data services, and their products, are generated within FLAMINGO and are currently using reference stations with freely available data coupled with some dedicated stations. Assisted GNSS and Google's raw measurements API are used to access to the Smartphone GNSS data which is converted to RTCM messages and used within the positioning engine. The control, stability and continuity of Smartphone GNSS is limited, making traditional PPP problematic. Also, this intermittent nature of Smartphone measurements forces non-standard approaches to be taken to combine short-lived and fluctuating single and dual frequency measurements. Decision logic controls the type of positioning that takes place. When devices are close to reference stations, an RTK-style solution is adopted, and this moves to SSR-based PPP-RTK as the distance increases. All data flows use RTCM standards and the combination of these techniques provides a service accuracy of 1m - 50cm on smartphones [RD.43].

FLAMINGO H2020 addresses mass-market devices such as smartphones and IoT devices, to facilitate and demonstrate reliable positioning and navigation in consumer applications. FLAMINGO is using the European Global Navigation Satellite System (E-GNSS) to build the enabling infrastructure and services for high-accuracy positioning [RD.01].

As discussed in Section 3.3.2, the provision of high-accuracy services to smartphones is limited by the hardware and architecture of the smartphone itself; because the antenna is embedded within the phone, it introduces additional interference sources and errors. Despite this, it is believed to be possible to achieve accuracies of several decimetres which can be used for applications such as surveying and augmented reality. [RD.43]

Multi-constellation GNSS is the key enabler of the FLAMINGO solution, because it provides additional satellites, improving signal availability especially within the environments in which the mass market applications operate. Galileo is the game changer. The provision of E5 on all satellites along with the introduction of compatible chipsets within Smartphones improves the E1 measurement (reducing multipath) and allows for the implementation of high accuracy positioning algorithms. It is hoped that FLAMINGO will become a commercial venture and developers will implement the API within their application, and immediately be able to deliver a more accurate positioning service. [RD.43].

4.4.2 Quasi-Zenith Satellite System Centimetre Level Accuracy Service

QZSS is a regional satellite constellation which aim is to provide positioning services over eastern Asia and Oceania regions, while maintaining compatibility with the GPS System. Apart from the standard navigation signals, QZSS also transmits L-band Experimental signal in L6 (1278.75 MHz) with a very high data rate (1744bps) for the provision of augmentation corrections which include orbit and clock corrections to support high-accuracy positioning applications. A summary of these high-accuracy services is provided in Exhibit 24.

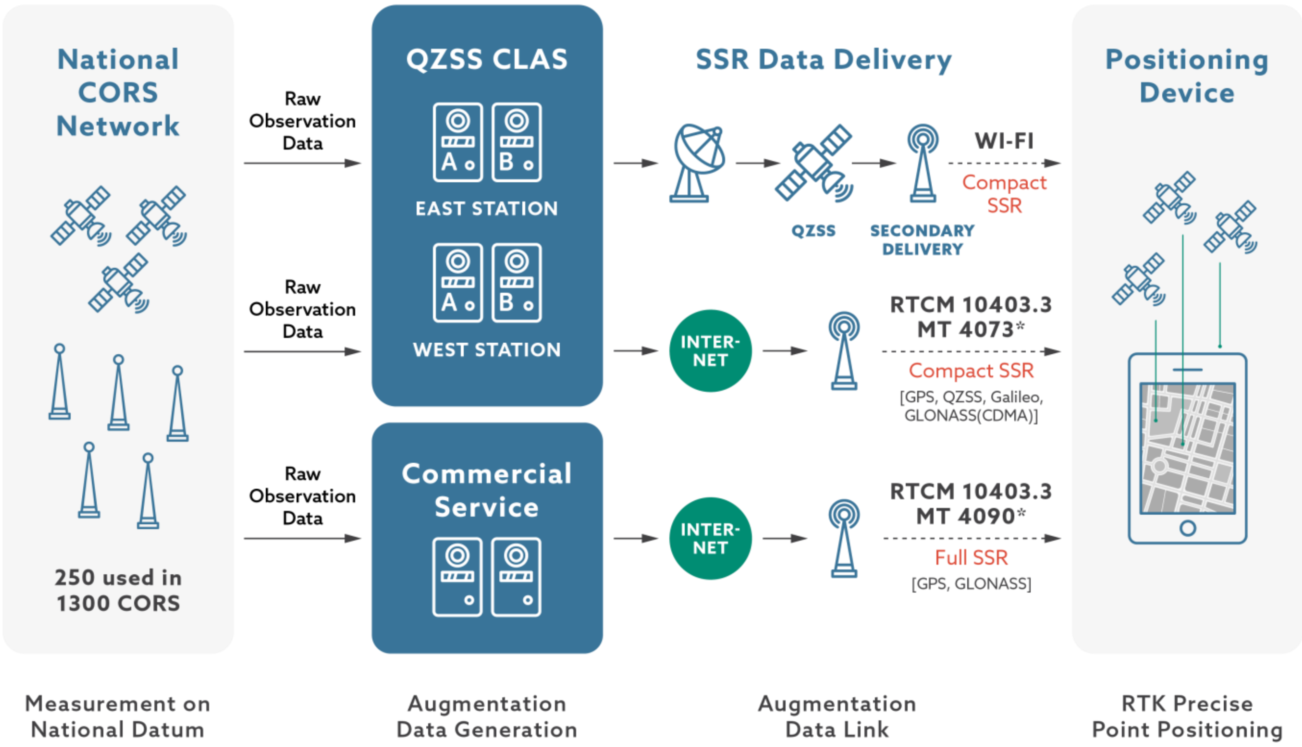
Exhibit 24: QZSS Summary of Information

Name of the service	Accuracy	TTFF	Main features	Coverage	Target customers	Time of commercialization
SLAS	H: $\leq$ 1.0m(95%) V: $\leq$ 2.0m(95%)	$\leq$ 30[sec] (95%)	Meter level system over Japan	Over japan and coastal waterways	All applications	2018
CLAS	Static: H $\leq$ 6cm(95%) V $\leq$ 12cm(95%) Kinematic: H $\leq$ 12cm(95%) V $\leq$ 24cm(95%)	1 min	cm-level system over Japan	Over Japan (up to 20-30 km distance from CORS)	Automotive, surveying, constructions, agriculture	2018 (trial)
MADOCA	Cm level	30 min (1 min by applying local corrections data)	cm-level system worldwide (via internet)	Global	Automotive, surveying, constructions, agriculture	2018 (trial)

The QZSS CLAS which utilises L6 signals to send centimetre level augmentation information. CLAS is targeting professional markets such as surveying, intelligent construction and precision agriculture and requires a dedicated L6 receiver [RD.31]. CLAS, which entered into full service in 2018, is based upon PPP-RTK and uses a Compact SSR data format.

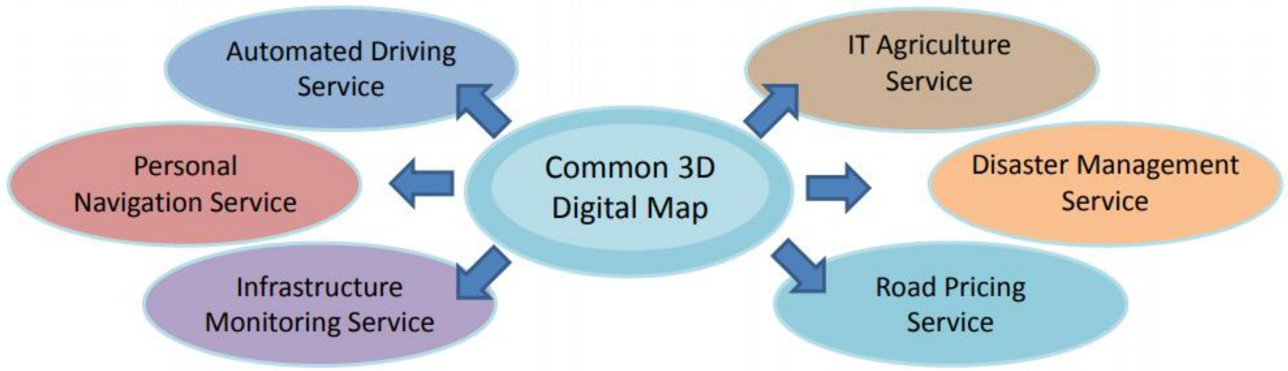
CLAS users must have a dedicated L6-band receiver and so is not currently suitable for use with unmodified mass-market devices. The system broadcasts all six corrections listed in ISO19187 (orbit error, clock error, code bias, carrier-phase bias, Ionospheric delay and Tropospheric delay) which are delivered through the framework shown below.

Exhibit 25: QZSS CLAS Framework [RD.19]



Japan has a well-developed infrastructure, with over 1,300 CORS already installed. The CLAS service reportedly only requires 250 of these stations, providing a high level of redundancy. Various applications of CLAS have been identified by Mitsubishi Electric, who plan on creating a high-accuracy 3D map using CLAS information that can be used for multiple applications [RD.35]. The Common 3D Digital Map Concept is currently being reviewed by the Council on Competitiveness-Nippon and is presented below (additional detail on these application areas can be found in Section 3).

Exhibit 26: QZSS CLAS Common 3D Digital Map Concept [RD.35]

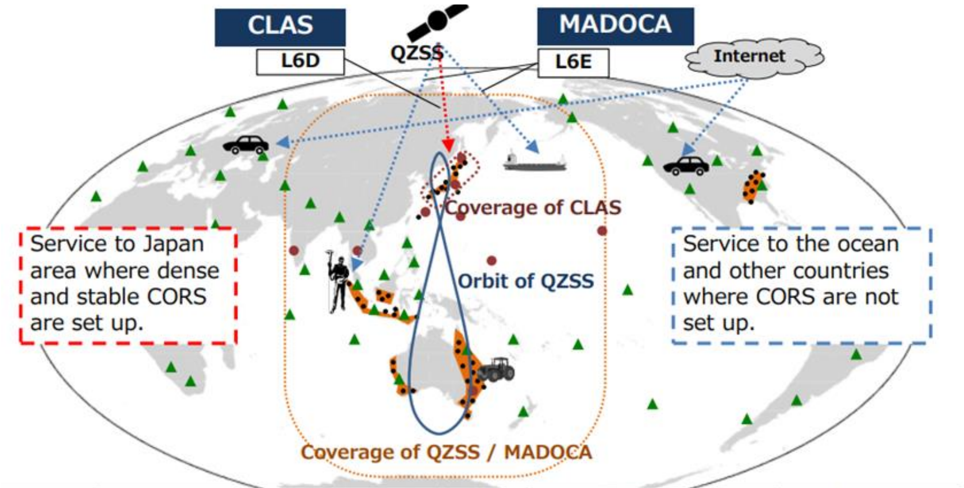


Additionally, Mitsubishi Electric put forward a proposal for EU-Japan Cooperative Activity regarding high-accuracy services in SOL applications [RD.35]. In particular, there was interest in investigating the following topics:

- How to provide a continuous and accurate navigation service with limited available satellites
- How to judge reliability of a navigation signal from each navigation satellite
- How to utilise integrity in SOL applications
- How to establish authentication methods in SOL applications
- How to standardise a Common 3D Digital Map for multiple applications

MADOCA, another of QZSS's services, provides a worldwide coverage – through QZSS satellites over its footprint or via internet connection over the rest of the world, with a convergence of 30 minutes. The target accuracy for MADOCA is less than 10 cm for horizontal and vertical (Root Mean Square (RMS)) and approximately 2 cm in the case of ambiguity resolution (PPP-AR). The relationship between CLAS and MADOCA are represented in Exhibit 27.

Exhibit 27: QZSS High Accuracy Services



Message	Service Area	Accuracy	TTFF	CORS	Data Size
CLAS	Around Japan	cm-level	1min	20 to 30 km interval	2kbps for Japan
MADOCA	Coverage of QZSS *All over the world via internet*	cm-level	30min **1min*	About 100 in the world	2kbps for World

4.4.3 Trimble CentrePoint RTX – Fast Regions

Building upon the success of Trimble's RTX technology, the Trimble CentrePoint service provides high-accuracy GNSS positioning services via satellite or internet delivery worldwide. It is ideal for jobs that require the highest level of accuracy, with expected accuracies reaching 2.5cm horizontal accuracy. RTX CentrePoint provides PPP-RTK to specific "FAST" regions (shown in Exhibit 22) with well-established CORS networks and PPP globally. The broadcasting of the signal enables users to connect to the service all around the global without the need for local infrastructure. The service is quoted as being able to withstand signal interruptions of up 200 seconds without the need for reinitialization and converges to full accuracy near instantly in the FAST regions, and in less than 15 minutes globally. Trimble RTX is compatible with multiple GNSS constellations, including GPS, GLONASS, Galileo, BeiDou and QZSS, however is only available for land use. **The reason for the restriction to land use is unclear as the signal is broadcast globally via satellite. Without the presence of CORS it is expected that the service would degrade to mimic standard PPP.**

4.4.4 Teria-Exagone

Teria-Exagone offers a wide range of services adapted to its customers' requirements and according to their application (such as civil aviation and marine surveying). The PPP-RTK TERIA service is available via the internet. The TERIAsat improves the accuracy of satellite geo-positioning using PPP-RTK. **In regions where PPP-RTK is not available, standalone PPP is provided. These corrections are sent via geostationary satellites and converted to N-RTK in RTCM format** to ensure that the receiver can operate in RTK mode. TERIAmove takes this one step further, by combining NRTK and PPP-RTK corrections, providing high availability and precise positioning with an integrity calculation. This gives the user two independent correction flows, calculating two positions. In addition to providing integrity, this also increases the availability of the service. **Currently this service has only been fully deployed in France, and partially deployed in nine partner nations**.

4.4.5 Fugro Marinestar G4+

The Fugro Marinestar G4 service is compatible with GPS, GLONASS, BeiDou, and Galileo, but does not use the two regional systems QZSS and IRNSS. **Marinestar provides a PPP service using GNSS data from a globally distributed network of 45 CORS. The Marinestar G4+ service is based on PPP-RTK using the uncalibrated phase delay approach** shown in Exhibit 10. This uses a network of reference stations with a density of 1000 – 2000km, enabling the estimation of UPDs for the GPS L1 observations and the wide-lane observations for every satellite in real-time. The UPD corrections are broadcast over the satellite links to the G4+ users. In the user's receiver, the integer values of GPS ambiguities are estimated using the Lambda method. The fixed GPS ambiguities are then used in the solution model to re-calculate more precisely the final position solution using GPS, GLONASS, BeiDou, and Galileo observations. The G4+ solution is quoted as providing 4cm horizontal accuracy [RD.60].

4.4.6 Geo++

Geo++ have been fundamental in the development of the GNSS signal augmentation market, having established the SSR data format and driving forward its standardisation [RD.12]. Technology developed by Geo++ has also been selected to be transmitted on the L6 channel of the Japanese QZSS CLAS.

Geo++ has also announced plans to deploy RTK on smartphones; however, this has proven technically challenging and is believed to still be in the early development stages. This has not yet been deployed and due to the proprietary nature of the technology, limited available information has been found on the status of its application.

Geo++ provides the SSRPOST which is a post-processing service based on GNSMART SSR data and a realisation of PPP-RTK. SSRPOST provides the user with a web interface to process the RINEX or raw data. The user can upload their own RINEX or raw data to the service and obtain the processed position based on data from the CORS network and the user's receiver. In theory, SSRPOST should achieve similar accuracies to RTK as long as proper environmental conditions were met.

4.5 European Industry SWOT analysis

The European market has been active in the high-accuracy positioning industry since it was founded, which has enabled it to become highly experienced and competitive. CORS networks are highly developed within Central Europe creating the perfect environment for the adoption of NRTK and PPP-RTK technologies. Europe also has highly advanced construction, agriculture, smartphone and automotive industries which are key consumers of high-accuracy signal augmentation services, this makes it an excellent market for service providers and the development of innovative high-accuracy solutions.

The deployment of Galileo HAS could further strengthen the European market and act as a key enabler to new applications of high-accuracy services, particularly within the mass-market. This is further supported by the strength of regional authorities across Europe, who could support the adoption of PPP-RTK much like Landesamt für Digitalisierung, Breiband and Vermessung (LDBV) – the Bavarian state office for digitisation, broadband and surveying have. Additionally, as Europe houses the headquarters of multiple global service providers any initiatives developed within Europe are likely to be transferred internationally. Service providers and hardware developers within Europe may also be able to take advantage of the rapid development of Chinese CORS networks. It is also worth noting that Mitsubishi Electric have considered the possibility of cooperation between QZSS and Galileo for SOL applications (such as aviation, rail, search and rescue, automotive) [RD.35]. This could provide a fantastic opportunity to further expand the influence of Galileo whilst also driving forward the adoption of enhanced GNSS technologies.

However, the European market faces significant challenges, most notably the lack of progress being made within the RTCM standardisation process for SSR data. It is believed that progress has stalled due to the interference of private companies who have already deployed assets which use a specific format of SSR data and are therefore unwilling to change formats. The lack of standardisation may lead to chipset developers looking further afield on how to enable SSR data, such as the Compact SSR data format being implemented by QZSS CLAS. Further details on the standardisation processes can be found in Section 5. In addition to the standardisation issues, the data delivery capabilities of Galileo may act as a bottleneck to the deployment of satellite-based correction services. Exhibit 28 presents a comparison of available satellite systems and their maximum data rates. Data rate limits the amount of data that can be delivered to each receiver, this would in turn reduce the quality of the ambiguity resolution, increasing convergence times.

Exhibit 28: Satellite System Data Comparison [RD.03]

Constellation	Augmentation Signal	Frequency (MHz)	Data Rate (bps) Approx.
EGNOS	E5b	1207.14	250
Galileo	E6	1278.75	500
BeiDou	B2b	1207.14	1000
QZSS	L6	1278.75	2000

Exhibit 29: Expert opinions on the European GNSS Market

We asked the experts how they saw the European market, the opinions presented below show how the European market is seen from both an internal and external viewpoint.

The European market is still maturing, with the innovative technologies (particularly the concepts of PPP-RTK) remaining in development. Europe has been working and researching in the field of augmented positioning services since the dawn of the technology. Europe has a very well established network of CORS, which makes it very well suited to the application of both NRTK and PPP-RTK. There was a general consensus that the European market is incredibly well-positioned and strong in the augmented GNSS industry, and that this position is supported by the collaborative sharing of data.

As most of the population lives in cities, they will not receive the excellent accuracy offered by services such as PPP-RTK. The interference from buildings and other infrastructure will degrade the main benefits of the technology.

Those interviewed stated that PPP-RTK will find its place in the market, however the market size and applications are unclear. Some experts believe that all users will transfer to PPP-RTK and this should be a relatively simple transition.

No expert was able to identify any notable new-comers to the market other than SwiftNavigation and PointOne. It is believed that the barriers to the market may be preventing new entrants, the high infrastructure and operational start-up costs of providing the service make it difficult to establish a niche within the market. **The main players within the market were identified as Geo++, Trimble, Hexagon, TopCon and StarFire**.

The mass-market is reportedly missing leadership and new services, currently there is no clear leadership and existing mass-market corporations are not well positioned to understand the complexities of these technologies. There is a gap between people who understand the technology and the mass-market players. Companies such as Google now have groups of geomatics engineering and the importance of Location Based Services (LBS) is gaining recognition. Additionally, changes would be required to the specific positioning algorithms to support the expected performance of mass-market devices. These algorithms continue to develop as urban and closed environments will still present challenges.

4.6 Conclusions

The European market is widely regarded as being a leader of the high-accuracy signal augmentation industry, with a well-established CORS network, high availability of cutting-edge technologies, strong leadership and highly advanced service providers. A summary of the key factors affecting the European market is presented in Exhibit 30.

The introduction of PPP-RTK is not expected to significantly disrupt the GNSS signal augmentation market. Many applications which are currently served by either PPP or RTK are unlikely to want to change to a new service without either clear financial or performance benefits. There is limited information available regarding the current usage statistics of PPP-RTK but based on the limited number of commercial services available and from expert interviews it is expected to have received limited adoption. This is likely due to users' lack of familiarity with the technology, if PPP-RTK can provide clear, demonstratable benefits in performance, cost or reliability user uptake will rapidly accelerate.

Conversely, the deployment of Galileo HAS will have a large impact on the market as this will directly compete with the commercial PPP and RTK solutions. Based upon a stakeholder consultation undertaken by the GSA in 2017 with 31 industry experts, it is expected that Galileo HAS will be well received by the market. 77% of those interviewed by the GSA supported the provision of a free HAS by Galileo [RD.47]. Galileo HAS is also anticipated to strongly complement the development of mass-market applications due to its low cost. To counter the market threat, commercial service providers may focus on SOL applications where position integrity is required, as this is not planned within the Galileo HAS service.

Exhibit 30: European Industry SWOT Analysis in regard to GNSS signal augmentation

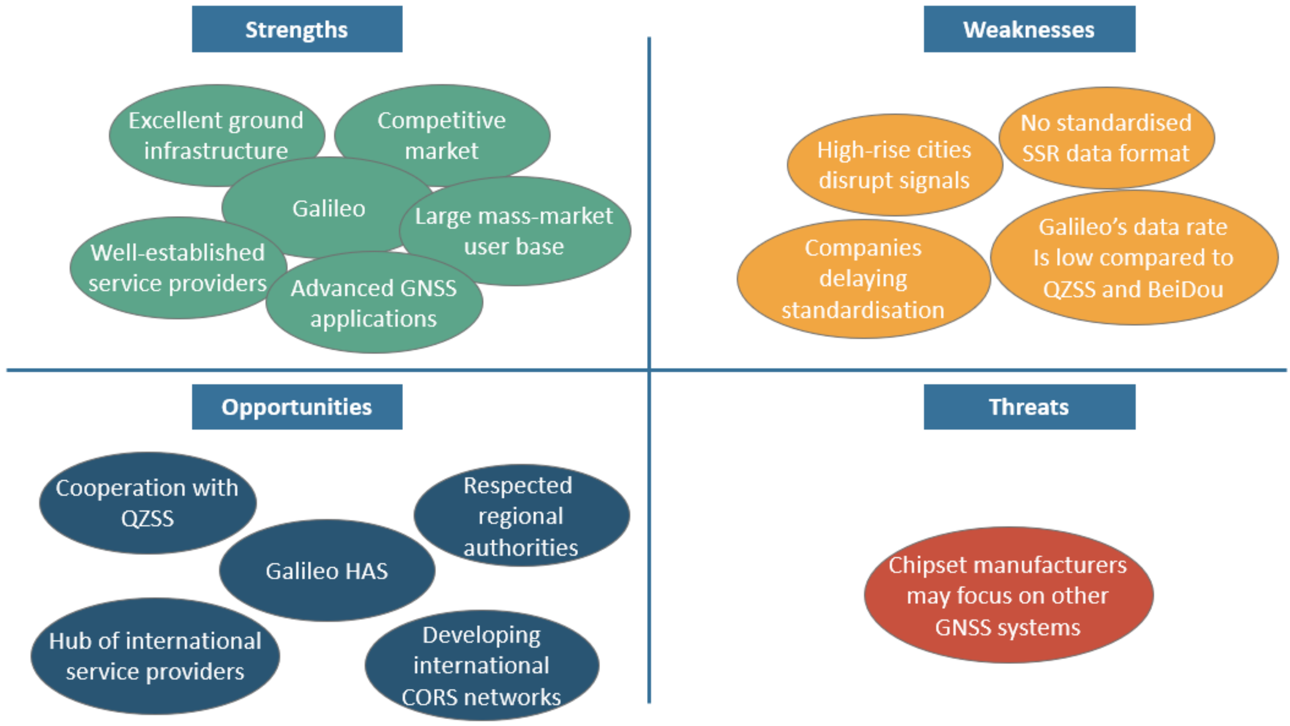


Exhibit 31: Stakeholder Opinions on how Galileo HAS will be incorporated into the GNSS market

When asked about how they expected Galileo HAS to be incorporated into the GNSS signal augmentation market, many experts claimed that there was some uncertainty surrounding the purpose and technical functionality of the service. This was further elaborated by a company who said that it was confusing as to what was included in the commercial service signal and what could be utilised.

Some experts believed that Galileo HAS would have a larger impact upon the mass-market than on professional applications, as these would continue to be served by the dedicated service providers. Commercial service providers are likely to see Galileo HAS as direct competition and are expected to differentiate their services through focusing on SOL applications and providing additional functionality.

5. Relevant Standardisation Activities

5.1 Introduction

While RTK is well standardized and conventional PPP is also supported by RTCM 3.3, the proposal for RTCM-SSR messages is still under the evaluation by the RTCM SC104 working group [RD.12]. That poses some challenges for the industry that may lead to other standardization organizations or industry groups developing an alternative non-RTCM standard as was the case of QZSS CLAS [RD.13]. Alongside the RTCM standardization process, there is also an effort dedicated to the inclusion of SSR (PPP-RTK) corrections in 3GPP standards as part of the assisted data via LTE Positioning Protocol in cellular networks.

Multiple free and open high-accuracy GNSS positioning services are either in the early stages of deployment or later phases of development (shown in Exhibit 32). **The interoperability between correction services and receivers is becoming increasingly important and so global standardization of these corrections signals is critical.**

Exhibit 32: Open Satellite-Based High-Accuracy GNSS Correction Services

System	Service	Satellite	Status	Signal	Data Rate	Format
QZSS CLAS	PPP-RTK	IGSO / GEO	Operational (2018)	1.278 GHz (L6D)	2,000 bps	Compact SSR
QZSS MADOCA	PPP	IGSO / GEO	Experimental (2017)	1.278 GHz (L6E)	2,000 bps	RTCM SSR
Galileo HAS	PPP	MEO	Development (2021)	1.278 GHz (E6b)	500 bps	Compact SSR (to be determined)
GLONASS	PPP	MEO / IGSO	Development (~2020)	1.207 GHz (L3)	Undefined	Undefined
BeiDou 3	PPP	GEO	Development (~2020)	1.207 GHz (B2b I/Q)	1,000 bps	Undefined
Austrian SBAS	PPP	GEO	Development (~2023)	1.5 GHz (L)	Undefined	Undefined

5.2 RTCM SC-104

The RTCM SC-104 working group was established in 1983 to develop standard for DGPS to achieve 5-meter accuracy and positioning. The initial version was replaced by Version 2.0 in 1990 due to implementation problems. Version 2.1 later added RTK messages enabling decimetre accuracies over short ranges in 1994. However, these messages remained inefficient; prompting the development of the more efficient, higher integrity and simpler Version 3.0 in 2004. Version 3.0 not only improved the deployment of RTK but also supported NRTK. Members of the SC-104 committee include vendors, service providers and government agencies from around the world.

The RTCM SC-104 is currently developing a standardised format to disseminate SSR information. The "State Space" working group is tasked with the development of SSR concepts and messages for all levels of targeted accuracies including RTK, and has laid out three key deliverables / stages [RD.15] [RD.61]:

- Stage 1 enables code-based PPP applications and consists of messages to transport satellite orbit corrections, satellite clock corrections and satellite signal code biases. This stage provides code-based real-time **PPP for dual frequency receivers**. Standardisation activities for this stage have been agreed upon and completed.
- Stage 2 is approaching standardisation and consists of messages for vertical ionospheric total electron contents to enable single frequency code-based PPP as well as messages for satellite signal phase biases to enable **phase-based PPP** and ambiguity resolution. This provides code-based real-time **PPP for single frequency receivers**.
- Stage 3 shall concentrate on the development of slant ionospheric total electron content messages as well as tropospheric delay messages to allow the use of **PPP-RTK**.

RTCM-SSR aims to be a self-contained format, such that the definition of RTCM-SSR contents shall not limit or restrict the generation of SSR streams, meaning that it shall remain observation model agnostic. To ensure this, international best practices shall be followed for observation modelling and corrections shall be well defined, documented and freely usable. **Different update rates will be allowed within the standard (as different error variables have different variability with time), further increasing its flexibility to different applications.**

The RTCM standardisation process remains in progress, but it is facing multiple challenges due to the complex nature of PPP-RTK data. The working group has not been able to agree on the performed interoperability testing; however, consensus is expected after testing has been undertaken on a complete set of SSR messages [RD.12]. Additionally, there are significant issues arising from the working group stakeholders. Many of the service providers and hardware developers have a personal interest in ensuring that the agreed upon standard does not deviate too far from their own proprietary format. As these companies have already deployed assets using their proprietary format, changing to a new standardised format would come at significant cost and disrupt customer operations. Mitsubishi Electric has stated that as of 27 June 2019, **RTCM SC-104 had made no progress since February 2011. The standardisation progress remains stuck in Stage-2, focused on messages for phase bias and VTEC [RD.59]**. However, standardisation is progressing within RTCM SC-134 for safety critical applications such as Automotive and Rail. RTCM-134 was established partly because SC-104 had become too large [RD.62].

5.3 3GPP LPP

3GPP recently released a new standard for Long-Term Evolution Positioning Protocol (LPP) – 3GPP TS 36.355 V15. The standard covers the broadcast of positioning assistance data including SSR Orbit

Corrections, SSR Clock Corrections and SSR Code Bias; however, this standard does not currently cover PPP-RTK [RD.66]. The 3GPP LPP standard is currently in the process of being adopted for use with PPP-RTK, however it is unclear when this will be finalised [RD.59].

5.4 Geo++ SSRZ

Geo++ is developing a proprietary standard for SSR data – SSRZ. This groups satellite and message information into a single data stream with an asynchronous update rate of the SSR parameters. The resolution of the SSR parameters is dynamic, enabling it to be optimised to fit the available bandwidth through compression (particularly the atmospheric SSR parameters). SSRZ could be expanded for specific services through the provision of GNSS integrity information and for private services the use of selective access control and message encryption. [RD.61]

5.5 Compact SSR

Compact SSR is a bandwidth efficient format of SSR for PPP-RTK services and has been implemented within QZSS CLAS [RD.13]. Following the successful deployment of QZSS CLAS, interest in the format has increased and several institutions such as LDBV have expressed an interest in using the Compact SSR data format. **Compact SSR is claimed to be significantly more efficient than the proposed RTCM SSR format, requiring a data rate approximately 71% lower** [RD.46]. As Compact SSR has been successfully deployed and RTCM standardisation continues to stall, it is expected that more companies and institutes will adopt alternate solutions [RD.61]. Compact SSR will also support quality indicators to enable the calculation of the protection levels.

Experts were asked about their understanding of the RTCM SSR standardisation process, as well as why it had not yet been finalised. The responses were common across all professions, with the common cause for a lack of progress in the RTCM SSR standardisation process arising from too many private entities with vested interests, making conflicting requests with little compromise. These companies have already deployed assets which operate on their proprietary version of SSR and want to maintain the functionality of these products. Disagreements during data format standardisation processes are nothing new, and many experts stated that the same issue arose during the standardisation of OSR. However, as these delays continue to mount, some industry members are beginning to look to alternatives. One expert suggests that it might be beneficial to introduce an independent entity to the process, who could mediate and direct the proceedings.

Automotive manufacturers are pushing standardisation as a key requirement for the incorporation of high accuracy positioning data; however, the lack of standardisation does not appear to be acting as a barrier to entry.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Key conclusions

- The baseline distance limitations of RTK prevent it from being a suitable technology for mass-market applications. PPP is very promising however due to the long convergence times; it is expected that mass-market users would not be willing to wait for such extended periods before receiving a high-accuracy position fix. **PPP-RTK alleviates both issues and in theory is a promising technology for mass-market applications**
- **PPP-RTK remains in the development and early-deployment stages**. Whilst multiple innovative PPP-RTK concepts have been identified, these are determined to be mathematically similar and their performance is expected to be equivalent. It is unclear if a comparison of these concepts in real-world applications would identify differences in performance and no literature undertaking this work has been found.
- **PPP-RTK combines the benefits of both PPP and RTK without the drawbacks of either technology**. Whilst this technology is experiencing slow adoption, it is expected that once its benefits and reliability have been proven to industry users this will rapidly increase. The pricing plan and performance of the service is likely to have a significant impact on how readily users swap from their current technologies which are well proven and familiar.
- **PPP-RTK is not expected to fully replace PPP or RTK services in the near future** as users will be reluctant to leave their current service which they are familiar with unless it is not directly meeting their needs. In addition, PPP-RTK is expected to be a higher cost subscription which would delay user uptake. As the service cannot provide position integrity, SOL applications are likely to also rely on a second service as proposed by TERIAmove.
- **PPP-RTK is not expected to significantly impact the deployment of Galileo HAS as these services will address different markets**. If the user's application is located in an area covered by CORS, then they will either be implementing an RTK-type solution or PPP-RTK. Applications exclusively outside of these areas will either use Galileo HAS or commercial PPP, the selection will be driven by service performance and cost (where Galileo HAS will have a distinct advantage).
- **Galileo HAS is expected to disrupt the industry by directly competing with commercial PPP solutions**. As Galileo HAS is intended as a free service it is expected to naturally replace many of the commercial PPP solutions if performance is comparable. The inclusion of CORS data within Galileo HAS would greatly improve its performance and further increase the disruption to the market.
- It is believed that **mass-market antennas will improve sufficiently to enable the use of high-accuracy positioning in the near future**. This would be beneficial for a wide variety of

applications such as autonomous navigation (automotive, robotic, drone, rail and potentially aerospace), augmented reality and sports tracking.

- The **European high-accuracy signal augmentation market is well developed and widely respected.** It is seen as innovative, with highly advanced services, technologies and a fully developed CORS network. This puts it in a good position of strength for the deployment of Galileo HAS. Whilst there are some challenges such as data rate limits of Galileo and the lack of SSR standardisation, these are not expected to act as significant barriers to the adoption of PPP-RTK or high-accuracy services in the mass-market. Other constellations are interested in cooperating with Galileo for SOL applications, which could offer fantastic opportunities for further development.
- The **standardisation of SSR data continues to challenge the industry**, with delays primarily being driven by conflicting personal interests of corporate members of the RTCM working group. Some experts have recommended that an independent advisory group be used to help progress the standardisation process.

ANNEX B: REFERENCE SOURCES AND LINKS

6.1.1 Reference Documents

The following table lists the key documents/ sources used as references for the study, and their and associated weblinks.

Reference ID	Title and date	Authors	Links
[RD.01]	GNSS User Technology Report 2018	GSA	https://www.gsa.europa.eu/system/files/reports/gnss_user_tech_report_2018.pdf
[RD.02]	Review and Principles of PPP-RTK Methods	P.J.G Teunissen Amir Khodabandeh	https://www.researchgate.net/publication/268520221_Review_and_principles_of_PPP-RTK_methods
[RD.03]	GNSS Precise Point Positioning	Suelynn Choy	http://www.unoosa.org/documents/pdf/icg/2018/ait-gnss/16_PPP.pdf
[RD.04]	Trimble RTX, an Innovative New Approach for Network RTK	Xiaoming Chen et al	https://positioningservices.trimble.com/wp-content/uploads/2019/02/Trimble_WhitePaper_Trimble-RTX-a-New-Approach-for-Network-RTK.pdf
[RD.05]	Report on Surveying User Needs and Requirements	GSA	https://www.gsc-europa.eu/system/files/galileo_documents/Surveying-Mapping-Report-on-User-Needs-and-Requirements-v1.0.pdf

[RD.06]	Global PPP with Ambiguity Resolution providing improved accuracy and instant position coverage	David Russel	https://dynamic-positioning.com/proceedings/dp2015/Sensors_Russell_2015.pdf
[RD.07]	An Introduction to GNSS	NovAtel Inc.	https://www.novatel.com/support/knowledge-and-learning/published-papers-and-documents/gnss-book
[RD.08]	Global Navigation Satellite Systems – Signal, Theory and Applications: Chapter 7 – Precise Real-Time Positioning Using Network RTK	Ahmed El-Mowafy	https://www.researchgate.net/publication/221923955_Precise_Real-Time_Positioning_Using_Network_RTK
[RD.09]	Geo++ SSR Brochure	Geo++	http://www.geopp.de/technology/state-space-representation/
[RD.10]	The Path to High GNSS Accuracy	Galileo GNSS	https://galileognss.eu/the-path-to-high-gnss-accuracy/
[RD.11]	PPP-RTK Precise Point Positioning Using State Representation in RTK Networks	Wübbena et al. (GEO++)	http://www.geopp.com/pdf/ion2005_fw.pdf
[RD.12]	Geo++ SSR + RTCM – Current Status	Gerhard Wübbena Martin Schmitz Jannes Wübbena	http://www.geopp.com/pdf/13_gpp_status_rtcm.pdf
[RD.13]	Quasi-Zenith Satellite System Interface Specification Centimetre Level Augmentation Service	Cabinet Office, Government of Japan	http://qzss.go.jp/en/technical/ps-is-qzss/ps-is-qzss.html
[RD.14]	Investing in GPS Guidance Systems?	Gordon Groover Robert Grisso Department of Agriculture and Applied Economics	https://www.pubs.ext.vt.edu/content/dam/pubs_ext_vt_edu/448/448-076/448-076_pdf.pdf
[RD.15]	PPP with Ambiguity Resolution (AR) using RTCM-SSR	Gerhard Wübbena Martin Schmitz Andreas Bagge	http://www.igs.org/assets/pdf/Workshop%202014%20-%20PY03%20-%20Schmitz%20-%20222%20-%20PPP%20with%20Ambiguity%20Resolution%20(AR)%20using%20RTCM-SSR.pdf

[RD.16]	A Comparison of Three PPP Integer Ambiguity Resolution Methods	Junho Shi, Yang Gao	https://www.researchgate.net/publication/265604636_A_comparison_of_three_PPP_integer_ambiguity_resolution_methods
[RD.17]	Using GNSS Raw Measurements on Android Devices	Gaetano Galluzzo et al.	http://ipin2018.ifsttar.fr/fileadmin/contributeurs/IPIN2018/Tutorials/Using_GNSS_Raw_Measurements_on_Android_Devices_-_IPIN_2018_Tutorial_FV.pdf
[RD.18]	Comparison of Common Representation Techniques	Geo++	http://www.geopp.de/wp-content/uploads/SSR_Flyer_v3_S2.jpg
[RD.19]	SSR assist for smartphones with PPP-RTK processing	Koki Asari Masayuki Saito Hisao Amitani	https://www.ion.org/publications/abstract.cfm?articleID=15147
[RD.20]	Precise RTK Positioning with GNSS, INS, Barometer and Vision	Patrick Henkel Alexander Blum Christoph Gunther	https://www.ion.org/publications/abstract.cfm?articleID=15246
[RD.21]	Global autonomous mobile robots market	QYResearch	https://www.globenewswire.com/news-release/2019/01/30/1707566/0/en/Global-Autonomous-Mobile-Robots-Market-to-reach-US-600-Mn-by-the-end-of-2025-QY-Research-Inc.html
[RD.22]	Safety robotic lawnmower with precise and low-cost L1-only RTK GPS positioning	Jean-Marie Codol Michele Poncelet Andre Monin Michel Devy	http://pnavhe11.irccyn.ec-nantes.fr/material/session3/Codol_paper.pdf
[RD.23]	Applications of GPS Technologies to Field Sports	Robert Aughey	https://www.researchgate.net/publication/51632087_Applications_of_GPS_Technologies_to_Field_Sports
[RD.24]	Wearable Fitness Tracker Market	P&S Intelligence	https://www.psmarketresearch.com/press-release/wearable-fitness-trackers-market
[RD.25]	Using Global Localisation to improve navigation	Google AI	https://ai.googleblog.com/2019/02/using-global-localization-to-improve.html
[RD.26]	Mining and Construction	Septentrio	https://www.septentrio.com/en/industries/mining-construction
[RD.27]	Real-Time GPS PPP-RTK Experiments for Mining Applications using Quasi-Zenith Satellite System Augmentation Signal	Luis Elneser Suelynn Choy Ken Harima James Millner	https://www.ion.org/publications/abstract.cfm?articleID=15267
[RD.28]	Precision Agriculture Market Analysis	Hexa Reports	http://www.hexareports.com/report/precision-agriculture-market

[RD.29]	Precise GNSS Positioning for Mass-market Applications	Yang Gao	https://www.fig.net/resources/proceedings/fig_proceedings/fig2018/papers/ts04e/TS04E_gao_9374_abs.pdf
[RD.30]	Towards PPP-RTK: Ambiguity resolution in real-time precise point positioning	J. Geng F. Teferle X. Meng A. Dodson	https://www.academia.edu/8815239/Towards_PPP-RTK_Ambiguity_resolution_in_real-time_precise_point_positioning
[RD.31]	Centimetre Level Augmentation Service Overview	Cabinet Office Japan	http://qzss.go.jp/en/overview/services/sv06_clas.html
[RD.32]	Enabling RTK-like positioning offshore using the global VERIPOS GNSS network	Pieter Toor	https://www.slideshare.net/hydrographicsocietybnl/enabling-rtklike-positioning-offshore-using-the-global-veripos-gnss-network
[RD.33]	Reference Station Network Information Distribution	Hans-Juergen Euler	http://www.wasoft.de/e/iagwg451/euler/euler.html
[RD.34]	A-PPP: Array-Aided Precise Point Positioning with Global Navigation Satellite Systems	P. Teunissen	https://ieeexplore.ieee.org/abstract/document/6164274
[RD.35]	Activities for Utilisation of CLAS from QZSS and Proposal for Cooperative Work for SOL Applications	Hiroshi Koyama	https://japan.gnss.asia/sites/default/files/up_img/5.MELCO_.pdf
[RD.36]	A Novel Un-differenced PPP-RTK Concept	Baocheng Zhang Peter Teunissen Dennis Odijk	https://www.researchgate.net/publication/259414264_A_novel_un-differenced_PPP-RTK_concept
[RD.37]	PPP-RTK: Results of CORS network-based PPP with integer ambiguity resolution	Baocheng Zhang Peter Teunissen Dennis Odijk	https://www.researchgate.net/publication/279645458_PPP-RTK_Results_of_CORS_network-based_PPP_with_integer_ambiguity_resolution
[RD.38]	Integer Ambiguity Resolution on Undifferenced GPS Phase Measurements and its Application to PPP and Satellite Precise Orbit Determination	D. Laurichesse F. Mercier J. Berthias P. Broca L. Cerri	http://www.ppp-wizard.net/Articles/laurichesse_navigation.pdf

[RD.39]	Resolution of GPS Carrier-Phase Ambiguities in Precise Point Positioning with Daily Observations	M. Ge G. Gendt M. Rothacher C. Shi J. Liu	http://www.ppp-wizard.net/Articles/JG2008.pdf
[RD.40]	Top 3 Positioning Challenges in Autonomous Marine Navigation	Septentrio	https://www.septentrio.com/en/insights/top-3-positioning-challenges-autonomous-marine-navigation
[RD.41]	Rethinking Maps for Self-Driving	Lyft Level 5	https://medium.com/@LyftLevel5/https-medium-com-lyftlevel5-rethinking-maps-for-self-driving-a147c24758d6
[RD.42]	Opening of PPP Services	Geoflex	http://www.geoflex.fr/opening-of-ppp-services/index.html
[RD.43]	FLAMINGO Unveils High-Accuracy Solution for Smartphones	GSA	https://www.gsa.europa.eu/newsroom/news/flamingo-unveils-high-accuracy-solution-smartphones
[RD.44]	2019 Trimble RTX Satellite Broadcast Frequency Coverage Map	Trimble	https://positioningservices.trimble.com/resources/coverage-maps/
[RD.45]	PPP-RTK & Open Standards Symposium	GIM International	https://www.gim-international.com/content/article/ppp-rtk-open-standards-symposium
[RD.46]	Compact SSR Messages with Integrity Information for Satellite Based PPP-RTK Service	Rui Hirokawa Yuki Sato Seigo Fujita Masakuzu Miya	https://www.researchgate.net/publication/321155436_Compact_SSR_Messages_with_Integrity_Information_for_Satellite_Based_PPP-RTK_Service
[RD.47]	Galileo High Accuracy Service and its importance for mobility applications	EC	https://www.kongress.intergeo.de/download/public/share/public/Intergeo/2018/Kongress/Geodaetische-Woche/Hernandez_Ignacio_Intergeo2018.pdf
[RD.48]	Galileo: user-tailored positioning and timing services made in Europe	GSA	N/A
[RD.49]	FLAMINGO: Encapsulation of High Accuracy Positioning Service for Smartphones and IoT	NSL	N/A

[RD.50]	Smartphone (PPP-RTK) – first results and challenges	Geo++	N/A
[RD.51]	Bridging between RTK and PPP-RTK to Develop New Survey Period	Satellite positioning research and application center	http://www.mod.gov.bn/survey/SitePages/Bridging%20between%20RTK%20and%20PPP-RTK%20to%20Develop%20New%20Survey%20Period%20-%20Mr%20Mikami%20Izumi.pdf
[RD.52]	Comparative analysis of positioning accuracy of GNSS receivers of Samsung Galaxy smartphones in marine dynamic measurements	C. Specht, P.S. Dabrowski, J. Pawelski, M. Specht, T. Szot	https://www.sciencedirect.com/science/article/pii/S0273117718304150
[RD.53]	GNSS Positioning using Android Smartphone	Paolo Dabove, Vincenzo Di Pietra, Shady Hatem and Marco Piras	http://www.insticc.org/Primoris/Resources/PaperPdf.ashx?idPaper=77648
[RD.54]	Handbook of Global Navigation Satellite Systems - Annex A: Data Formats	Oliver Montenbruck, Ken MacLeod	https://link.springer.com/content/pdf/bbm%3A978-3-319-42928-1%2F1.pdf
[RD.55]	RTCM State Space Representation Messages, Status and Plans	Geo++	http://www.geopp.com/pdf/gpp_ppprtk12_msg_f.pdf
[RD.56]	IGS White Paper on Satellite and Operations Information for Generation of Precise GNSS Orbit and Clock Products	IGS Multi-GNSS Working Group	https://kb.igs.org/hc/en-us/article_attachments/115001174952/Whitepaper_SatelliteMetaData_IGS_170725.pdf

[RD.57]	Multi-GNSS PPP-RT: From Large- to Small-Scale Networks	Nandakumaran Nadarajah, Amir Khodabandeh, Kan Wang, Mazher Choudhury and Peter J. G. Teunissen	https://www.ncbi.nlm.nih.gov/pubmed/29614040
[RD.58]	Single-frequency PPP-RTK: Theory and experimental results	Dennis Odijk, P. Teunissen, Amir Khodabandeh	https://www.researchgate.net/publication/264708004_Single-frequency_PPP-RTK_Theory_and_experimental_results
[RD.59]	Recent Activity of International Standardization for High-Accuracy GNSS Correction Service	Mitsubishi Electric Corporation	http://www.unoosa.org/documents/pdf/psa/activities/2019/UN_Fiji_2019/STS-39.pdf
[RD.60]	FUGRO Marinestar G4+ PPP-RTK Developments	Hydro International	https://www.hydro-international.com/content/article/gnss-improvements-for-offshore-applications
[RD.61]	Real-Time PPP using open CORS Networks and RTCM Standards	Andrea Stuerze, Wolfgang Sohne, Georg Weber	https://www.researchgate.net/publication/312056229_Real-Time_PPP_using_open_CORS_Networks_and_RTCM_Standards
[RD.62]	RTCM Background and SC-134 Evolution	RTCM	http://rtcm.info/sc134/086-2018-SC134-005.pdf
[RD.63]	Location based services: ongoing evolution and research agenda	Haosheng Huang Georg Gartners Jukka Krisp Martin Raubal Nico Van de Weghe	https://www.tandfonline.com/doi/full/10.1080/17489725.2018.1508763

[RD.64]	Report on location-based services user needs and requirements	GSA	https://www.gsc-europa.eu/sites/default/files/sites/all/files/Report_on_User_Needs_and_Requirements_LBS.pdf
[RD.65]	CORSnet – NSW: Towards statewide CORS infrastructure for New South Wales, Australia	Volker Janssen Thomas Yan	https://eprints.utas.edu.au/9776/
[RD.66]	ETSI TS 136 355 V15.0.0 LTE: Evolved universal terrestrial access; LTE Positioning Protocol	3GPP	https://www.etsi.org/deliver/etsi_ts/136300_136399/136355/15.00.00_60/ts_136355v150000p.pdf
[RD.67]	EGNOS and Galileo for Aviation	GSA	https://www.gsa.europa.eu/system/files/documents/aviation_gnss.pdf
[RD.68]	E-GNSS Applications in Rail	GSA	https://www.sizi.cz/file.php?nid=14068&oid=4665642