4th edition
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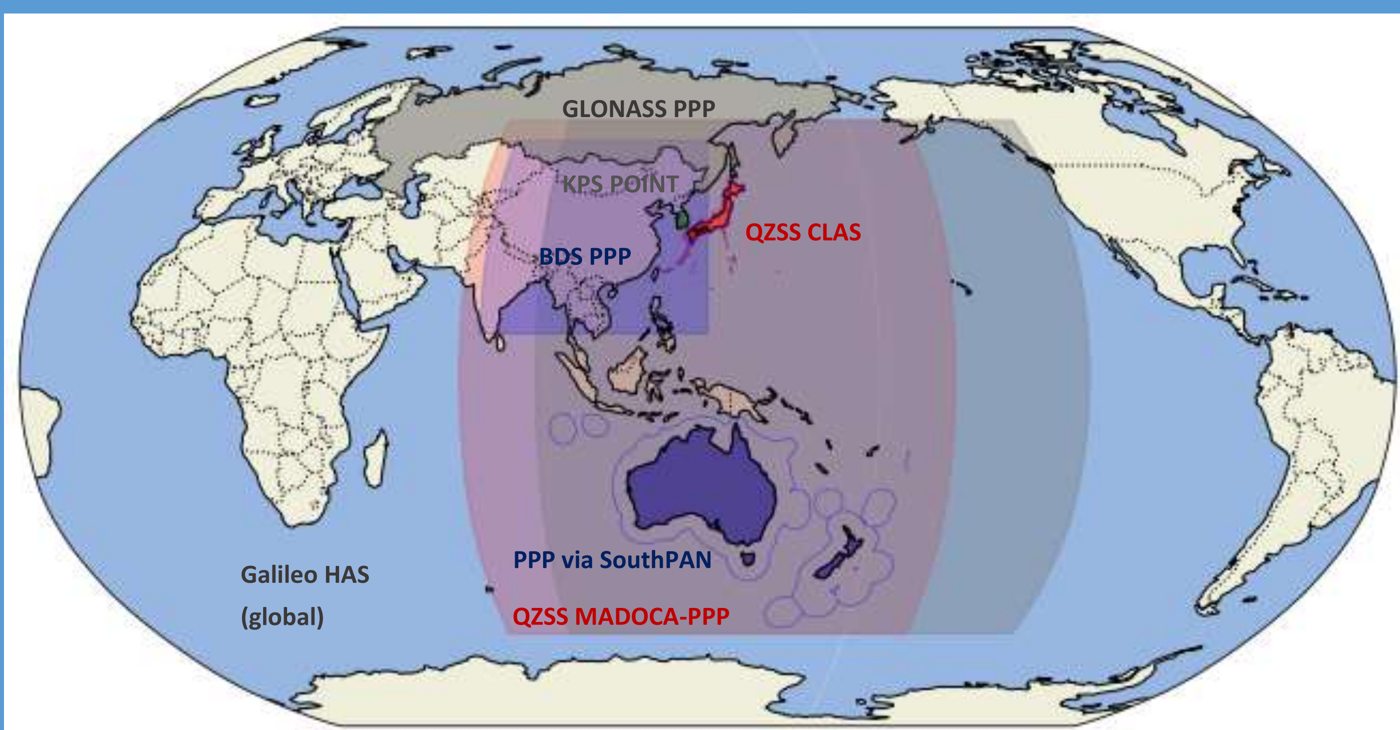
PPP/PPP-RTK Service Providers Report



ICG – WG-S - PPP Interoperability Task Force

INTRODUCTION

The International Committee on GNSS (ICG) has established a Task Force within the WG-S Interoperability and Service Standards Subgroup focused on improving the interoperability of Precise Point Positioning (PPP) services. The first duty of this task force, also known as PPP Interoperability Task Force, has been to collect information from all institutional service providers providing or intending to provide PPP/PPP-RTK services: Japan, China, Europe, Australia/New Zealand, Russia and Korea.

This report presents the main characteristics of the PPP/PPP-RTK services under operational provision, under initial capability or planned. The information is based on a form filled in by the providers and is presented in this report. Note that commercial services are not included in this list. Coordination with commercial service providers is left for future versions of this Report.

The report is organized as follows: Firstly, it introduces the main used in later sections. Secondly, it presents the main characteristics of PPP/PPP-RTK providers, which are detailed in full extent in Table 3, provided as an annex. Then, it presents the standard formulation of PPP equations and the application of SSR corrections as defined by the current PPP providers. Finally, further work and the participants list are presented.

MAIN CONCEPTS

This section defines the main concepts and terms used in the report to describe PPP/PPP-RTK services. High accuracy positioning technology can be categorized into observation space representation (OSR) and state space representation (SSR) methods. OSR methods provide corrections for carrier phase and/or pseudorange measurements, or *observations*, between a given satellite and station. SSR methods provide corrections to the individual error contributions at the user receiver, or error *states,* such as signal-in-space terms (satellite orbit, clock and signal biases) and atmospheric corrections (ionosphere and troposphere).

Conventional RTK (Real-Time Kinematic) is an OSR-based method that requires carrier phase and pseudorange corrections (or measurements) from local reference stations. It provides almost-instantaneous convergence and cm-level positioning accuracy; however, it has the major drawback on the scalability, as RTK users need stations nearby.

Within the realm of PPP, for the sake of this report, some distinctions are made. PPP is defined as an SSR-based method that requires only corrections for the signal-in-space errors (orbit, clock, code biases) [1]. Conventional PPP has the great advantage of scalability; however, it has the great challenge of a slower convergence time than that of RTK, typically devoted to estimate the state of the individual error contributions, which is not necessary for RTK.

A core feature of PPP is the estimation of the carrier phase measurement ambiguities. In order to solve the ambiguities as an integer number, the PPP algorithm needs the satellite carrier phase biases, in addition to the abovementioned PPP corrections (orbit, clock, code biases). Ambiguity resolution techniques allow a higher accuracy and a faster convergence. Allowing PPP with phase biases will be called PPP-AR (Ambiguity Resolution). Within this report we also define *Fast-PPP* as a service providing PPP with local or regional ionospheric corrections, also for a faster convergence.

If the service provides both accurate ionospheric and tropospheric corrections, allowing the full correction of the atmospheric errors, this is defined as PPP-RTK, which provides almost-instantaneous convergence and cm-level accuracy, but consumes more bandwidth than PPP.

This report describes services ranging from PPP to PPP-RTK. Figure 1 provides a summary of these services. It also shows the decrease in scalability from RTK to PPP and the improvement in convergence time (the figure omits PPP-AR as phase biases are usually provided together with Fast-PPP or PPP-RTK).

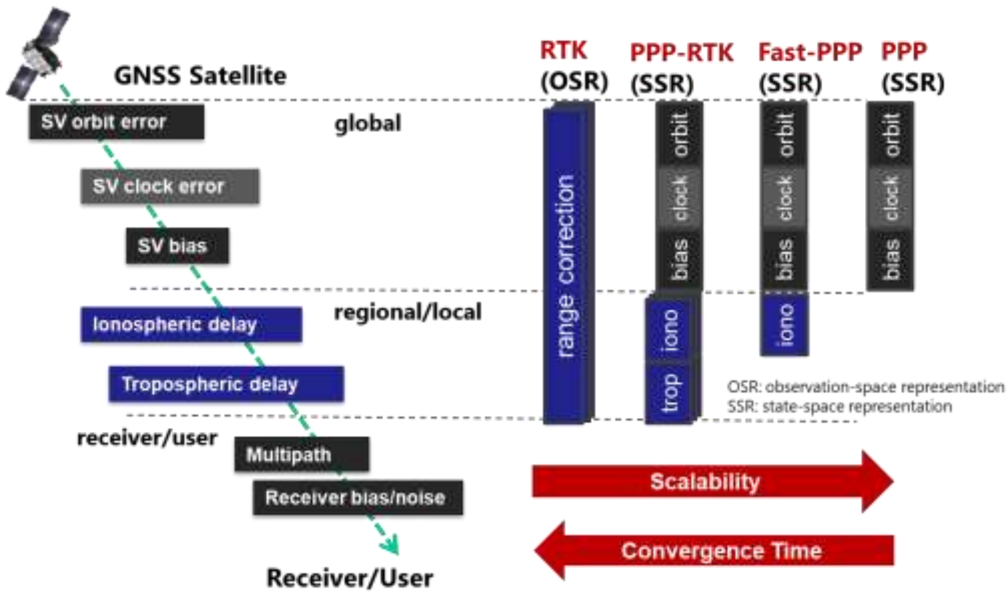


Figure 1 – RTK to PPP services and corrected errors

We now describe the two main performance metrics, and their interrelations: positioning accuracy and convergence time. Positioning accuracy is expressed as the horizontal and vertical accuracy [m], both at the 95%. It relates to convergence time as convergence time is defined as the time required to permanently[1] reach the specified positioning accuracy, including the time to receive the correction data. These two magnitudes are depicted in Figure 2.

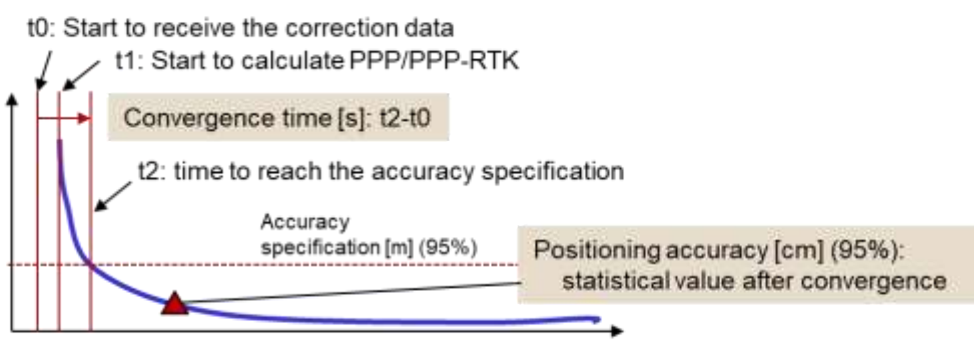


Figure 2 – Convergence time and positioning accuracy

[1] The term *permanently* is added to clarify that if the positioning error reaches the accuracy specification but then it raises above it during the convergence process, the receiver positioning error should not be considered as converged.

PPP/PPP-RTK SERVICE CHARACTERISTICS

This section presents the characteristics of the PPP/PPP-RTK services offered by the different providers. These characteristics are exhaustively listed in Table 3. The table uses the OSI (Open Systems Interconnection) model framework to group the many different features [2]. The model is followed from top to bottom: application, presentation, session, transport, network, data, and physical layers. For each layer, typical GNSS service and signal features are grouped. For simplicity, some layers are provided jointly (e.g., Network/Data and Physical), as they concern GNSS properties that are interrelated. The following subsections provide a summary of the main properties of the PPP/PPP-RTK services reported for each of the layers. Further definitions are provided as footnotes in Table 3.

Service Operator, Coverage and Performance (Application Layer)

The current institutional service providers of PPP/PPP-RTK are Japan (QZSS), China (BDS), EU (Galileo), Australia/New Zealand (SouthPAN), Russia (GLONASS) and Korea (KPS). At the time of writing this report, only Japan, China and EU provide an operational service: QZSS CLAS [3], BDS PPP [4], and Galileo HAS [5], respectively. Australia/New Zealand is also offering an early open service of PPP via SouthPAN on L5 [6]. Russia is offering a ground-based experimental service and developing their satellite-based service [7, 8]. Finally, Korea is developing an open service of PPP-RTK via KPS [9]. All providers offer PPP, and only some offer also PPP-RTK or intend to do it: QZSS with CLAS (already operational), Russia (TBC), and Korea (in development). Galileo will also provide regional ionospheric corrections in Europe (*Fast-PPP* according to the previous definitions). Concerning the U.S., some initiatives have been proposed for a ground-based PPP service but still without any plans of operational provision [10].

Figure 3 shows the service area of the PPP/PPP-RTK services. Regarding coverage, most services are provided regionally: QZSS CLAS for Japan and MADOCA-PPP for the Asia-Oceania region [11], PPP via SouthPAN in Exclusive Economic Zone (EEZ) of Australia/New Zealand and BDS in China and its surroundings. Only Galileo HAS is provided globally, although with a temporary limitation excluding the Asia-Pacific region from the official service area during the initial service phase (Phase 1) [12]. There are plans for a global service also from GLONASS PPP.

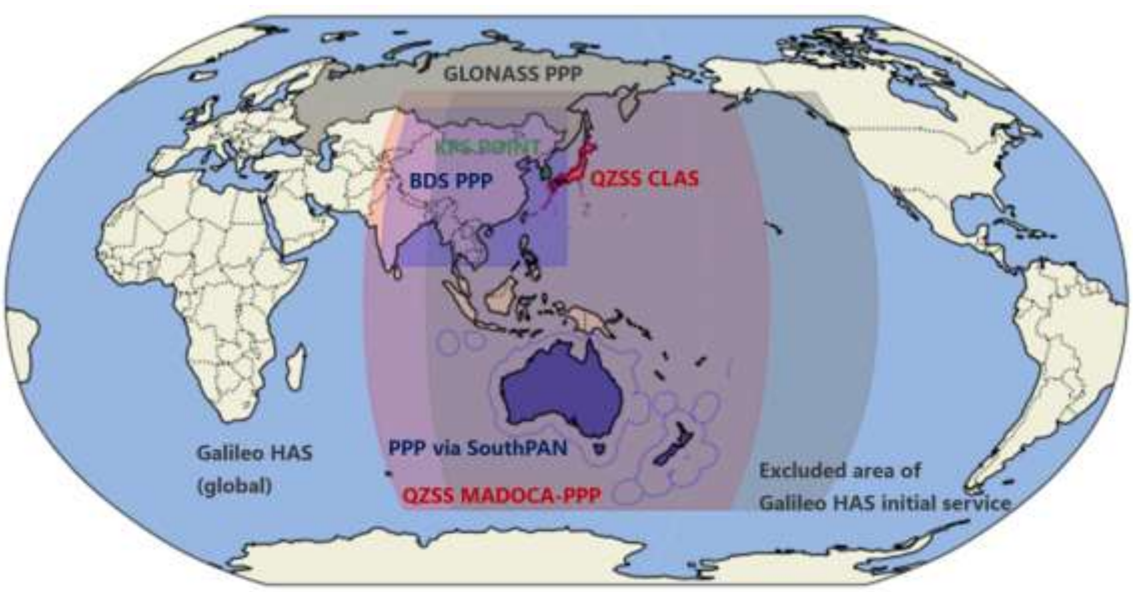


Figure 3 Service area of the PPP/PPP-RTK services

Service accuracies (95%) range, in the horizontal domain, from 6 cm (QZSS CLAS, static) to 30 cm (QZSS MADOCA-PPP, BDS PPP, GLONASS PPP), and in the vertical domain, from 12 cm (QZSS CLAS, static) to 60 cm (BDS PPP). Convergence times are more variate, as they depend also on user algorithm and environment assumptions: QZSS CLAS provides PPP-RTK service including atmospheric correction, it proves the fast conversion of 60 sec including time to receive correction time (30 sec). The convergence time of PPP service varies from 300 sec planned for Galileo HAS to 40 minutes planned for PPP via SouthPAN. Some PPP service providers such as Galileo plan to add ionospheric corrections in some specific region to improve the convergence time, thanks to which Galileo HAS expects to improve convergence time down to 100 sec over Europe. The convergence and accuracy of the different services is depicted in Figure 4.

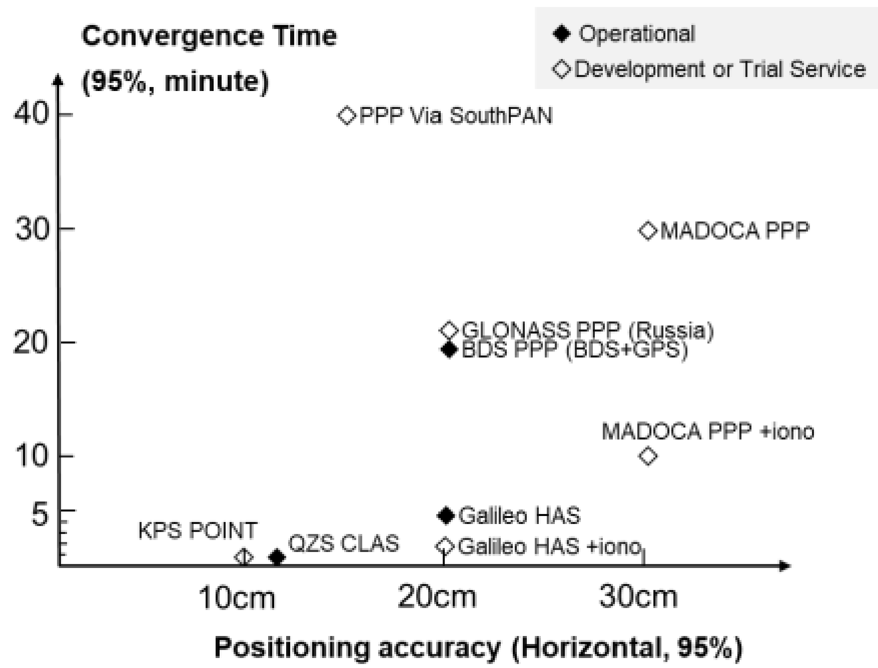


Figure 4 – Horizontal accuracy and convergence time of the PPP/PPP-RTK services

Corrections Format, Content, Additional Information and Bandwidth (Presentation Layer)

Most services use Compact SSR (CSSR), as QZSS does, or adaptations of it, as Galileo and BDS do. Regarding the GNSS corrected, all services correct between two and four constellations: GPS and the PPP/PPP-RTK system provider, and in some cases another two GNSS.

For the supported GNSS for correction, most services support GPS, and their own navigation system, QZSS for QZSS CLAS and QZSS MADOCA-PPP, Galileo for Galileo HAS, BDS for BDS PPP, GLONASS for GLONASS PPP, KPS for KPS POINT. QZSS CLAS also support Galileo, QZSS MADOCA-PPP also support Galileo and GLONASS, and PVS (PPP via SouthPAN) supports GPS and Galileo. For supported navigation message, LNAV is supported for all GPS and QZSS correction providers, I/NAV is supported for Galileo except for PVS [6]. CNAV1 is supported for BDS by BDS PPP [4].

Regarding satellite corrections, all corrections are provided for satellite broadcast orbits and clocks. Code biases are provided for between multiple signals, where GPS L1C/A is one of them in all cases. Other corrected signals include L5/E5a, E5b/B2, L2C/L2OF and E6. Phase biases are provided by QZSS and will be provided by Galileo and GLONASS.

Note that biases are closed related to satellite antenna phase centers. Usually PPP/PPP-RTK service providers will align their satellite clock products with the satellite center of mass (Ref. CoM) or the satellite antenna phase centers (Ref. APC). Which reference point, CoM or APC, to be used will lead to different code/phase bias corrections, and they are totally incompatible. Therefore, the observations used for code/phase bias estimation are corrected by the APC corrections, in order to reconcile the signal bias to a uniform and frequency-independent reference point for both the server side and the user side. This has been a common practice in bias estimation processes using geometry-related observations (e.g., for ionosphere-free phase bias) for long time, but it was not clear until recently for bias estimation processes using geometry-free observations (e.g., for MW phase bias and differential code bias) [13]. The APC issue should be considered when accounting for the interoperability of PPP bias products.

Regarding atmospheric corrections, ionosphere corrections are already provided by QZSS through STEC (Slant Total Electron Content) and will be provided by Galileo through VTEC (Vertical Total Electron Content) as part of the so-called Service Level 2 in Europe. Other PPP providers have not shared yet any plans to provide ionospheric corrections. QZSS CLAS is the only system providing tropospheric corrections over the Japan area, as part of CLAS. KPS will provide the atmospheric correction for PPP-RTK.

Additional data also provided by some operators includes a confidence level on the corrections, such as URA (User Range Accuracy) or equivalent, integrity, and authentication. URA is provided by QZSS and BDS and confidence values for corrections will be also provided by Galileo (HAS Phase 2). Authentication is not yet provided but foreseen by QZSS, Galileo and GLONASS.

The PPP/PPP-RTK messages are transmitted at a rate between 2,800 bps (GLONASS PPP) to 448 bps (Galileo HAS) per satellite. Both have been proven sufficient to provide corrections with a high-enough update rate for their intended service.

Time and Correction Synchronization, Message Error Correction, Signal Properties (Session, Transport, Network, Data-Link Layers)

PPP/PPP-RTK Messages are synchronized with their own system time reference through a preamble or synchronization pattern transmitted regularly, as is the case for most GNSS signals. The satellite corrections are linked to the corrected broadcast messages through the broadcast IODs and satellite ID. Error detection and/or correction codes are added in all messages, including a checksum by CRC, encoding by LDPC, Reed-Solomon or convolutional codes.

Figure 5 shows the frequency of PPP/PPP-RTK signals. The signal carrier frequencies used for the PPP/PPP-RTK signals coincide with those used for GNSS: 1278.75 MHz (Galileo E6, QZSS L6, KPS L6), 1207.14 (BDS B2b, SouthPAN E5b), or 1202.025 MHz (GLONASS L3). Signal power ranges across the typical GNSS power levels, from -160dBW to -153dBW on earth. All signals are RHCP.

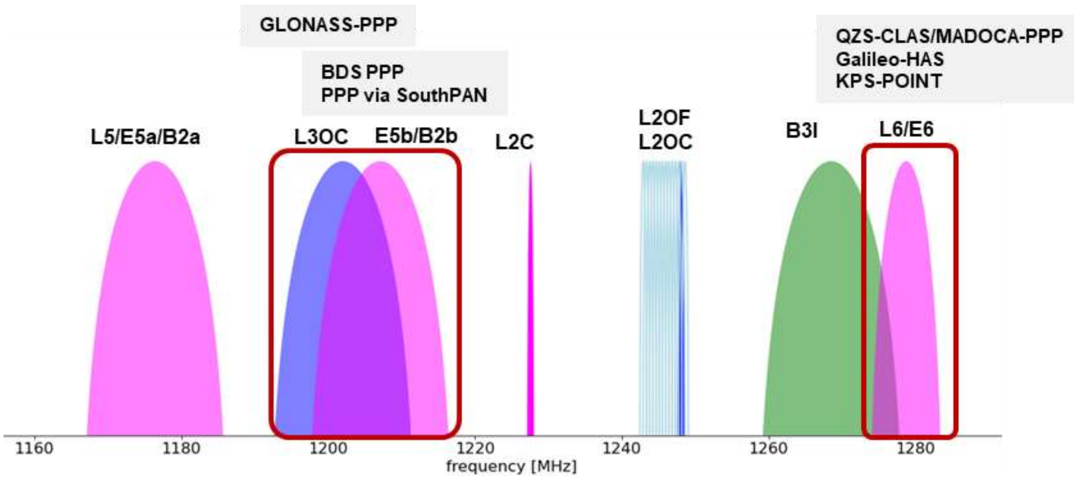


Figure 5 – Power spectrums vs frequency of the main PPP/PPP-RTK signals

Concerning signal modulation, all signals are DS-SS (Direct Sequence-Spread Spectrum) using BPSK code modulations: BPSK(5) for L6/E6 (QZSS, Galileo) and L3 (GLONASS); and BPSK(10) for E5b-B2b (BDS, SouthPAN). They use shift register (Gold, Kasami) or memory codes, at least in those publicly defined. The correction message is multiplexed with the code in a binary phase-modulated way for all cases but QZSS, which uses Code Shift Keying (CSK) to transform 250 sps into the 2000 bps abovementioned.

Space and Ground Transmitters (Physical layer)

PPP/PPP-RTK is provided from navigation satellite payloads (MEO/GEO/IGSO), and from ground also in the case of Galileo, SouthPAN and GLONASS. Regarding the satellite constellations, most use geosynchronous orbits such as GEO or IGSO for QZSS. However, Galileo uses a subset of 20 of its MEO satellites connected to ground at a certain time. Galileo, GLONASS and SouthPAN have also confirmed a ground channel for distributing the corrections, through a free user registration process in the case of Galileo [14]. GPS, while not officially sharing plans of providing a PPP service, has started discussions on a potential ground-based PPP service, e.g. based on DGPS stations [15].

FORMULATION OF OBSERVATION EQUATIONS

In this section, a standard formulation of measurement equations for PPP is presented for both the uncombined method and the ionosphere-free combination. A standard formulation of observation equations for pseudorange $p^s_{r,i}$ and carrier-phase $\Phi^s_{r,i}$ for frequency *i* based on [16] is introduced in this section. In this notation, subscript *r* and superscript *s* denote receiver and satellite respectively. The measurements equation for pseudorange and carrier-phase are defined as follows:

$$\boldsymbol{p^s_{r,i} = \rho^s_r + \mu_i I^s_{r,1} + m^s_r T_r + c\left(dt_r - dt^s + d_{r,i} + d^s_i\right) + e^s_{r,i}} \tag{1}$$

$$\boldsymbol{\phi^s_{r,i} = \rho^s_r - \mu_i I^s_{r,1} + m^s_r T_r + c\left(dt_r - dt^s + \delta_{r,i} + \delta^s_i\right) + \lambda_i N^s_{r,i} + \epsilon^s_{r,i}} \tag{2}$$

The observations depend on the geometric range $\rho^s_r = \|\boldsymbol{r}^s - \boldsymbol{r}_r\|$ between satellite position $\boldsymbol{r}^s$ and receiver position $\boldsymbol{r}_r$, the speed of light *c*, the tropospheric mapping function m^s_r , the zenith tropospheric delay T_r, the slant ionospheric delay $I^s_{r,i}$, the code biases $d_{r,i}$ and d^s_i, the clock offsets dt_r and dt^s, the phase biases $\delta_{r,i}$ and δ^s_i, the integer ambiguity $N^s_{r,i}$, the wavelength λ_i, and the residual error including noise and multipath for pseudorange $e^s_{r,i}$ and carrier phase $\epsilon^s_{r,i}$. Note that $\mu_i = \frac{f_1^2}{f_i^2} = \frac{\lambda_i^2}{\lambda_1^2}$ is the ionosphere scaling factor by which $I^s_{r,i}$ is expressed as a function of $I^s_{r,1}$. Note also that some parameters such as the phase-center offset and variation, the carrier-phase wind-up and the earth tide correction have been omitted to achieve a compact notation.

Observation equations and states for PPP using the uncombined method

The inter-satellite single difference between a satellite *s* and a reference (pivot) satellite *p* is applied for the observations, where $x^{ps}_r = x^s_r - x^p_r$ is used:

$$\boldsymbol{p^{ps}_{r,i} = \rho^{ps}_r + \mu_i I^{ps}_{r,1} + m^{ps}_r T_r + c\left(d^{ps}_i - dt^{ps}\right) + e^{ps}_{r,i}} \tag{3}$$

$$\boldsymbol{\phi^{ps}_{r,i} = \rho^{ps}_r - \mu_i I^{ps}_{r,1} + m^{ps}_r T_r + c\left(\delta^{ps}_i - dt^{ps}\right) + \lambda_i N^{ps}_{r,i} + \epsilon^{ps}_{r,i}} \tag{4}$$

In a PPP service, the error of the satellite orbit and clock and the satellite code and phase biases in the observations are corrected. This leads to the following state vector $\boldsymbol{x}$ including the receiver position $\boldsymbol{r}_r = [x_r\ y_r\ z_r]$ and the zenith tropospheric delay T_r, the single-difference slant ionospheric delay $I^{ps}_{r,i}$ and the single difference integer ambiguity $N^{ps}_{r,i}$ to be estimated on the receiver for *n* tracked satellites and *m* signals:

$$\boldsymbol{x_{PPP} = \left[x_r \quad y_r \quad z_r \quad T_r \quad I^{p0}_{r,1} \cdots I^{p(n-1)}_{r,1} \quad N^{p0}_{r,0} \cdots N^{p(n-1)}_{r,0} \cdots N^{p0}_{r,m} \cdots N^{p(n-1)}_{r,m}\right]} \tag{5}$$

Observation equations and states for PPP using the ionosphere-free combination method

By applying the ionosphere-free combination in Eq. (1) and (2), the ionosphere-free combination of measurement equations is defined as follows:

$$\boldsymbol{p^s_{r,IF} = \rho^s_r + m^s_r T_r + c\left(dt_r - dt^s + d_{r,IF} + d^s_{IF}\right) + e^s_{r,IF}} \tag{6}$$

$$\boldsymbol{\phi^s_{r,IF} = \rho^s_r + m^s_r T_r + c\left(dt_r - dt^s + \delta_{r,IF} + \delta^s_{IF}\right) + \lambda_{IF} N^s_{r,IF} + \epsilon^s_{r,IF}} \tag{7}$$

Where, the ionosphere-free combination of pseudorange and carrier-phase and the combined wavelength for frequency f_1 and f_2 are defined as follows:

$$\boldsymbol{p}_{r,IF}^{s} = \frac{f_1^2 p_{r,1}^s - f_2^2 p_{r,2}^s}{f_1^2 - f_2^2}, \phi_{r,IF}^s = \frac{f_1^2 \phi_{r,1}^s - f_2^2 \phi_{r,2}^s}{f_1^2 - f_2^2}, \lambda_{IF} = \frac{f_1^2 \lambda_1 - f_2^2 \lambda_2}{f_1^2 - f_2^2} \tag{8}$$

In the same manner as with the uncombined method, the inter-satellite single difference between a satellite s and a reference (pivot) satellite p is applied for the observations:

$$p_{r,IF}^{ps} = \rho_r^{ps} + m_r^{ps} T_r + c\left(d_{IF}^{ps} - dt^{ps}\right) + e_{r,IF}^{ps} \tag{9}$$

$$\phi_{r,IF}^{ps} = \rho_r^{ps} + m_r^{ps} T_r + c\left(\delta_{IF}^{ps} - dt^{ps}\right) + \lambda_{IF} N_{r,IF}^{ps} + \epsilon_{r,IF}^{ps} \tag{10}$$

The states of ionosphere-free combination to be estimated for PPP are defined as follows:

$$x_{PPP} = \begin{bmatrix} x_r & y_r & z_r & T_r & N_{r,IF}^{p0} \cdots N_{r,IF}^{p(n-1)} \end{bmatrix} \tag{11}$$

Observation equations and states for PPP-RTK

For PPP-RTK service, the slant ionospheric delay and the zenith tropospheric delay are also corrected in Eq. (5), the following state vector should be estimated on the receiver.

$$x_{PPP-RTK} = \begin{bmatrix} x_r & y_r & z_r & N_{r,0}^{p0} \cdots N_{r,0}^{p(n-1)} \cdots N_{r,m}^{p0} \cdots N_{r,m}^{p(n-1)} \end{bmatrix} \tag{12}$$

APPLICATION OF SSR CORRECTIONS

The SSR corrections provided by PPP/PPP-RTK services are used for the correction in the rover receiver. Most service providers use the convention defined in the RTCM 3 standard [17] with some exceptions, which are noted.

The orbit correction is provided in Satellite Coordinate System (SCS) NTW (radial, along-track, cross-track) reference frame defined at reference time t_0 as follows.

$$\boldsymbol{\delta r^{NTW}} = \begin{bmatrix} \boldsymbol{\delta O_{radial}} \\ \boldsymbol{\delta O_{along}} \\ \boldsymbol{\delta O_{cross}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{\delta \dot{O}_{radial}} \\ \boldsymbol{\delta \dot{O}_{along}} \\ \boldsymbol{\delta \dot{O}_{cross}} \end{bmatrix} (\boldsymbol{t} - \boldsymbol{t_0}) \tag{13}$$

The orbit correction terms, and the time derivate terms are defined in RTCM 3 standard, whereas most satellite-based correction services only providing the orbit correction terms.

$$\boldsymbol{\delta r^{NTW}} = \begin{bmatrix} \boldsymbol{\delta O_{radial}} \\ \boldsymbol{\delta O_{along}} \\ \boldsymbol{\delta O_{cross}} \end{bmatrix} \tag{14}$$

The correction in SCS NTW reference frame is converted to ECEF reference frame:

$$\boldsymbol{\delta r} = \boldsymbol{A\delta r^{NTW}} \tag{15}$$

Where,

$$\boldsymbol{A} = [\boldsymbol{e_r} \quad \boldsymbol{e_a} \quad \boldsymbol{e_c}] \tag{16}$$

$$\boldsymbol{e_a} = \frac{\dot{\boldsymbol{r}}}{|\dot{\boldsymbol{r}}|}, \boldsymbol{e_c} = \frac{\boldsymbol{r} \times \dot{\boldsymbol{r}}}{|\boldsymbol{r} \times \dot{\boldsymbol{r}}|}, \boldsymbol{e_r} = \boldsymbol{e_a} \times \boldsymbol{e_c} \tag{17}$$

Where $\boldsymbol{r}$ and $\dot{\boldsymbol{r}}$ are the range and velocity vectors of satellite in ECEF frame.

Note that a different convention is used in BDS PPP [4]:

$$\boldsymbol{e_r} = \frac{\boldsymbol{r}}{|\boldsymbol{r}|}, \boldsymbol{e_c} = \frac{\boldsymbol{r} \times \dot{\boldsymbol{r}}}{|\boldsymbol{r} \times \dot{\boldsymbol{r}}|}, \boldsymbol{e_a} = \boldsymbol{e_c} \times \boldsymbol{e_r} \tag{18}$$

For the early open service of PPP via SouthPAN, the format is based on the DFMC SBAS, the correction is provided in the ECEF reference frame.

The orbit correction is applied to correct the broadcast orbit $\boldsymbol{r_b^s}$:

$$\boldsymbol{r^s} = \boldsymbol{r_b^s} - \boldsymbol{\delta r} \tag{19}$$

Note that Galileo HAS in SIS is using the different (positive) sign convention:

$$\boldsymbol{r^s} = \boldsymbol{r_b^s} + \boldsymbol{\delta r} \tag{20}$$

For the clock correction, the correction is defined in RTCM 3 standard [17] as follows:

$$\boldsymbol{\delta C} = \boldsymbol{C_0} + \boldsymbol{C_1}(\boldsymbol{t} - \boldsymbol{t_0}) + \boldsymbol{C_2}(\boldsymbol{t} - \boldsymbol{t_0})^2 \tag{21}$$

For most satellite-based service providers, only the bias term C_0 is provided.

$$\boldsymbol{\delta C} = \boldsymbol{C_0} \tag{22}$$

The broadcast satellite time t_b is corrected with the clock correction as follows:

$$\boldsymbol{t_{sat}} = \boldsymbol{t_b} - \frac{\boldsymbol{\delta C}}{\boldsymbol{c}} \tag{23}$$

For code and phase bias correction, the pseudo-range (PR) observation and the carrier phase (CP) observation are corrected using the code bias correction ($d^s_{cb,i}$) and the phase bias correction ($d^s_{pb,i}$) as follows:

$$\widehat{\boldsymbol{p}}^s_{r,i} = \boldsymbol{p}^s_{r,i} + \boldsymbol{d}^s_{cb,i} \tag{24}$$
$$\widehat{\boldsymbol{\phi}}^s_{r,i} = \boldsymbol{\phi}^s_{r,i} + \boldsymbol{d}^s_{pb,i} \tag{25}$$

Note that QZSS CLAS and BDS PPP are using the difference (negative) sign convention:

$$\widehat{\boldsymbol{p}}^s_{r,i} = \boldsymbol{p}^s_{r,i} - \boldsymbol{d}^s_{cb,i} \tag{26}$$
$$\widehat{\boldsymbol{\phi}}^s_{r,i} = \boldsymbol{\phi}^s_{r,i} - \boldsymbol{d}^s_{pb,i} \tag{27}$$

Table 1 summarizes the sign conventions for PPP correction services [16].

Table 1 – Sign conventions for PPP correction services

	CLAS	MADOCA-PPP	Galileo HAS (SIS)	BDS PPP
Orbit	$\boldsymbol{r}^s = \boldsymbol{r}^s_b - \delta\boldsymbol{r}$	$\boldsymbol{r}^s = \boldsymbol{r}^s_b - \delta\boldsymbol{r}$	$\boldsymbol{r}^s = \boldsymbol{r}^s_b + \delta\boldsymbol{r}$	$\boldsymbol{r}^s = \boldsymbol{r}^s_b - \delta\boldsymbol{r}$
Matrix A	$\boldsymbol{e_a} = \frac{\dot{\boldsymbol{r}}}{\lvert\dot{\boldsymbol{r}}\rvert}$ $\boldsymbol{e_c} = \frac{\boldsymbol{r}\times\dot{\boldsymbol{r}}}{\lvert\boldsymbol{r}\times\dot{\boldsymbol{r}}\rvert}$ $\boldsymbol{e_r} = \boldsymbol{e_a}\times\boldsymbol{e_c}$	$\boldsymbol{e_a} = \frac{\dot{\boldsymbol{r}}}{\lvert\dot{\boldsymbol{r}}\rvert}$ $\boldsymbol{e_c} = \frac{\boldsymbol{r}\times\dot{\boldsymbol{r}}}{\lvert\boldsymbol{r}\times\dot{\boldsymbol{r}}\rvert}$ $\boldsymbol{e_r} = \boldsymbol{e_a}\times\boldsymbol{e_c}$	$\boldsymbol{e_a} = \frac{\dot{\boldsymbol{r}}}{\lvert\dot{\boldsymbol{r}}\rvert}$ $\boldsymbol{e_c} = \frac{\boldsymbol{r}\times\dot{\boldsymbol{r}}}{\lvert\boldsymbol{r}\times\dot{\boldsymbol{r}}\rvert}$ $\boldsymbol{e_r} = \boldsymbol{e_a}\times\boldsymbol{e_c}$	$\boldsymbol{e}_r = \frac{\boldsymbol{r}}{\lvert\boldsymbol{r}\rvert}$ $\boldsymbol{e_c} = \frac{\boldsymbol{r}\times\dot{\boldsymbol{r}}}{\lvert\boldsymbol{r}\times\dot{\boldsymbol{r}}\rvert}$ $\boldsymbol{e}_a = \boldsymbol{e}_c\times\boldsymbol{e}_r$
Clock offset	$t_{sat} = t_b - \frac{\delta C}{c}$	$t_{sat} = t_b - \frac{\delta C}{c}$	$t_{sat} = t_b - \frac{\delta C}{c}$	$t_{sat} = t_b - \frac{\delta C}{c}$
Code bias	$\widehat{\boldsymbol{p}}^s_{r,i} = \boldsymbol{p}^s_{r,i} - \boldsymbol{d}^s_{cb,i}$	$\widehat{\boldsymbol{p}}^s_{r,i} = \boldsymbol{p}^s_{r,i} + \boldsymbol{d}^s_{cb,i}$	$\widehat{\boldsymbol{p}}^s_{r,i} = \boldsymbol{p}^s_{r,i} + \boldsymbol{d}^s_{cb,i}$	$\widehat{\boldsymbol{p}}^s_{r,i} = \boldsymbol{p}^s_{r,i} - \boldsymbol{d}^s_{cb,i}$
Phase bias	$\widehat{\boldsymbol{\phi}}^s_{r,i} = \boldsymbol{\phi}^s_{r,i} - \boldsymbol{d}^s_{pb,i}$	$\widehat{\boldsymbol{\phi}}^s_{r,i} = \boldsymbol{\phi}^s_{r,i} + \boldsymbol{d}^s_{pb,i}$		

FURTHER WORK

Further work considered for future versions of this reports, or future reports of this Task Force, includes:

- Confirming the TBC/TBDs of the table.
- Studying interoperability between corrections (e.g. clocks, code biases) from different providers in a combined user receiver solution [18].
- Definition of the phase wind-up correction, and origin of the satellite phase-center.

PARTICIPANTS

The following participants and institutions have contributed to this report:

Table 2 – Participants in the PPP/PPP-RTK Providers Report

Region	Organization	Representatives
Japan	Mitsubishi Electric Corp.	R. Hirokawa
Australia	Geoscience Australia	S. Reynolds
European Union	European Commission DG DEFIS	I. Fernandez-Hernandez, T. Senni
China	China Academy of Space Technology	Xin Nie
Russian Federation	JSC “Research and Production Corporation “Precision Systems and Instruments”	Vladimir Braginets
Republic of Korea	Korea Research Institute of Ships and Ocean Engineering	SulGee Park

Table 3 – PPP/PPP-RTK Services

Application

Parameters	Japan		EU		Australia/ New Zealand	China	Russia	Korea
Service Name	CLAS	MADOCA-PPP	Galileo HAS Service Level 1 (SL1)	Galileo HAS Service Level 2 (SL2)	PPP Via SouthPAN (PVS)	BDS PPP	System for High-Precision Determination of Ephemeris and Clock Data (GLONASS PPP / GLONASS HiPreServ)	POINT (Precise POsitioning & INTegrity monitoring)
Operator	Cabinet Office, Japan	Cabinet Office, Japan	European Union		Geoscience Australia, Land Information New Zealand	China Satellite Navigation Office	ROSCOSMOS, State Space Corporation, Russian Federation	Ministry of Oceans and Fisheries and Ministry of Science and ICT, Republic of Korea
Status	Operational (since Nov 2018)	Operational (since Apr 2024)	Operational, Initial Service (since Jan 2023)	Development (Operational service by end of 2025)	Development (early open service: Sep 2022-)	Operational (since Jul 2020)	Operational and modernization	Development
Technology (PPP,PPP-AR,PPP-RTK,…)	PPP-RTK	PPP	PPP-AR	PPP-AR Fast-PPP (iono) over Europe	PPP	PPP	PPP (PPP-AR, PPP-RTK[2])	PPP-RTK
Service Area	Japan	Asia-Oceania 60°S~60°N, 70°E~200°E	Global[3]	Regional	Australian and New Zealand Exclusive Economic Zones	China and its surrounding areas in the scope of 10°N~55°N, 75°E~135°E	Russian Federation (global[2])	Republic of Korea
Coordinate System	ITRF2014	ITRF2014	GTRF		ITRF2014	BDCS	ITRF2014	TBD
Time System	QZSST	QZSST	GST		TBD	BDT	UTC+3h	TBD
Positioning Accuracy [cm] (95%)	12cm horizontal, 24cm vertical (kinematic) 6cm horizontal, 12cm vertical (static)	30cm horizontal, 50cm vertical (static)	20 cm horizontal, 40 cm vertical		15cm (For early open service, 37.5cm horizontal, 52.5cm vertical)	30cm horizontal, 60cm vertical (using BDS only) 20cm horizontal, 40cm vertical (BDS+GPS)	20cm horizontal 30cm vertical	10cm horizontal, 20cm vertical

[2] To be added in a later phase

[3] Some areas in Asia-Pacific temporarily excluded from the official service area, as per [12].

	Parameters	Japan		EU		Australia/ New Zealand	China	Russia	Korea
Presentation	**Convergence Time [s] (95%)**	60 sec (Including time to receive correction data)	30 minutes	300 sec	100 sec	40 minutes (For early open service, 80 minutes)	30 minutes (BDS only) 20 min (BDS+GPS)	1200 sec	60 sec
	Message Format	Compact SSR	Compact SSR	Own format (Similar to CSSR in some fields.)		TBD (DFMC SBAS MT32 for early open service)	Customized Compact SSR	RTCM-SSR (ground) Own format based on Compact SSR [2](space)	Own format (Similar to CSSR in some fields)
	Message Length[4]	Variable	Variable	Variable		TBD	Fixed	Variable	Variable
	GNSS and Signals Corrected	GPS: L1CA, L2P, L2C, L5 Galileo: E1, E5a QZSS: L1CA, L2C, L5	QZSS: L1CA, L1CB, L1C, L2C, L5 GPS: L1CA, L1P, L1C, L2C, L2P, L5 GLONASS: G1, G2 Galileo: E1, E5a	GPS: L1CA, L2C, L5 Galileo: E1, E5a, E5b, E5, E6		GPS: L1CA, L5 Galileo: E1, E5a	BDS: B1C GPS: L1CA TBC	GLONASS: L1OF, L2OF GPS: L1CA, L2CM Galileo: E1, E5a, E5b BDS: B1I, B2I (Other signals[2])	GPS: L1CA, L2P, L2C) Galileo: E1, E5a KPS: L1C, L2C
	Satellite Selection (Mask)[5]	Yes	Yes	Yes		Yes	Yes	Yes[2] (space)	Yes
	Orbit Correction (Coordinate System)[6]	Yes (SCS NTW)	Yes (SCS NTW)	Yes (SCS NTW)		Yes (TBD)	Yes (SCS NTW)	Yes	Yes (TBD)
	Code Bias	Yes	Yes	Yes		Yes	Yes	Yes[2]	Yes
	Phase Bias	Yes	Yes	Yes (Q3 2024)		TBD	No	Yes[2]	Yes
	Confidence Bounds	Yes	Yes	Yes (Phase 2, 2025)		No	Yes	No	Yes
	Ionospheric Correction (STEC,VTEC)	Yes (STEC)	Yes (STEC) from 2024 (technology demonstration)	No	Yes (VTEC, Phase 2, 2025)	No	No	Yes (STEC[2])	Yes (TBD)
	Ionospheric Grid Definition	(Yes) TBC	No	No	Yes (Phase 2, 2025)	No	No	Yes (ground[2])	Yes
	Tropospheric correction	Yes	No	No		No	No	Yes[2]	Yes
	Tropospheric Grid Definition	(Yes) TBC	No	No		No	No	Yes (ground[2])	Yes
	Integrity	Basic	Basic	No TBC		No	TBD	Yes[2]	Basic

[4] Defined for the PPP/PPP-RTK message, where 'fixed' means that all messages have a fixed length.
[5] Defines whether satellites for which corrections are provided can be defined through a mask.
[6] Coordinate system in which orbit corrections are provided. SCS (Satellite Coordinate System) NTW, where N, T and W represent radial, tangential and normal components.

Layer	Parameters	Japan		EU	Australia/ New Zealand	China	Russia	Korea
	Message Authentication	Yes (2024)	No	Yes (Phase 2, 2025)	No	TBD	Yes[2]	No TBC
	Bandwidth (per transmitting satellite)	2,000 bps	2,000 bps	448 bps	TBD bps	456 bps (TBC)	2,800 bps	TBD
	Efficiency[7]	8.5 bps/sat, 0.24 bps/sat/grid	8.5 bps/sat	24.4 bps/sat[8]	TBD	TBD	15.7 bps/sat	TBD bps/sat
	Extensibility[9]	Yes TBC	Yes TBC	Yes	-	Yes	Yes TBC	Yes TBC
Session	**Consistency Check for Ephemeris Update**	Yes, using IOD-SSR	Yes, using IOD-SSR	Yes, using IOD Set ID	Yes	Yes	Yes	Using IOD-SSR
	Satellite Grouping[10]	No	No	Yes	No	No	No	No
Transport	**Framing Design**	Preamble+payload+error correction	Preamble+payload+error correction	Preamble+payload+error correction	Preamble+payload+error correction	Preamble+payload+error correction	Preamble+payload+error correction	Preamble+payload+error correction
	Checksum and Error Correction	Reed-Solomon (255,223)	Reed-Solomon (255,223)	CRC and FEC (r=1/2) at 1 sec page level. HPVRS at message level.	TBD (16bits per word available)	Each message 486 bits, wherein the lowest 24 bits are CRC. After 64-ary LDPC(162, 81) encoding, the frame length shall be 972 symbols.	CRC-24Q Reed-Solomon (250,218)	TBD
	System Alert	Yes	Yes	-	No	TBD	No	Yes
	Generator ID[11]	Yes	Yes	No TBC	No	No	No	No
Network	**Signal**	L6D	L6E	E6-B	TBD	B2b	L3SVO	L6
Data-link	**Carrier Frequency**	1278.75MHz		1278.75MHz	1207.14MHz (For early open service, 1176.45MHz)	1207.14MHz	1202.025MHz	TBD

[7] Defined as the data rate divided by the number of satellites for correction.
[8] Assuming 24 Galileo satellites + 31 GPS satellites, and 3 HAS-transmitting Galileo satellites in view.
[9] Defined as the capability to be extended to provide corrections to other systems and signals.
[10] Satellite Grouping capability implies that different groups of satellites (e.g. those with a given frequency standard) can be corrected at different rates. See [2] for more details.
[11] Capability to switch between different SSR generators and report it to the users.

	Parameters	Japan		EU	Australia/ New Zealand	China	Russia	Korea
Physical	Signal Polarization	RHCP		RHCP	RHCP TBC	RHCP	RHCP	TBD
	Signal power	-156.82 dBW (On ground,0-dBi RHCP antenna, satellite elevation > 10 degrees)		-153dBW … -158.25dBW (On ground, assuming a 0-dBi RHCP antenna)	-158 dBW (On-ground, 0-dBi RHCP antenna, satellite elevation >5 degrees)	-160 dBW (measured at the output of a 0 dBi RHCP antenna, satellite elevation > 5 degrees)	-155.3 dBW (On-ground, 0-dBi RHCP antenna, satellite elevation >5 degrees)	TBD
	Spectrum	42.0MHz		10MHz (double sided) (40.92MHz defined as reference receiver bandwidth in Galileo SIS ICD [19])	20.46MHz	20.46MHz	10.23MHz	TBD
	DS-SS Chip Modulation	BPSK(5)		BPSK(5)	BPSK(10) TBC	BPSK(10)	BPSK(5)	TBD
	DS-SS Chip rate	5.115Mcps		5.115Mcps	10.23Mcps TBC	10.23Mcps	5.115Mcps	TBD
	DS-SS Code Length	4ms		1 ms	1 ms (TBC)	1 ms (TBC)	2ms	TBD
	DS-SS Spectrum Code	KASAMI		Memory Codes	TBD	Gold code	KASAMI	TBD
	Data Modulation	CSK		BPSK	TBD	BPSK	BPSK	TBD
	Data Rate	2,000bps (250 sps) (1744b + 256b RS)		492 bps (984 sps) (448b + 24b CRC + 20b other)	500 bps TBC (250 bps for early open service, sharing with DFMC SBAS)	486 bps (972 sps) (462b + 24b CRC)	-	TBD
	Type (Satellite, Ground)	Satellite	Satellite	Satellite, Ground	Satellite, Ground	Satellite	Ground (Satellite[2])	Satellite
	Number of Transmitting Satellites	4	4	20	TBD	TBD	3[2]	TBD
	Orbit	IGSO (QZO), GEO	IGSO (QZO), GEO	MEO	GEO	GEO	GEO	IGSO, GEO

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