1. 
2. Review of the quality of global PPP for positioning
3. *D2.3 of the DRF-Iceland-S1 project*

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**Review of the quality of global Precise Point Positioning (PPP)**

Martin Håkansson

# Introduction

This document is a part of the project Dynamic Reference Frame of Iceland-S1 (DRF-Iceland-S1), established by the Nordic Geodetic Commission (NKG). The aim of DRF-Iceland-S1 is that it shall be used as a basis for a future implementation of a dynamic reference frames (DRFs) as a national reference frame in Iceland. The purpose of this document is to investigate PPP as a positioning technique that provides direct access to positions as DRF-coordinates. It will investigate the current possibilities and limitations of existing real-time Precise Point Positioning (PPP) services, as well as to give an outlook for what might be expected in the future.

## Background

Satellite based positioning has emerged as an efficient and globally accessible method to determine absolute positions in a global terrestrial reference frame realization, such as ITRF2014 (Hofmann-Wellenhof et al. 2008).

A common problem when using absolute satellite positioning techniques is that the national reference frames often are statically or semi-dynamically defined, and that a transformation of coordinates therefore is required between the global reference frame employed by the satellite positioning system and the local national reference frame. Static reference frames are furthermore problematic in areas with internal crustal deformations. Iceland is an example of such an area, located at the Mid-Atlantic Ridge. Deformations of the Icelandic crust have over the years kept a regular demand for newly introduced static reference frames.

A fairly new concept for national reference frames is to define the frames as DRFs, i.e. as aligned to a global terrestrial reference frame, normally the latest International Terrestrial Reference Frame (ITRF). In practice, this means that fixed points on the ground move continuously in relation to the DRF, and coordinates must thus be given as 4-dimensional, with the epoch time as one of the components in addition to the 3D position in space. Comparison of DRF coordinates is then done by transforming them to a common epoch, by applying known models for crustal dynamics. This is opposed to static or semi-dynamic reference frames where the coordinates already from the beginning are given for the same reference epoch.

DRF-Iceland is a project that study the DRF-approach for a national reference frame in Iceland. This approach will have the potential benefit to mitigate some of the issues associated static reference frames in areas of high crustal dynamics.

Satellite based positioning naturally provides positions directly in a DRF, as it simultaneously provides ITRF 3D positions of the current reference epoch and accurate time estimates. In order to increase positioning accuracies, precise satellite based positioning techniques have been developed over the years. Traditionally, precise positioning was achieved with relative or differential techniques, where positions are given in relation to one or several reference stations with fixed coordinates. These techniques will thus not necessarily provide coordinates in a DRF, as the estimated position will be given in the same reference frame as the reference receiver.

The emergence of PPP as an alternative to traditional relative precise positioning techniques has caught on in recent years, as it provides several advantages over relative approaches. As an absolute positioning technique, it provides precise positioning as a service with global coverage in a global terrestrial reference frame. This means greater operational flexibility not limited to any specific region. PPP is performed with externally determined corrections in the form of precise orbits and satellite clocks which requires a less dense network of Continuously Operating Reference Station (CORS) infrastructure in comparison with differential or relative techniques. This reduces the operational costs for PPP divided per coverage area in comparison with relative techniques.

## Outline of this document

This document is divided into three parts: the first part gives a short introduction to PPP and the extension techniques PPP with Ambiguity Resolution (PPP-AR) and Real-Time Kinematic with State Space Representation (SSR-RTK); the second part presents expected performances for PPP and the extension techniques; the third part presents and compares some of the today’s available real-time PPP services.

# Basic principles of PPP

PPP was presented by the Jet Propulsion Laboratory (JPL) in the late 1990’s as a computationally efficient method to process Global Navigation Satellite System (GNSS) observations from large numbers of reference stations (Zumberge et al. 1997). This is due to the fact that PPP permits each station to be processed individually, in contrast to relative approaches where several baselines with surrounding stations need to be processed. Individual processing also has the advantage to more clearly reveal issues related to individual stations.

PPP is performed with precise orbits and clocks supplied to the user, and by explicit consideration of each of the error sources that affects the expected positioning accuracy. The precise orbits and clocks are determined from a globally distributed CORS network. The explicit handling of various error sources is one of the ways PPP distinguishes itself from relative positioning techniques.

In differential or relative processing, spatially correlated errors such as atmospheric refraction, orbital errors and short-term crustal deformations are eliminated by applying corrections or combining observations from a reference receiver located in close proximity to the user receiver. Characteristic for these kinds of errors is that they tend to be similar on nearby locations, and the mismodeling for differential/relative positioning techniques will thereby increase by the distance from the reference receiver. Other spatially uncorrelated errors, such as satellite clock errors, are totally eliminated regardless of the reference station distance. Distinctive for differential/relative positioning techniques is that the individual errors are not handled explicitly; instead, they are lumped together in the corrections supplied to the user. The reference station distance will thereby always be of significant relevance for the expected positioning accuracy when these techniques are employed, as the contributions for spatially correlated errors are included as an inseparable part of the corrections provided.

In PPP, the most significant part of the orbital error is eliminated, as precise orbits are estimated and provided to the users. Precise satellite clock error corrections are furthermore estimated separately, in contrast to differential/relative positioning where everything is lumped together. This way of separate error handling is commonly referred to as State Space Representation (SSR), whereas lumped error handling is referred to as Observation Space Representation (OSR). The remaining spatially correlated atmospheric errors, consisting of the tropospheric and ionospheric contributions, and short term crustal deformations, consisting of solid earth tides and ocean loading, are handled in the position estimation process at the user side, either by elimination/estimation or by some predefined deterministic model.

As PPP efficiently handles all spatially correlated errors it will not be sensitive to the distance to a reference receiver. This gives a more homogeneous performance for PPP over large areas. PPP will on the other hand set other requirements on the reference station side. Precise orbit and clock determination demands a globally distributed network of reference receivers. This network can be considerably sparser than networks dedicated for differential/precise positioning for the coverage of an area, but still requires a considerable amount of infrastructure operated globally.

## Error sources

PPP, in contrast to relative positioning, has to explicitly deal with each of the error sources involved, as the errors no longer are lumped in the corrections or observations derived from the reference station. PPP will thus provide accurate positioning solutions, only if each error source is carefully considered, either by some predefined model, by estimation/elimination, or by externally provided corrections. Table 1 lists error sources that should be considered in PPP.

Table 1 Some error sources that should be considered in PPP

|  |  |
| --- | --- |
| **Error source** | **Handled in** |
| **Earth orientation (Polar motion etc.)** | Orbit determination |
| **Solar radiation pressure** | Orbit determination |
| **Sun and moon gravitation** | Orbit determination |
| **Receiver clock error** | Estimated/Eliminated |
| **Tropospheric refraction** | Estimated |
| **Ionospheric refraction** | Estimated/Eliminated |
| **Satellite clock error** | External correction |
| **Solid earth tides** | Deterministic model |
| **Ocean loading** | Deterministic model |
| **Satellite phase center offset** | Pre-calibrated values (if COM ephemerides) |
| **Phase wind up** | Deterministic model |
| **Relativistic effects** | Deterministic model |
| **Various hardware biases** | Pre-calibrated/external correction |
| **(Atmosphere loading)** | External atmospheric pressure data |

Site dependent effects, such as antenna phase center variations and multipath, will have an impact on both relative positioning and PPP. For the antenna phase center, the effects can be handled with pre-calibrated values for the antennas. The multipath can to some extent be handled by various multipath mitigation techniques of the GNSS receivers and antennas.

## Handling of the atmosphere in “traditional” PPP

Atmospheric refraction is a significant error source in GNSS positioning and so also in PPP. Precise position estimation demands knowledge or elimination of each of the error sources with an accuracy of a few centimeters. As PPP relies on explicit handling of each of the significant error sources the atmospheric contributions will either need to be eliminated or estimated in the traditional approach. Fast elimination of the atmospheric error sources to the required accuracy, as in relative positioning, is in PPP not possible as they initially are determined from the code observations alone through elimination or estimation by combining observations associated with multiple carrier frequencies. Together with the fact that traditional PPP relies on float ambiguity resolution means that its solution will need some time to converge in real-time scenarios. The atmosphere will thereby influence both the accuracy and the convergence time of PPP.

By employing observations associated with more than one carrier frequency, the contribution of ionospheric refraction on the code and phase observations can be handled in the positioning process at the user side. As a dispersive part of the upper atmosphere, the ionosphere will affect signals of different carrier frequency differently for the frequency band employed by GNSS. Observations associated with multiple carrier frequencies can thereby be combined in various ways to deal with the ionosphere. This is done either be elimination, by forming an ionosphere-free linear combination of the multi-frequency observations, or by estimation with an additional ionosphere parameter and processing of all observations uncombined. Mitigation of the ionospheric contribution is however initially only achieved for the noisier code observations, as the corresponding ionosphere-free phase observation is ambiguous by an unknown float number originating from the phase ambiguities of the combined phase observations. The noise of the formed ionosphere-free observations is furthermore considerably higher than for the uncombined observations due to the laws of error propagation (Tegedor et al. 2016).

As the tropospheric part of the atmosphere is not dispersive, it cannot be handled by combining observations of multiple carrier frequencies as for the ionospheric case. The influence of tropospheric refraction is on the other hand more local than the ionospheric refraction for the observations collected by a single receiver, as the troposphere consists of the layer of the atmosphere located closest to the surface of the earth. This admits handling of the troposphere by the introduction of a single parameter common for all satellites. This parameter is referred to as the zenith tropospheric delay, which is related to the slant delays of each of the satellites by an elevation dependent mapping function.

## Additional error sources to consider

Precise orbit and clocks are determined from a globally distributed CORS, e.g. the International GNSS Service (IGS) or third-party reference stations. As a consequence of PPP being an absolute positioning technique, the estimated positions will be given in the same reference frame as the orbits supplied to the user.

Precise orbits are one of the corrections that are supplied to the PPP user. Orbit calculations is performed in an inertial reference frame that conforms with Newtonian mechanics by application of various force models for gravitational and solar radiation pressure effects. Terrestrial reference frame orbits, in for instance some ITRF realization, is determined from the inertial frame orbit calculations by considering the Earth’s orientation, with polar motion, sidereal time, nutation, and precession (Hofmann-Wellenhof et al. 2008; Kouba and Héroux 2001).

Besides precise orbits, precise satellite clocks are also required for PPP. For the accuracies of satellite clocks that are required for PPP, extrapolation by a linear or quadratic relation is not sufficient as for the satellite clocks distributed in the broadcast ephemerides. At the required level of accuracy of a few centimeters, the satellite clocks short-term variations behave in a much more unpredictable way, with the consequence that they cannot be predicted satisfactorily. The alternatives for the PPP processing are therefore either post processing with determined satellite clocks of former epochs, or real-time processing with satellite clocks determined in near real-time. Due to the unpredictable nature of the short-term variations, the latency on the user side for the acquired satellite clock corrections will have some effect on the expected accuracy of the estimated positions (Hadas and Bosy 2015). It is therefore of crucial importance for real-time PPP service providers to determine and distribute satellite clock corrections with as low latencies as possible.

PPP also needs to consider some additional effects that either cancel out or are negligible in relative positioning or Single Point Positioning (SPP). Two of these are related to the satellite attitude which therefore has to be considered in the positioning process.

The first effect is due to the fact that the antenna phase center of the satellite does not coincide with its center of mass. As GNSS measurements are related to the phase centers of the receiver and satellite antennas, phase center offsets to the reference points at the receiver and satellite side must be taken into account. Precise orbits are, in contrast to broadcast orbits, often given in relation to the center of mass of the satellite. The satellite phase center location must therefore be determined in the positioning process. This can be done with knowledge of both the antenna phase center offset in the antenna body frame, and the satellite attitude (Kouba and Héroux 2001).

The second effect is due to phase wind-up, which appear as a change in carrier phase when either the receiver or the satellite antenna is rotated around its vertical axes. This effect almost cancels out in relative positioning for baselines shorter than a few hundred kilometers. While the receiver antenna is often fixed, the satellites undergo slow rotations in order to orient their solar panels against the sun. More unpredictable rapid rotations also occur in eclipsing seasons for reorientation of the solar panels. Corrections for this effect can be applied as long as satellite and receiver antenna rotations are known (Kouba and Héroux 2001).

PPP also has to consider shorter term crustal deformations not captured by the ITRF frame, such as solid earth tides and ocean loading. Solid earth tides appear due to gravitational forces of the Moon and the Sun, and can to a great extent be corrected for by deterministic displacement models described by spherical harmonics (Kouba and Héroux 2001). The ocean loading is a crustal deformation effect that appears in coastal regions due to the load of the ocean tides. Even though ocean loading correction models exist, residuals might affect PPP especially in coastal regions where this effect is most prominent (Seepersad and Bisnath 2014). This might also be true in some cases of relative positioning.

Hardware biases are present in both code and carrier phase GNSS observations, for instance as a result of differences between hardware architectures and signal structures of satellites and receivers, as well as between GNSS constellations. These affect the position estimation in various ways where some biases always must be considered, and others have to be considered in specific cases. These cases might for instance be multi-GNSS positioning, positioning involving GLObalnaja NAvigatsionnaja Sputnikovaja Sistema (GLONASS), or PPP-AR later mentioned. A review of hardware biases and how they affect various precise positioning cases can be found in Håkansson et al. (2017).

The effect of atmospheric loading occurs as a displacement of the earth’s crust due to atmospheric pressure. Although atmospheric loading has a noticeable effect in techniques such as Very Long Baseline Radio Interferometry (VLBI) and Satellite Laser Ranging (SLR), its effect in GNSS and PPP is marginal due to the level of uncertainty of other error sources. The effect of atmospheric loading is therefore often omitted in PPP processing, even though some of its effects can be corrected for by global atmospheric pressure models (Urquhart 2009).

## PPP extension techniques

### PPP with ambiguity resolution (PPP-AR)

As PPP deals with undifferenced or between satellites single differenced observations, errors that in differential/relative positioning cancel out in a lumped manner, remain for the PPP model and have to be considered explicitly, as mentioned previously. Even though the traditional PPP model handles most of these errors, integer ambiguity resolution, as familiar from relative positioning techniques, still is not possible due to unhandled carrier phase biases originating from the satellites hardware. While eliminated in relative positioning by formation of double differences, these biases are in traditional PPP handled as merged with the phase ambiguities, which efficiently impair the ability to estimate them as integers.

Techniques which have emerged since 2007 offers the ability to resolve the ambiguities as integers also in PPP, provided that an additional satellite phase bias correction is supplied to the PPP user (Collins et al. 2010; Ge et al. 2008; Geng et al. 2012; Laurichesse et al. 2009). These techniques are commonly referred to as PPP-AR. Several approaches have been suggested for PPP-AR, which essentially differs in the parametrization of the supplied satellite phase bias corrections to the user. The two main approaches are the ”Uncalibrated Hardware Delays” method where Fractional Cycle Biases (FCBs) are provided to the user (Ge et al. 2008; Geng et al. 2012), and the ”Decoupled Clock model” method where the satellite phase biases are merged with the satellite clock corrections (Collins et al. 2010; Laurichesse et al. 2009). These approaches have been proved to be equivalent, but it is essential that the same parametrization is employed both at the service provider and the user end (Teunissen and Khodabandeh 2014).

### SSR-RTK

Atmospheric refraction is an error source that significantly contributes to the convergence time of traditional PPP and PPP-AR. The PPP solution starts of mainly determined by the less accurate code observations, which is reflected in a less accurate initial estimate of the state vector. Besides the geometric position, the receiver clock error, and the phase ambiguity, the state vector is composed of the atmospheric state, captured by the zenith tropospheric delay parameter, and optionally, if not eliminated, the ionospheric delay for each of the satellites. A better initial knowledge of the atmospheric state may thereby reduce the PPP convergence time considerably. The convergence time can be reduced to some degree by applying atmospheric information derived from external models. This information may for instance, for the ionospheric state, be collected from global ionospheric maps (GIMs) produced by the IGS, or some ionospheric model like the Klobuchar model. The corresponding information for the troposphere may be collected from prediction models such as UNB3, UNB3m, and GPT (Leandro et al. 2011).

Even though atmospheric information derived from the sources mentioned above may reduce the PPP convergence time, their typical accuracies of a few decimeters are insufficient for rapid to instantaneous resolution of the integer phase ambiguity in PPP-AR (Choy et al. 2017). To accomplish rapid phase ambiguity resolution, the initial atmospheric states must be known with accuracies of no more than a few centimeters. Derivation of atmospheric information with these levels of accuracy requires a denser regional CORS network.

SSR-RTK was first proposed by Wübbena et al. (2005), and can be described as a hybrid technique of network-RTK and PPP. While using precise orbits and clocks, as in regular PPP, and satellite phase bias corrections as in PPP-AR, the solution is enhanced with atmospheric corrections estimated from a dense regional network. This enables rapid to instantaneous convergence of the positioning solution, with a performance comparable to OSR network-RTK (Li et al. 2011; Wübbena et al. 2005; Xiaoming et al. 2011). This technique is also commonly referred to as PPP-RTK, but the term SSR-RTK has been suggested by Choy et al. (2017) to better distinguish it from traditional PPP which only employs a sparse global CORS network.

# Expected performance

This section presents expected accuracies and convergence times of the PPP techniques previously presented. These are also summarized in Table 2.

## ”Traditional” dual frequency PPP

Traditional dual frequency PPP has been employed since the late 1990’s (Zumberge et al. 1997). It is thus well known what can be expected in terms of accuracy from this technique. The vertical component will generally be of worse quality than the horizontal component, due to the satellite geometry, mismodeling of the troposphere, earth tides, and ocean loading effects. Several studies have demonstrated that 24 hours static dual frequency PPP (GPS only) has the ability to achieve accuracies below one centimeter in the horizontal component (Kouba and Héroux 2001; Zumberge et al. 1997). For kinematic positioning the corresponding accuracies are slightly worse, with accuracies below one decimeter. The whole observation period is typically needed to achieve maximum accuracy. For lower accuracy demands, a study performed by Seepersad and Bisnath (2014) demonstrated that accuracies below one decimeter in the horizontal component for static PPP generally need at least 20 minutes of convergence time. The corresponding convergence time for an accuracy of 5 centimeters is at least one hour. For kinematic PPP, it takes about 80 minutes to get below an accuracy of 20 centimeters (Choy et al. 2017).

## PPP-AR

PPP-AR has the capability to reduce the convergence time and increase the positioning accuracy, especially in the east component (Collins et al. 2008). Initial accuracies of the solution are comparable to that of a float solution, as both PPP and PPP-AR initially are heavily dependent on code observations. However, after about 15 minutes PPP-AR will surpass PPP in terms of accuracy for static dual frequency PPP (Choy et al. 2017). Ambiguity resolution has its greatest benefits for the accuracy and convergence in the short run, and for longer observation periods (several hours) PPP and PPP-AR again demonstrate comparable performances.

PPP-AR also offers the possibility of fast re-convergence after short data gaps by extrapolating the ionospheric state to its value just before the data gap (Choy et al. 2017; Xiaoming et al. 2011). In a similar way, fast convergence from a cold start is possible if the position of the receiver is known (Xiaoming et al. 2011).

## SSR-RTK

SSR-RTK might be thought of as a hybrid technique between traditional PPP and OSR network-RTK, that uses a global solution of precise orbits and clocks, at the same time as a regional CORS network is employed to estimate atmospheric corrections. The SSR and OSR network-RTK techniques are comparable in terms of accuracies and initialization times (time to fixed integer ambiguities) (Li et al. 2011; Wübbena et al. 2005; Xiaoming et al. 2011). In both techniques, a fairly dense network of reference stations is used for modeling of the spatially correlated atmospheric errors. As a denser network will give more accurate atmospheric models, the inter-station distance will be one of the parameters that decides the expected performance.

Table 2 Expected accuracies of some PPP techniques (Choy et al. 2017; Kouba and Héroux 2001; Li et al. 2011; Seepersad and Bisnath 2014; Wübbena et al. 2005; Xiaoming et al. 2011; Zumberge et al. 1997)

|  |  |  |
| --- | --- | --- |
| **PPP technique** | **Expected accuracy** **(horizontal, 1 sigma)** | **Convergence time** |
| **PPP (static)** | < 0.01 meter | 23 hours |
| **PPP (kinematic)** | < 0.05 meter | 23 hours |
| **PPP (kinematic)** | <0.2 meter | 80 minutes (not converged) |
| **PPP-AR (kinematic)** | <0.05 meter | 20-40 min (dual), 5 min (triple) |
| **SSR-RTK (kinematic)** | A few centimeters | < 1 minute |

## Future prospects

Future PPP will benefit from the deployment of additional GNSS systems, and the upgrade of existing systems with additional signals. By 2020 it is expected that four global fully operational systems will be in service as a result of the development of Galileo and BeiDou. This will greatly improve the satellite availability, and the ability to perform positioning in challenging environments. Also, convergence times and accuracies for PPP are expected to improve. A study performed by Choy et al. (2017)demonstrates improvements of 20% and 30% in the horizontal and vertical components for usage of GPS+GLONASS+BeiDou in comparison with GPS only. The corresponding convergence time is expected to improve by 20%. Multi-GNSS PPP also has the benefit to give positioning solutions that are more stable over time (Choy et al. 2017).

The addition of a third frequency will primarily improve the convergence time of the PPP solution. For PPP-AR, the time for ambiguity fixing can be reduced to a few minutes, thanks to extra-wide-lane ambiguity resolution (Choy et al. 2017).

# PPP Services

A number of commercial and free of charge PPP services are offered today. Common for most of these services are that they have the ability to provide its corrections via L-band satellite link, which enhances the accessibility also in remote areas. It is with this solution possible to receive the correction directly through the satellite antenna to a receiver that have support for the specific service. While most services provide support both for the GPS and GLONASS constellations, some have also already introduced support for all four constellations (Tegedor et al. 2017).

Table 3 presents some of the today’s available real-time PPP services.

Table 3 Some real-time PPP service providers

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Service** | **Price** | **PPP-AR** | **SSR-RTK** | **Additional information** |
| **IGS-RT** | Free of charge | Stäng | Stäng | <http://www.igs.org/rts> |
| **Trimble** | Subscription required | Bock | Bock[[1]](#footnote-1) | <http://www.trimble.com/positioning-services/> |
| **Fugro** | Subscription required | Bock | Stäng | [www.fugro.com/satellite-positioning](http://www.fugro.com/satellite-positioning) |
| **Veripos** | Subscription required | Bock | Stäng | <https://veripos.com/>On land:<http://www.terrastar.net/about-terrastar.html> |
| **NavCom** | Subscription required | Bock | Stäng | <https://www.navcomtech.com/en/product/globalcorrectionservice/>Offshore:<https://www.oceaneering.com/positioning-solutions/> |

# Concluding remarks

The expected performance of a PPP solution is very much dependent on the underlying technique that is used. “Traditional” PPP and newer extension techniques were here presented and analyzed. “Traditional” PPP and PPP-AR provides services with global coverage only require a sparse global CORS network for estimation of precise orbits, clocks, and satellite phase bias corrections. These techniques will on the other hand need some time to converge due to atmospheric effects. SSR-RTK is a more efficient alternative when it comes to convergence, but it requires on the other hand a dense CORS network for the determination of atmospheric corrections. The SSR-RTK technique is thus very similar to OSR based network-RTK both in infrastructure demands, and expected performance. Some improvement in accuracy and convergence time might be expected in the future, due to the development of two additional GNSS systems, and modernization of already existing systems.

# Abbreviations

AR Ambiguity Resolution
CORS Continuously Operating Reference Stations
DRF Dynamic Reference Frame
FCB Fractional Cycle Bias
GIM Global Ionospheric Map
GLONASS GLObalnaja NAvigatsionnaja Sputnikovaja Sistema
GNSS Global Navigation Satellite System
IGS International GNSS Service
ITRF International Terrestrial Reference Frame
JPL Jet Propulsion Laboratory
NKG Nordic Geodetic Commission
OSR Observation Space Representation
PPP Precise Point Positioning
PPP-AR PPP with Ambiguity Resolution
RTK Real-Time Kinematic
SLR Satellite Laser Ranging
SPP Single Point Positioning
SSR State Space Representation
SSR-RTK RTK with SSR
VLBI Very Long Baseline Radio Interferometry

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1. Only in areas with regional CORS network coverage. Positioning will otherwise fall back on PPP-AR. [↑](#footnote-ref-1)