DYNAMIC POSITIONING CONFERENCE
October 13-14, 2015

SENSORS SESSION

Global PPP with Ambiguity Resolution providing improved accuracy and instant position convergence

By David Russell

VERIPOS

Abstract

This paper will provide an overview of a new global high accuracy GNSS positioning service developed by Veripos enabling Precise Point Positioning with Ambiguity Resolution (PPP-AR). This new technique is an extension to the existing PPP technique and by resolving the ambiguities, a user can achieve an accuracy of just a few centimetres in real-time, globally and independent from their location relative to the GNSS reference station network.

In order to resolve carrier phase ambiguities, orbit, clock and observation bias information with an optimum data quality and data latency is broadcast to the user via geo-stationary satellites. The paper will explain the global GNSS tracking and communication infrastructure, the correction generation processes and the service data delivery to the end users.

Two of the key benefits of PPP with ambiguity resolution over regular PPP are (a) fast recovery after GNSS data gaps and (b) higher accuracy. The paper will present results demonstrating these benefits and how they benefit DP users.

Introduction

Veripos provides GNSS augmentation data which is used to support precise position solutions for offshore oil and gas exploration and operations. In March 2015, Veripos introduced a new global high accuracy service for its land business called TerraStar-C. This new service extends the capabilities offered by the existing PPP service, by enabling PPP with ambiguity resolution. The technique enables a higher accuracy and improved re-convergence compared to regular PPP. A near-instantaneous return to high accuracy positioning after short gaps in GNSS observations is a significant benefit of PPP with ambiguity resolution and this feature improves the robustness and availability of the solution.

In order to resolve carrier phase ambiguities within a user receiver, additional correction data needs to be determined and broadcast. The server processing the observations from a global network of reference stations needs to estimate code & phase biases in addition to the orbit & clock corrections required by regular float PPP applications. These additional parameters are then broadcast to users via geostationary communication satellites. At the receiver, these additional messages must then be decoded and applied correctly within the positioning algorithms to provide improved performance.

Infrastructure

A key requirement for operating a real-time global positioning service is to have a network of GNSS reference stations that provide high quality GNSS data in real-time, with a maximum continuity and minimum latency. Therefore all GNSS reference stations are situated in secure locations and are equipped with dual redundant systems plus back-up power. Diverse communications are also employed at the reference stations, with a minimum of two separate communication links for each site. The majority of stations are gathering data using Septentrio multi-constellation receivers and AeroAntenna Technology choke ring antennas. All sites are controlled from fully redundant Network Control Centres (NCCs), located in Aberdeen (UK) and Singapore, with a 24/7 response system available at each reference site. Raw GNSS observation and navigation data from the entire tracking network are sent to both NCC's through the communication network in real-time. Altogether Veripos operates a global network of ~85 stations capable of tracking the four global GNSS constellations and QZSS. Figure 1 indicates the locations of these reference stations. The network density and distances between stations in the network are of key importance for reliable ambiguity resolution.

Figure 1- Veripos Reference Stations

The raw binary GNSS data from stations is delivered to the Orbit and Clock Determination Systems (OCDS) installed in three NCCs, two located in Aberdeen and one located in Singapore. The choice of locations for the NCC's in Aberdeen gives good logistical support as well as reliable communications infrastructures, with Singapore in addition being the major communications hub for South East Asia. Figure 2 shows the multiple servers (5) that are simultaneously operated. Only data from one of the servers is uplinked at any time for broadcast to users, with the other servers acting as hot spares. The system will automatically switch to an alternative server should the primary server fail to meet thresholds in terms of augmentation data quality or availability. The multi-server and multi-location architecture is key to providing the Veripos services to a wide range of professional applications that require augmentation data with a maximum continuity and availability.

Center	System	RTES	Orbits	SV Clocks	QC Clients	Since Last Update
Dyce_Duty	1.3 0.2 1.4 13.3 6.8	83/95	30/30-24/24	30-24 82-74 12.7 on 30-0 82-0 16.3 on	14/16	4 Seconds
Dyce_Standby	1.8 1.0 1.7 4.7 5.6	81/95	30/30-24/24	30-24 80-73 9.8 on 30-0 80-0 15.9 on	12/16	4 Seconds
Singapore_Duty	1.2 1.2 2.1 4.3 4.7	83/94	30/30-24/24	30-24 83-73 12.8 on 30-0 84-0 21.6 on	12/16	3 Seconds
Singapore_Standby	1.3 1.0 1.8 0.5 7.5	83/94	30/30-24/24	30-24 81-72 12.7 on 30-0 82-0 25.9 on	12/16	4 Seconds
Greenwell	2.0 1.1 1.4 3.0 6.2	67/76	30/30-24/24	30-24 68-67 12.2 on 30-0 67-0 24 on	12/14	3 Seconds

Figure 2- OCDS Server Status Information

Each server estimates GPS & GLONASS satellite orbit & clock correction data as well as code and phase biases for the GPS constellation and this data is delivered to the users via geostationary communication satellites. Veripos leases bandwidth on 7 geostationary communication satellites for the distribution of the augmentation data. This data is broadcast at L-band frequencies of ~1539Mhz and with a data rate of 1200bps. The augmentation data is encoded in a proprietary correction data format in order to deliver the optimum GNSS positioning performance within the limited bandwidth available on GEO satellite channels.

PPP-AR

The PPP-AR service data which enables ambiguity resolution, consists of the follow:

1. satellite orbit corrections,
2. satellite clock corrections,
3. satellite hardware biases of the code observations, and
4. satellite hardware biases of the phase observations.

The service augmentation data are estimated in real-time by the orbit and clock determination system (OCDS). The tracking network GNSS data is first processed by the NAPEOS orbit determination software to generate predicted orbits for use in real-time. New predicted orbits are computed every 15 minutes to keep the prediction time window as short as possible, generally well below 30 minutes. This process is capable of estimating the GPS and GLONASS orbits to better than 5 cm. This statistic is derived from orbit overlap monitoring (see Figure 4) as well as from comparisons with IGS final orbits. The remaining components of the augmentation data are estimated in real-time by software which is based on a Kalman filter algorithm. The predicted orbits and the real-time station data streams are inputs to the estimation of the real-time clocks as shown in Figure 3. The real-time server run has two parts – the PPP-NB filter and the PPP-AR filter. The PPP-NB filter estimates clocks and code biases using the code & phase observations available from the reference station network. The estimated orbits, clocks, and code biases are then passed to the PPP-AR filter that resolves the ambiguities to their integer values and estimates the Melbourne-Wuebbenna and ionosphere-free biases. The biases are subsequently converted into signal specific biases for the observables processed by the PPP-AR filter.

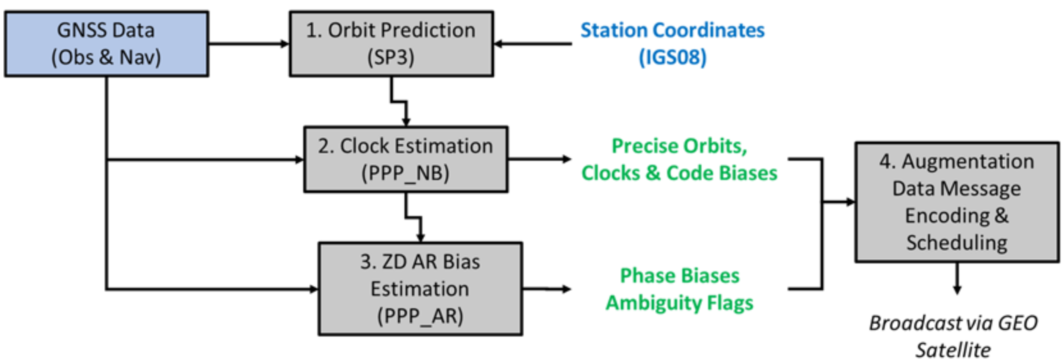

Figure 3- Orbit, Clock and Bias Determination

The hardware code biases are divided into two parts. The larger, constant in time, part of the code bias is added to the satellite clock corrections. Thus a PPP client can work using the satellite orbit and clock corrections only (the remaining code bias is small enough to be neglected for the purposes of a PPP client that does not attempt to resolve the initial phase ambiguities to their integer values). The satellite clock corrections refer to the ionosphere-free linear combination of the original measurements.

The code biases, their small remaining parts, as well as the phase biases are vital for resolving the ambiguities in the Veripos PPP-AR service. The biases are transmitted for all observation types (tracking modes) that are being processed at the server side, currently for C-code for the GPS L1 signal and the P-code for the GPS L2 signal. Taking into account the received biases the client is able to resolve the wide-lane ambiguities using the Melbourne-Wuebbenna linear combination and the narrow-lane ambiguities using the corresponding ionosphere-free linear combination, see [1]. The ambiguities are being resolved on the single (between satellites) difference level.

All estimated parameters are passed on to the correction encoding & scheduling software and the encoded proprietary messages are then included in the data stream for GEO satellite transmission.

PPP-AR Service Performance

The quality of the augmentation data is monitored by the OCDS servers in real-time. Figure 4 shows the RMS errors of the estimated satellite positions based on comparing overlapped orbit results.

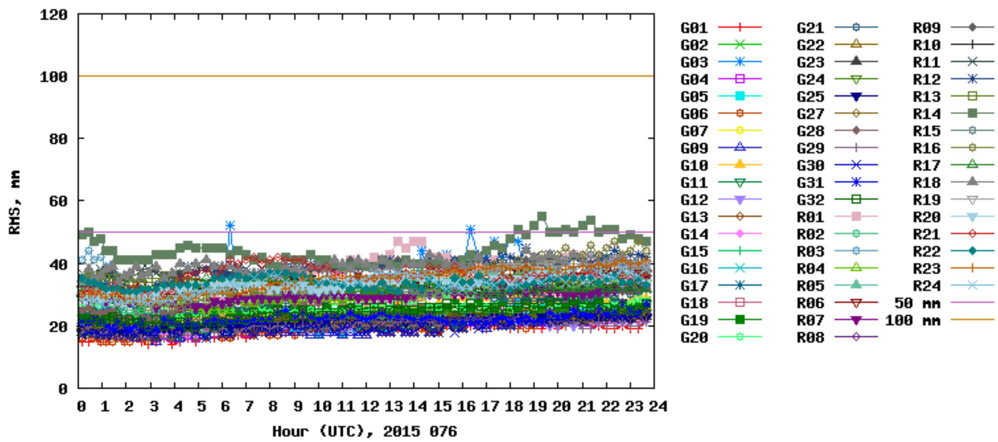

Figure 4- Operational Orbit Quality Monitoring (3D RMS Error)

Figure 4 indicates that the real-time orbits for GPS and GLONASS are computed with an accuracy of typically 2-4cm. When compared to the IGS final product the 3D orbit accuracy is 50mm and the clock accuracy is 40mm for the GPS constellation while the GLONASS performance is only slightly worse.

Figure 5 illustrates the behaviour of the signal specific biases required by the PPP-AR service. These are inherently stable for code observations. The phase biases are equally stable in principle but their values may occasionally need to be reset depending on the observability of the satellite in the network. In that case a phase bias discontinuity flag is passed on to the client application as part of the augmentation data.

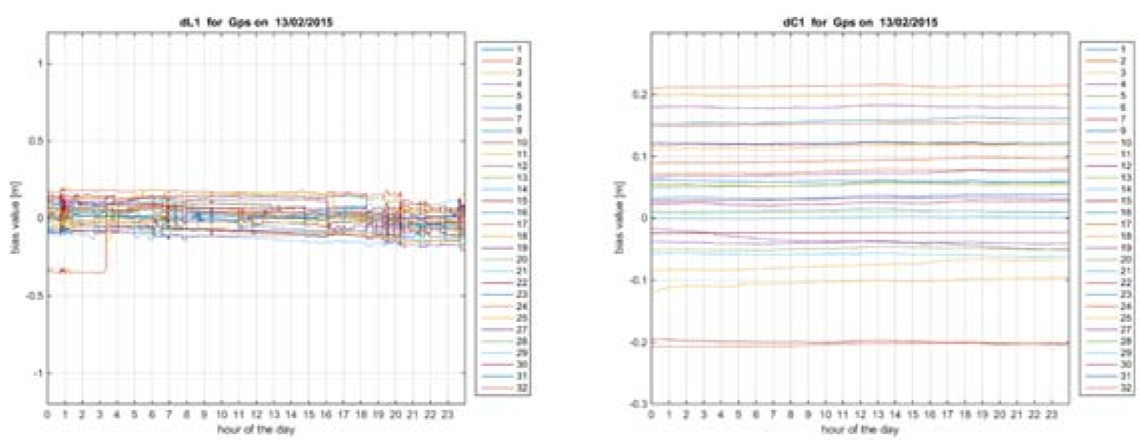

Figure 5- Examples of Phase Bias (l) and Code Bias (r) Stability

The ultimate test of the quality of the augmentation data is provided by the usage of the service augmentation data for the estimation of the client position. Figure 6 shows the typical positioning performance of the PPP-AR service over a 24-hour period when compared against a known coordinated point.

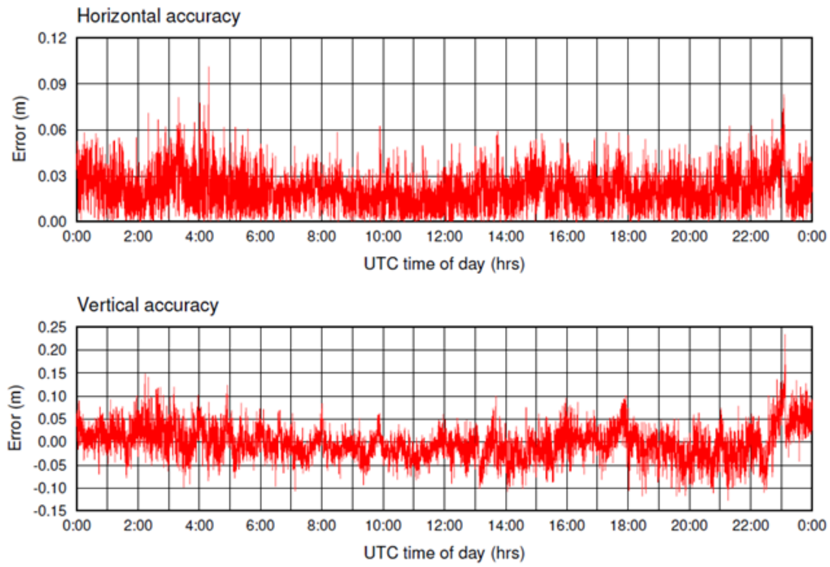

Figure 6 - PPP-AR Service Performance (29th December 2014)

The PPP-AR service performance over a 2 week period is demonstrated in Figure 7 for a monitoring site in Aberdeen, Scotland. The graph also shows the corresponding Veripos Apex[2] PPP service performance. Typical performance statistics for PPP-AR service is typical better than 3cm horizontal and 8cm vertical both at 2-sigma (95%) confidence level.

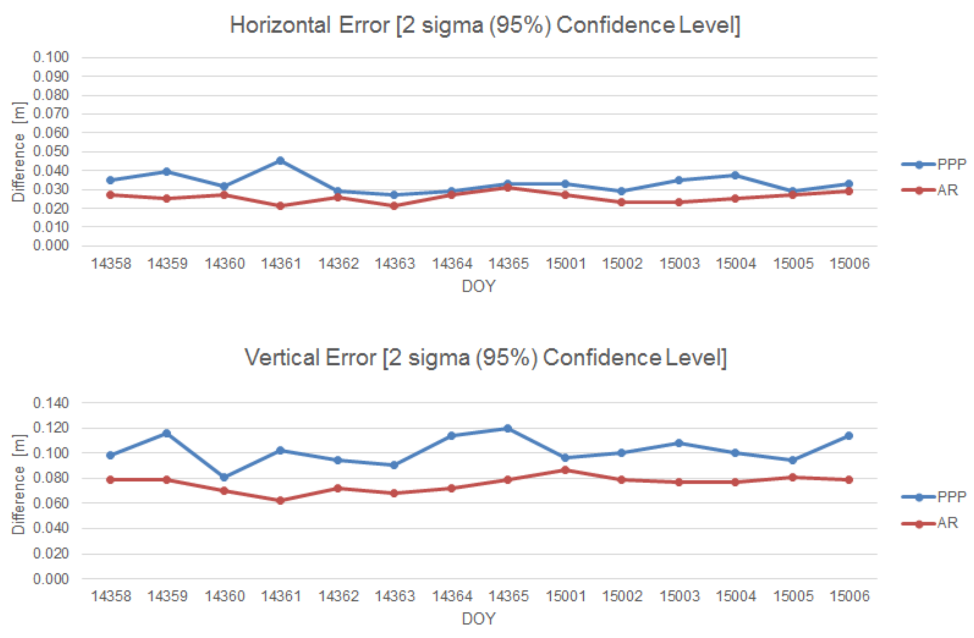

Figure 7 - Accuracy Performance of PPP-AR service (red) vs PPP service (blue) at Aberdeen Monitoring Site

The Veripos monitoring system is running continuous real-time client tests to monitor the corrections generated by the server. These client tests use corrections directly from the server – not packaged for over-the-air transmission. The main purpose of these tests is to evaluate the quality of corrections coming from the server. These tests do not account for errors introduced by data latency (~1-2 sec) experienced by regular users of the service who receive the corrections via satellite link. Also the client receiver data used for this monitoring comes from the reference network which has a slight data quality advantage over typical user equipment. However this advantage is considered small.

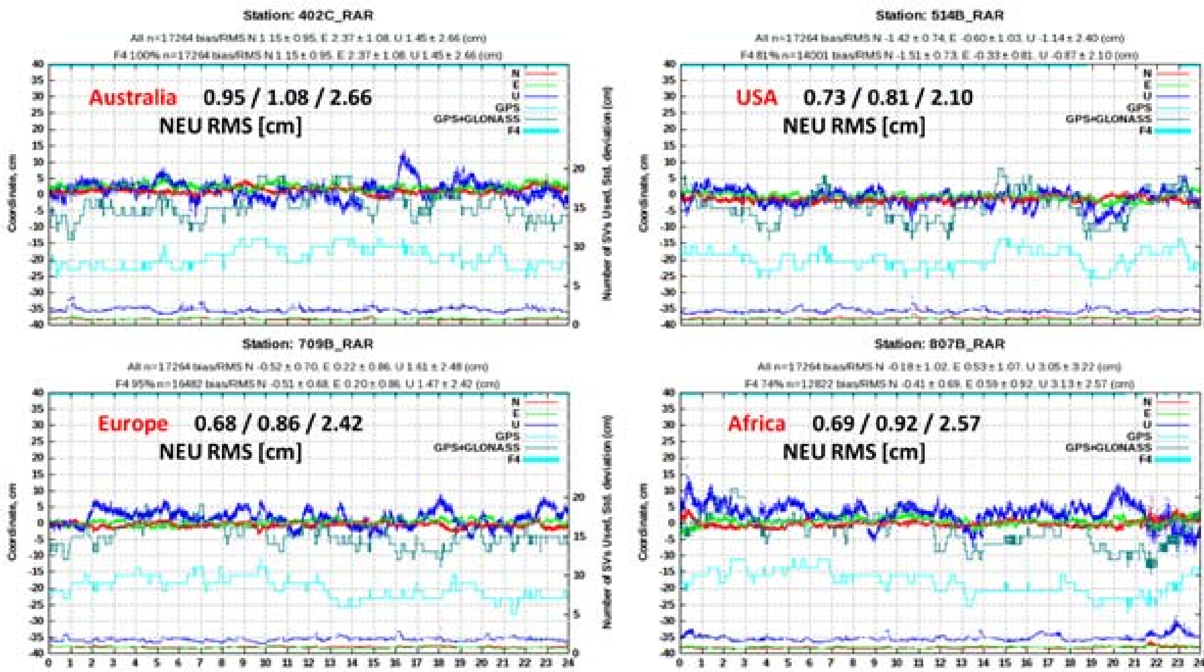

Figure 8 - PPP AR client solutions for an example day (26 March 2015)

Figure 8 shows the time series and RMS values for 4 client solutions at different monitoring locations, in Australia, USA, Europe and Africa on 26 March 2015. Although the monitoring takes place at fixed sites, these client solutions are processed in full kinematic mode to be representative of users in dynamic scenarios. The time series show that steady-state performances are achieved at a 1-2cm horizontal and a 2-5cm vertical level. The parameter F4 indicates the percentage of fixes that have ambiguities resolved (fixed to their integer values) for 4 or more satellites. For the Australia site this was 100%, whilst the lowest fix percentage was at the African site (74%). The time series for the Africa site shows some impacts of scintillation during the period 21:00-24:00, when the GNSS tracking was degraded, though it is also clear from the plot that the PPP-AR positioning capability remains stable and to a large extend accurate during this period

PPP-AR Re-Convergence Performance

While cold-start or initial convergence is similar for PPP and PPP with ambiguity resolution, the situation is much better for hot-start re-convergence of a PPP with ambiguity resolution solution. For example if a user experiences masking of GNSS satellite for a period of time the PPP-AR solution can instantly re-convergence to the same positioning accuracy and quality that was being experienced prior to loss of GNSS signals. Compared to a standard or float PPP solution which generally needs to be fully reset and repeat the cold-start process. This fast re-convergence can be achieved if the client software estimates the satellite specific line-of-sight ionospheric delays at all times. These delays can then be applied after re-acquiring satellites as a constraint to fix the carrier phase ambiguities almost instantly. Tests of this technique are indicated below in Figure 9.

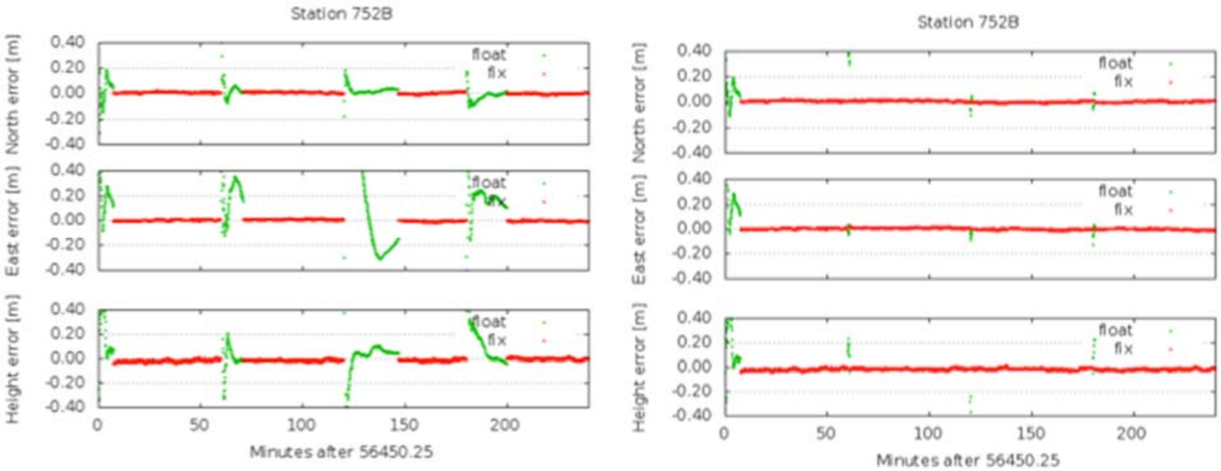

Figure 9 - Position Errors of a Client Solution with Several 2-minute gaps

In Figure 9 the ambiguity-free solutions are shown in green, the ambiguity fixed solutions are shown in red. The left panel illustrates how long it takes after the gap before carrier phase ambiguities are re-resolved without using pre-gap ionosphere as a constraint. The right panel shows the much faster gap recovery succeed if the pre-gap ionosphere is used as a constraint. Figure 9 indicates that the PPP-AR service enables client users to achieve rapid gap recovery, which for many applications offers a significant benefit compared to regular PPP.

Further results shown in Figure 10 demonstrate the difference between a PPP-AR solution and the Veripos Apex[2] from a NovAtel receiver. The left hand graphs shows how quickly the solutions re-converge after a 5-second outage of GNSS observations with the blue representing the PPP-AR solution while the red and green show different implementations of the Veripos Apex[2] positioning algorithms. The right hand shows the same but a 30-second outage of GNSS observations.

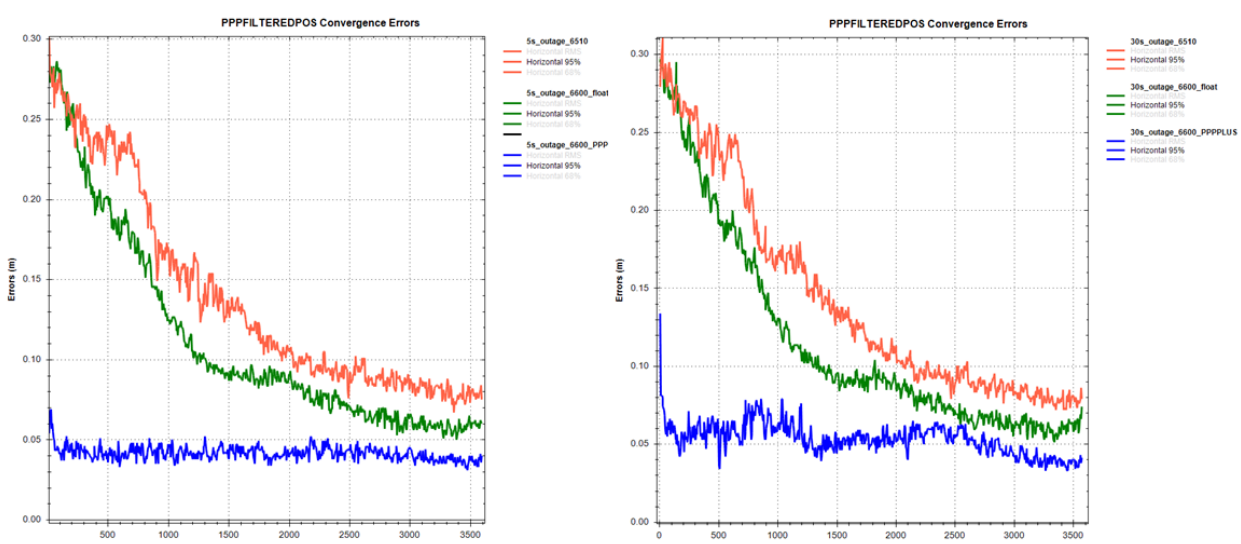

Figure 10 - Comparing PPP-AR and PPP Positioning Re-convergence

Conclusion

Global PPP with ambiguity resolution is enabled by a reliable and redundant global GNSS infrastructure estimating precise orbits, clocks and signal specific observation biases in real-time. A key benefit of ambiguity resolution, compared to regular PPP, is that a horizontal positioning accuracy of <5cm can be quickly restored in most operational environments where short gaps in GNSS observation data are inevitable. This makes PPP-AR an attractive solution for many DP applications where the solution can quickly recover.

The current system architecture can be extended to process orbits, clocks & biases for any GNSS signal. Adding augmentation data for the QZSS, BEIDOU and GALILEO signals into the corrections streams will further enhance the PPP with ambiguity resolution performance, particularly in terms of convergence time and in terms of availability and stability in non-clear sky environments.

Acknowledgements

The author would like to acknowledge the support of NovAtel in providing results from their testing for this paper.

References

1. L. Mervart, Z. Lukes, C. Rocken, T. Iwabuchi, “Precise Point Positioning With Ambiguity Resolution In Real-Time”, ION Meeting, Savannah, September 2008.