Ambiguity-Resolved Real-Time Precise Point Positioning as a Potential Fill-In Service for Sparse CORS Networks

Thomas Grinter
Spatial Services, NSW Department of Customer Service, Australia
Thomas.Grinter@customerservice.nsw.gov.au

Craig Roberts
School of Civil & Environmental Engineering, University of New South Wales, Australia
c.roberts@unsw.edu.au

Volker Janssen
Spatial Services, NSW Department of Customer Service, Australia
Volker.Janssen@customerservice.nsw.gov.au

Abstract

Precise Point Positioning (PPP) employs readily available Global Navigation Satellite System (GNSS) orbit and clock correction products to perform point positioning using a single GNSS receiver. Recently, attention has turned to Ambiguity-Resolved Real-Time PPP (AR-RT-PPP), allowing PPP to potentially offer a viable alternative to Real-Time Kinematic (RTK) positioning provided by local or regional Continuously Operating Reference Station (CORS) networks. Using an extensive dataset covering all of New South Wales (NSW), Australia, this paper showed that AR-RT-PPP is achievable, on average providing positioning quality down to a few centimeters with an average ambiguity-resolution success rate of 84.3% and average convergence times of between 40 minutes and 1 hour. The paper highlighted the advantages and disadvantages of this positioning technique from a user's perspective and then outlined the current limitations and possible future direction of AR-RT-PPP as a fill-in service for sparser local or regional CORS networks.

Keywords: Precise Point Positioning; Global Positioning System (GPS); real time; ambiguity resolution; CORSnet-NSW.

Introduction

Precise Point Positioning (PPP) is a positioning method that employs widely and readily available Global Navigation Satellite System (GNSS) orbit and clock correction products, e.g. provided via the International GNSS Service (IGS) (IGS 2019), to perform point positioning using a single GNSS receiver (e.g. Heroux and Kouba 1995; Zumberge et al. 1997; Gao and Kongzhe 2004; Rizos et al. 2012; Choy et al. 2015b; Kouba 2015). This provides PPP with an advantage over differential techniques in that only a single receiver is necessary (at the user's end), removing the need for the user to establish a local base station or access data from a surrounding local or regional Continuously Operating Reference Station (CORS) network.

Consequently, the spatial operating range limit of differential Real-Time Kinematic (RTK) or Network RTK (NRTK) techniques is negated, as well as the need for simultaneous, continuous, high-rate (1 Hz) data streams from the reference station(s) to the rover. This, in turn, can reduce labor and hardware/communication costs, simplify operational logistics, and service areas that have intermittent communication issues (i.e. black spots or poor latency) or communication restrictions (e.g. operating frequencies or transmission power). However, a sparse, global CORS network is essential for calculating the GNSS orbit and clock correction products required for PPP. Because this global CORS network is so far removed and practically hidden from the user, PPP is assumed to provide standalone point positioning.

The use of a single GNSS receiver for PPP also invokes major disadvantages. The most significant disadvantage is the long convergence time necessary (> 20 minutes) for the float solution to converge to centimeter accuracy, thus limiting its use in real-time applications. PPP requires a number of corrections to limit the effects of centimeter-level variations of undifferenced code and phase observations. Phase wind-up corrections, satellite antenna phase center corrections, solid earth tide corrections and ocean loading corrections are all necessary for precise PPP solutions, but are not considered for standard differential positioning techniques (i.e. short-/medium-length static baselines, kinematic and real-time techniques). Recent developments in PPP were reviewed by, e.g., Grinter and Roberts (2011), Rizos et al. (2012) and Choy et al. (2017).

The availability of Real-Time PPP (RT-PPP), using float solutions, promotes PPP as a potentially viable alternative to differential GNSS techniques such as the highly productive and practical RTK/NRTK solutions. This has led to several RT-PPP products and services being available to the practical user (Grinter and Roberts 2013). However, the long convergence times necessary to obtain a precise position solution continue to hinder PPP's potential. Recently, several methods have been developed to allow Ambiguity-Resolved Real-Time PPP (AR-RT-PPP) (e.g. Ge et al. 2008; Laurichesse et al. 2009; Collins et al. 2010; Geng et al. 2010, 2011). In all cases, a CORS network is utilized to aid fixed-integer ambiguity resolution.

Although these AR-RT-PPP methods allow slightly faster, precise centimeter-level solutions compared with converged float solutions (Bisnath and Collins 2012), the ability to constrain and correctly predict the ionospheric delay remains a crucial factor in enabling ambiguity-resolved PPP (Collins and Bisnath 2011). Alternatively, if high-quality ionospheric (and potentially tropospheric) corrections are available (e.g. via a local or regional CORS network), rapid ambiguity resolution is possible – this is sometimes referred to as RTK-PPP or PPP-RTK (e.g. Wübbena et al. 2005; Teunissen and Khodabandeh 2015; Odijk et al. 2016, 2017).

This study addressed AR-RT-PPP from a user's perspective (with currently available software and application-focused), not PPP-RTK from an academic perspective (with software currently under development, e.g. Odijk et al. 2017). It investigated the topic from the perspective of a government agency interested in providing services for the public good, deliberately did not consider commercial services. Consequently, this paper employed a modified open-source RTKLIB (Takasu and Yasuda 2009; Takasu 2013) processing engine to determine simulated AR-RT-PPP solutions for 6 days during a 4-week period at 26 CORSnet-NSW sites across New South Wales (NSW), Australia, to investigate the viability of PPP as a standalone positioning solution from a user's perspective. These results were verified using actual real-time data collected for a subset of the sites. The paper discussed the current limitations and possible future direction of AR-RT-PPP as a fill-in service for sparser local/regional CORS networks.

Study Area and Data Used

CORSnet-NSW is Australia's largest government-owned and operated network of permanent GNSS reference stations. It is built, owned and operated by Spatial Services, a unit of the NSW Department of Customer Service (e.g. Janssen et al. 2016; NSW Spatial Services 2019). As of August 2019, the network consisted of 202 reference stations, providing fundamental positioning infrastructure that is authoritative, accurate, reliable and easy-to-use for a wide range of applications across New South Wales.

For the purposes of this study, 26 CORSnet-NSW sites were selected (Figure 1). The sites were chosen based on geometry (i.e. providing an even spread across the State), hardware (i.e. a mix of state-of-the-art receiver-antenna/radome combinations) and site environment (i.e. monuments that were proven to be very stable and exhibiting a clear sky view). Lord Howe Island (LORD) is situated 600 km off the east coast of NSW.

For each site, six 24-hour observation files containing 1-second data were obtained over a 4-week period in June and July 2015 (DOY 173, 178, 183, 186, 194 and 198). This study was carried out as part of the first author's Masters degree, undertaken part-time over several years. The receiver-antenna/radome combinations used at these sites at that time, along with the number of occurrences of each combination, are listed in Table 1.

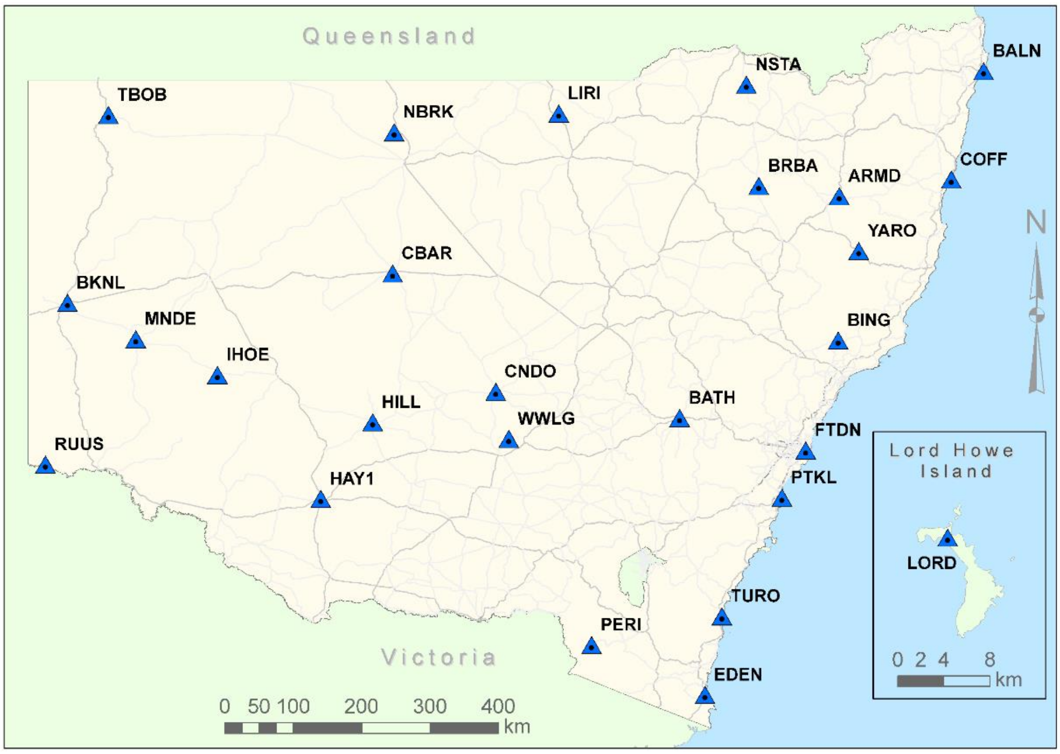

Figure 1. Selected CORSnet-NSW sites used in this study.

Table 1. Receiver-antenna/radome combinations used for this study.

Receiver Type	Antenna Type	Radome Type	Count
TRIMBLE NETR9	TRM59800.00	SCIS	6
LEICA GRX1200+GNSS	LEIAR10	NONE	4
LEICA GRX1200GGPRO	LEIAT504GG	SCIS	3
TRIMBLE NETR9	TRM57971.00	NONE	3
LEICA GRX1200+GNSS	LEIAR25.R3	LEIT	2
LEICA GRX1200+GNSS	LEIAX1203+GNSS	NONE	2
LEICA GRX1200GGPRO	LEIAX1202GG	NONE	2
TRIMBLE NETR9	TRM59900.00	SCIS	2
LEICA GR25	LEIAR10	NONE	1
LEICA GRX1200GGPRO	LEIAT504GG	NONE	1

Data Processing and Testing Methodology

Data Processing in Simulated Real Time

Six 24-hour RINEX 2.11 observation and navigation files taken from 26 CORSnet-NSW sites (NSW Spatial Services 2019) were processed in simulated real time. Navigation files were required in this case because the IGS real-time orbit and clock products are corrections to be added to the navigation message in order to save bandwidth for real-time operation. Simulating a real-time scenario in post-processing mode using readily available data from a CORS network along with PPP correction data provided via the IGS allowed testing to occur without requiring field work and avoided any intermittent communications and latency issues that may occur. Data were processed at a 1-second rate, resulting in 518,400 positions for each site and equating to almost 13.5 million position calculations in total. All positioning solutions were generated using modified RTKLIB software (Takasu and Yasuda 2009; Takasu 2013). The observables were collected using survey-grade GNSS receiver-antenna combinations (Table 1), and IGS antenna models (igs08_1848.atx) were applied.

The open-source RTKLIB software utilized was modified by Dr. Ken Harima (RMIT University, Melbourne) as part of a separate study in order to provide an AR-RT-PPP solution for GPS-only processing (Choy et al. 2015a). The modification included enabling ambiguity-resolved PPP, adding a function that allowed RTKLIB to read the message that includes the GPS phase biases (message 1265), and adding a success rate test for ambiguity validation, because incorrectly fixed ambiguities are more likely in a PPP solution due to the difficulty of constraining and correctly predicting the ionospheric delay. The success rate test tests the probability of successful ambiguity resolution by determining whether there is a valid solution among the calculated solution candidates. Combined with the standard ratio test, this provides confidence that the best solution is selected and that it is reliable (e.g. Verhagen 2005).

The ambiguity-resolution method for PPP implemented in RTKLIB is based on Ge et al. (2008). This method utilizes the ionosphere-free linear combination (LC) of code and carrier phase observations, and the Melbourne-Wübbena combination was used to recover the integer nature of the ambiguities. The L1 ambiguity then is resolved using the modified LAMBDA method (Chang et al. 2005).

Table 2 lists the settings applied during RTKLIB processing. This study employed the static PPP processing mode. This was justified by acknowledging that many RTK/NRTK users are willing to remain stationary for a short period (e.g. 2 minutes) in order to collect several epochs of data and obtain a more accurate and more reliable positioning solution (e.g. Janssen and Haasdyk 2011). When investigating the potential of AR-RT-PPP as a viable alternative to RTK/NRTK in practice, the same philosophy should be applied in the first instance.

Table 2. RTKLIB settings applied (ZTD = Zenith tropospheric delay, APC = antenna phase center).

RTKLIB Option	Selection
Positioning mode	PPP static
Ionospheric correction	Iono-free LC
Tropospheric correction	Estimate ZTD
Satellite ephemeris/clock	Broadcast + SSR APC
Integer ambiguity resolution	Modified LAMBDA
Earth tide corrections	Solid

In PPP, dual-frequency observations typically are used to eliminate the first-order effects of the ionosphere (via ionosphere-free combinations). Differential Code Biases (DCBs), which are differences among the hardware-dependent biases in the observation equations, are calculated by the IGS analysis centers as a by-product of their estimated ionospheric products, such as Global Ionospheric Maps (GIMs). By convention, the IGS analysis centers do not apply DCB corrections when generating the IGS clock products. Consequently, DCBs are not required when using IGS clock products for a simple, dual-frequency (float) PPP solution, which requires only orbit and clock corrections (Teunissen and Khodabandeh 2015). However, single-frequency PPP users must apply these DCBs to the L1 pseudorange observations in order to be compatible with the IGS clock products and the single-frequency code measurement.

Differential Phase Biases (DPBs), and, similarly, Uncalibrated Phase Delays (UPDs) or Fractional Cycle Biases (FCBs), are present in single-receiver positioning using carrier phase measurements (e.g. Geng et al. 2012; Li et al. 2013; Zhang et al. 2017). These are differences between hardware-dependent phase biases in the satellite and receiver, and thus need to be considered in order to enable ambiguity resolution. Detailed discussions of code and phase biases were given by, e.g., El-Mowafy et al. (2016) and Håkansson et al. (2017).

A dual-frequency AR-PPP solution requires, in theory, at least two biases (e.g. two code biases, two phase biases, one code and one phase bias, or a narrow-lane and a wide-lane bias). Formal explanations of the theory were given by, e.g., Teunissen and Khodabandeh (2015). Which and how many biases are used depends on how the solution provider sets up the solution.

The basic orbit/clock correction products required for RT-PPP solutions can be streamed from the IGS Real-Time Service (RTS) and are provided in the Radio Technical Commission for Maritime Services (RTCM) State Space Representation (SSR) message format (e.g. Hadas and Bosy 2015; Elsobeiey and Al-Harbi 2016; IGS 2019). In this study, the IGS real-time CLK91 stream generated by the French Space Agency (CNES) was selected to provide the required corrections for AR-RT-PPP (archived to use in simulated real time).

CLK91 contains real-time estimates of observation-specific GPS code and phase biases together with GPS orbit and clock corrections (Table 3). Because CLK91 is designed for both dual-frequency PPP and single-frequency PPP, it includes a GIM (message 1264) along with the code biases (1059) and phase biases (1265). This study utilized data in RINEX 2.11 format, which does not specify the tracking mode, and hence the RTKLIB software defaulted to using the C1C and C2W biases in this case. Consequently, for GPS processing, RTKLIB uses biases for C1C, C2W, L1C and L2W. Because the CLK91 corrections at the time did not contain the phase biases necessary to perform AR-RT-PPP using other GNSS constellations, this study was limited to GPS-only solutions.

Table 3. Selected IGS RTS correction messages and types for GPS-only AR-RT-PPP.

Correction	Message	Correction Type
CLK91	1060	GPS orbits/clocks
CLK91	1059	GPS code biases
CLK91	1265	GPS phase biases (L1/L2)

More-recent studies have shown that the so-called raw model (rather than the ionosphere-free model) can improve AR-PPP, and the CLK93 stream is designed to account for this parameterization (i.e. the biases are observation-specific rather than differential) as well as allowing multi-GNSS (e.g. Liu et al. 2017a; Wang et al. 2018).

Comparison with 24-hour Static Solution

The coordinate output from RTKLIB was provided in the ITRF2008 reference frame (Altamimi et al. 2011) and converted from X, Y and Z to East, North and Up (E, N, U) for easier real-world user analysis. For each of the 26 CORSnet-NSW sites, the output coordinates for each epoch were then compared with a 24-hour AUSPOS solution (post-processed differential GPS-only solution using IGS final orbits and surrounding CORS, see GA 2019a) in the same datum for DOY 173 to evaluate the quality of the AR-RT-PPP results.

The convergence time for each 24-hour AR-RT-PPP observation was recorded to the nearest 15 minutes for each coordinate component using the graphical RTKLIB output, along with an exact numerical value for the position determination using the RTKLIB position file output. Because it was necessary to consider coordinate differences of opposite signs, the Root Mean Square (RMS) of each coordinate component (E, N, U) was determined for all epochs after successful ambiguity resolution.

Results and Discussion

Results of Simulated Real-Time Processing

Table 4 lists the results obtained for three representative CORSnet-NSW sites, providing examples of good (Broken Hill, BKNL), average (Bathurst, BATH) and bad (Coffs Harbour, COFF) results in regards to convergence time. For each 24-hour session, Table 4 lists the RMS (1 sigma, calculated from the epoch-by-epoch differences from the 24-hour AUSPOS solution used as the ground truth) in each coordinate component, the percentage of ambiguity resolution (i.e. number of ambiguity-resolved epochs versus total number of epochs), and the time to convergence (TTC) – defined here as the time required for the position to converge to within 0.05 m of the ground truth, i.e. the nominal accuracy sought by the Positioning Australia program (GA 2019b) – for each coordinate component and the position (obtained from the RTKLIB output). DOY 194 is highlighted due to a much longer initialization time. Graphical representations of the RTKLIB processing results for BATH are shown in Figures 2-7. The discontinuities visible in the time series likely were due to cycle slips and changing satellite geometry, because these were GPS-only solutions with between 5 and 11 satellites visible at a time.

Table 4. Simulated AR-RT-PPP results for BATH, BKNL and COFF, showing RMS (1 sigma) in each coordinate component, percentage of ambiguity resolution (Fix) and time to convergence in each coordinate component as well as the position solution (Pos). DOY 194 is highlighted due to a much longer initialization time.

Station	DOY (2015)	RMS E (m)	RMS N (m)	RMS Up (m)	Fix (%)	TTC E (h:mm)	TTC N (h:mm)	TTC Up (h:mm)	TTC Pos (h:mm)
BATH	173	0.018	0.032	0.018	92.0	1:15	0:45	0:45	1:05
	178	0.020	0.035	0.019	82.8	1:00	0:45	0:45	0:42
	183	0.022	0.037	0.027	93.2	0:45	0:30	0:30	0:36
	186	0.020	0.033	0.006	96.9	0:45	0:45	0:45	0:29
	194	**0.007**	**0.007**	**0.022**	**79.8**	**4:15**	**2:00**	**2:00**	**4:06**
	198	0.029	0.015	0.050	76.1	0:45	0:30	0:30	0:26
BKNL	173	0.017	0.032	0.020	92.4	0:45	0:30	0:30	0:40
	178	0.019	0.036	0.017	90.0	0:45	0:30	0:30	0:29
	183	0.018	0.035	0.019	91.2	1:15	0:30	1:00	1:01
	186	0.018	0.032	0.006	90.7	1:00	1:00	1:00	0:44
	194	**0.010**	**0.010**	**0.032**	**76.7**	**4:00**	**1:45**	**1:30**	**4:02**
	198	0.026	0.014	0.053	80.1	0:45	0:30	0:30	0:39
COFF	173	0.017	0.028	0.048	94.4	2:00	2:00	1:00	1:15
	178	0.019	0.032	0.040	89.0	1:00	1:00	1:00	0:56
	183	0.017	0.027	0.069	91.5	1:00	1:00	1:00	0:50
	186	0.017	0.026	0.047	92.9	1:00	1:00	0:45	0:58
	194	**0.010**	**0.005**	**0.053**	**75.7**	**6:30**	**2:00**	**5:00**	**6:28**
	198	0.008	0.006	0.076	86.6	4:30	4:30	4:30	1:22

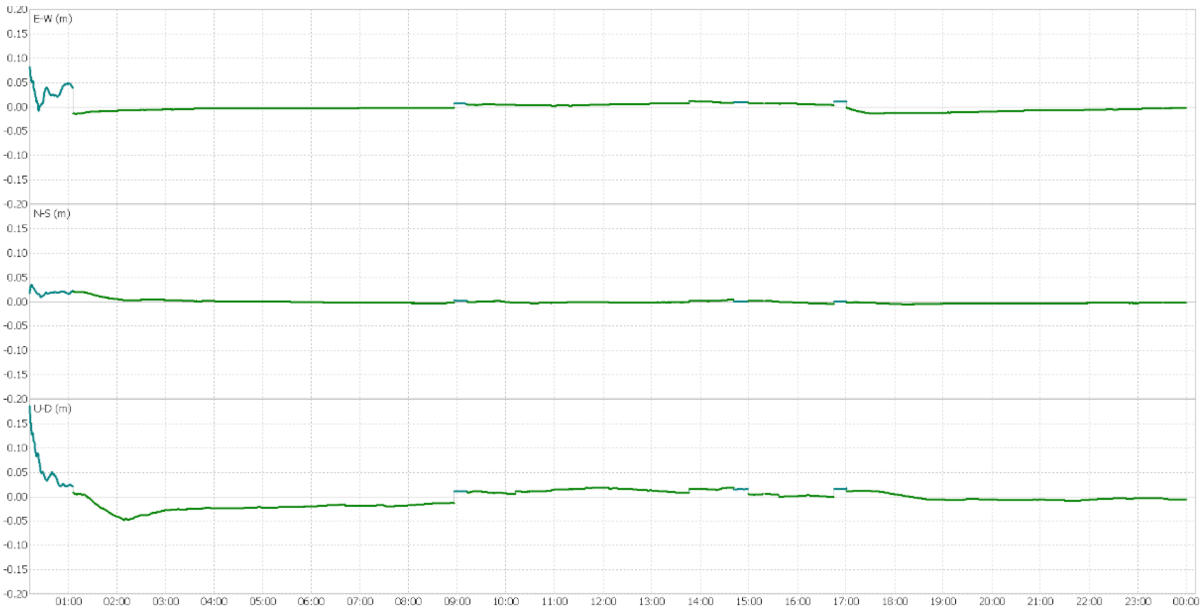

Figure 2. RTKLIB processing results, showing position differences from the mean position in the East (E-W), North (N-S) and Up (U-D) components over 24 hours (meters) versus time (hours), for BATH on DOY 173.

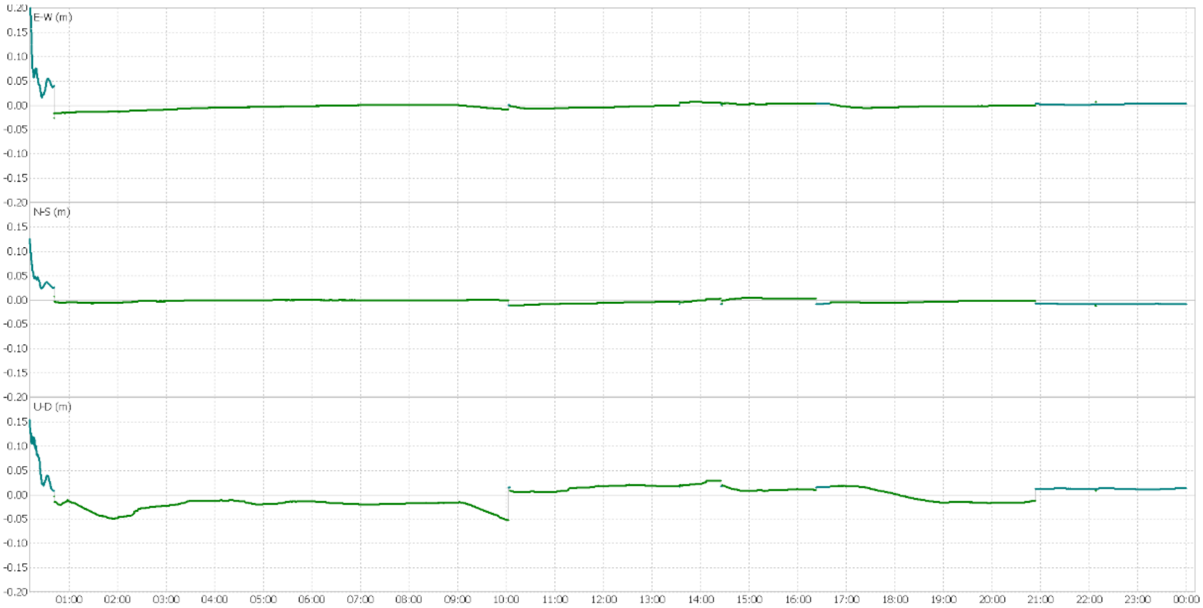

Figure 3. RTKLIB processing results, showing position differences from the mean position in the East (E-W), North (N-S) and Up (U-D) components over 24 hours (meters) versus time (hours), for BATH on DOY 178.

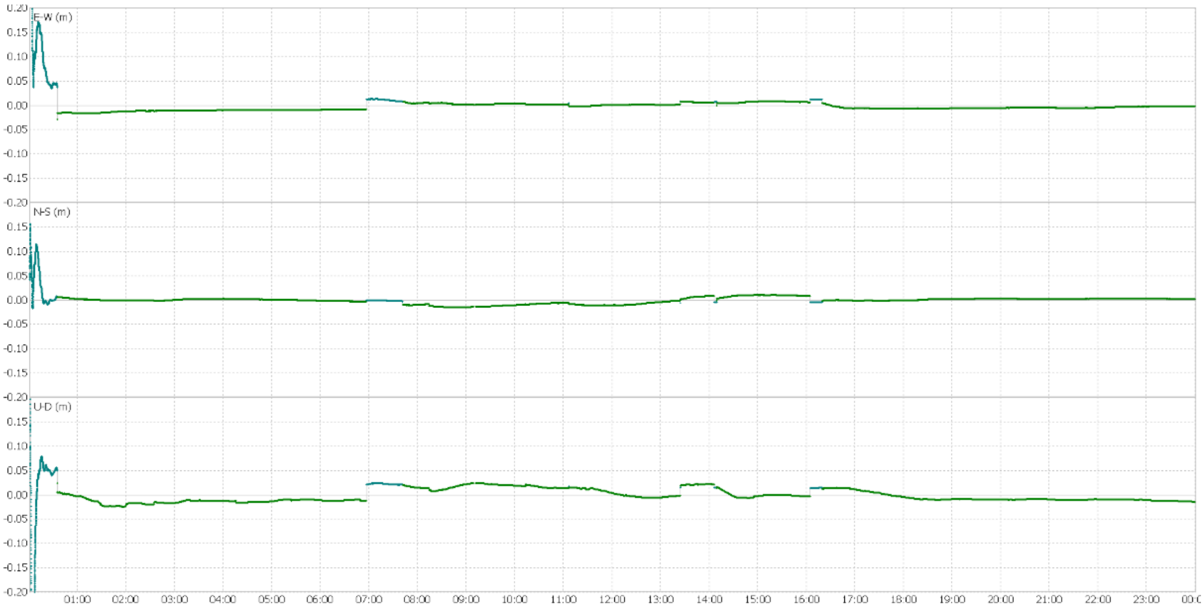

Figure 4. RTKLIB processing results, showing position differences from the mean position in the East (E-W), North (N-S) and Up (U-D) components over 24 hours (meters) versus time (hours), for BATH on DOY 183.

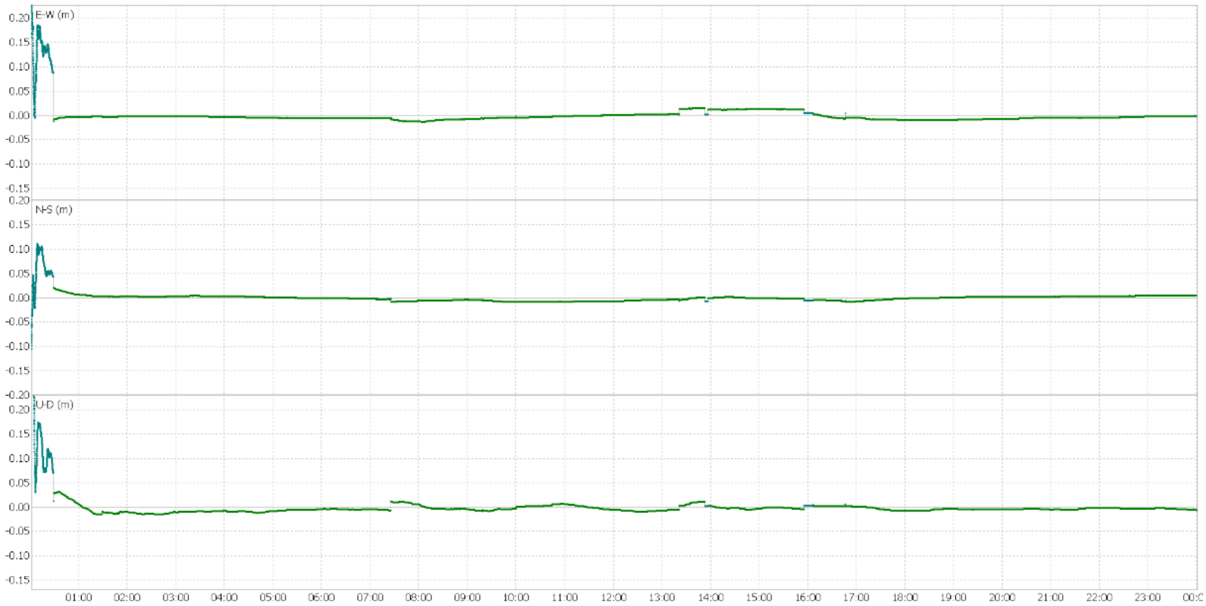

Figure 5. RTKLIB processing results, showing position differences from the mean position in the East (E-W), North (N-S) and Up (U-D) components over 24 hours (meters) versus time (hours), for BATH on DOY 186.

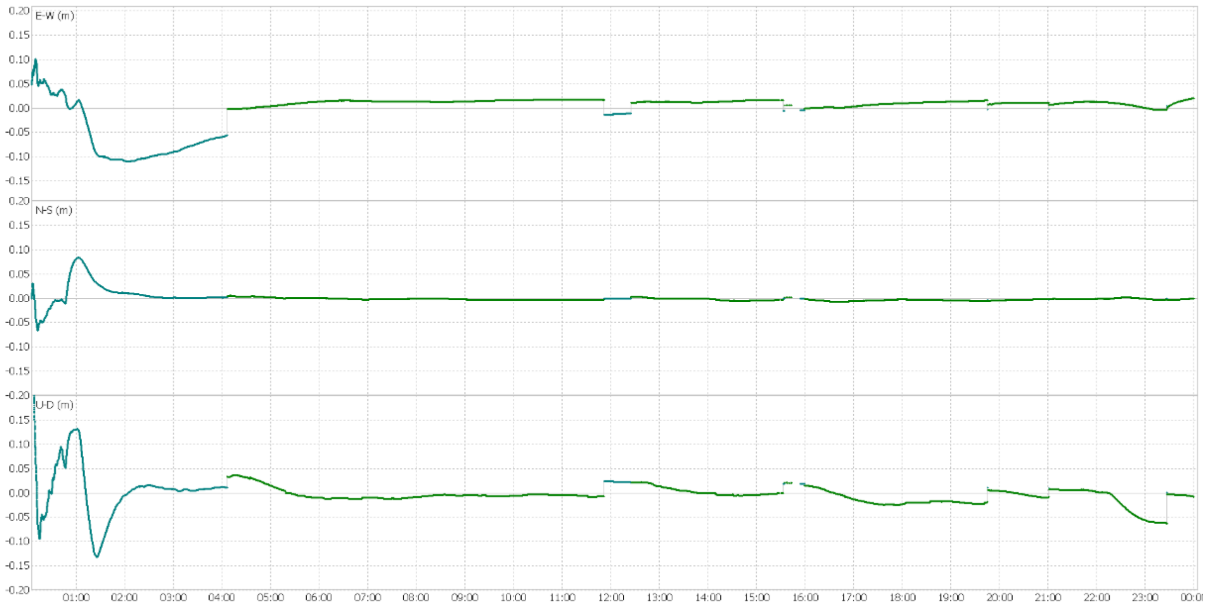

Figure 6. RTKLIB processing results, showing position differences from the mean position in the East (E-W), North (N-S) and Up (U-D) components over 24 hours (meters) versus time (hours), for BATH on DOY 194.

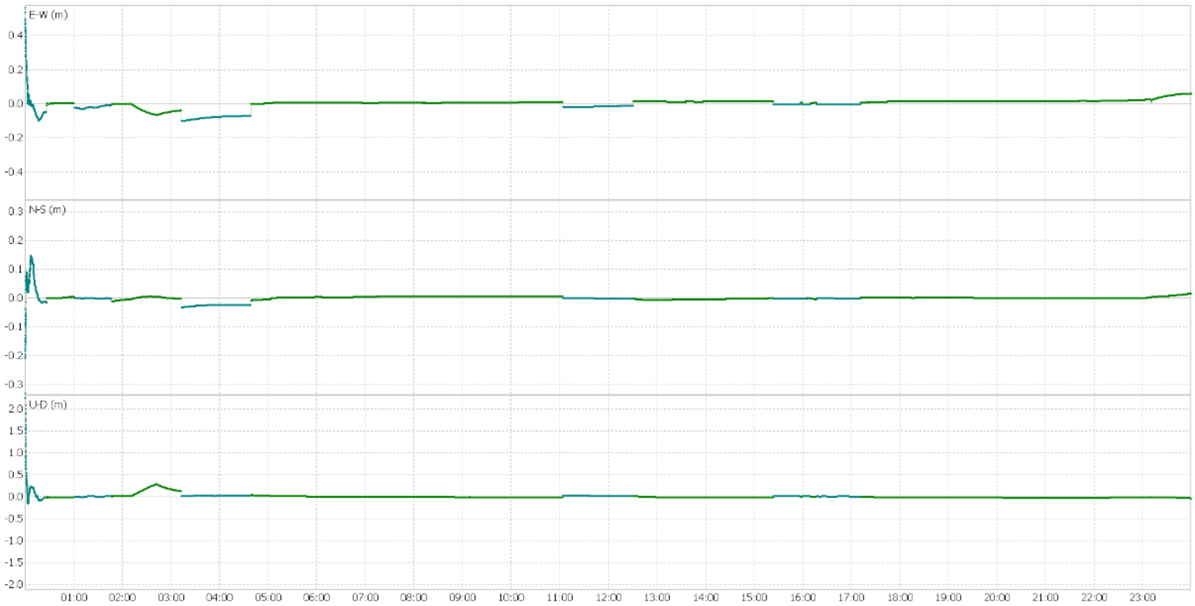

Figure 7. RTKLIB processing results, showing position differences from the mean position in the East (E-W), North (N-S) and Up (U-D) components over 24 hours (meters) versus time (hours), for BATH on DOY 198.

Investigating TTC versus Ionospheric Disturbances

Across the entire dataset, it was clearly evident that TTC values were as much as about 4 times slower for DOY 194 compared with all other days (e.g. 4 hours rather than 30-45 minutes). The ability to constrain and correctly predict the ionospheric delay is crucial in enabling integer ambiguity resolution for PPP (Collins and Bisnath 2011), and this study did not apply any external ionospheric corrections. Consequently, ionospheric disturbances may have hindered ambiguity resolution on that day. Because the Earth's geomagnetic field and the ionosphere are linked in complex ways, a disturbance in the geomagnetic field often causes a disturbance in the ionosphere through fluctuations in electron density. However, although DOY 194 (July 13, 2015) experienced heightened geomagnetic storm activity, so did DOY 173 (June 22, 2015), to an even larger extent (e.g. NOAA 2019; Space Weather Live 2019), but without such a negative effect on TTC.

The (planetary) Kp-index is the widely used global geomagnetic storm index and an excellent indicator of disturbances in the Earth's geomagnetic field. Figure 8 illustrates the daily Kp-index for June and July 2015 (the bars are intuitively colored according to low, medium, and high geomagnetic activity). The finalized Kp-index ranges from 0.0 to 9.0 and is expressed in a scale of thirds, i.e. it has 28 values including the use of +, o and − to indicate the finer grading. Figure 8 also shows the daily Ap-index (solid circles), which is derived from the Kp-index and provides a linear scale (ranging from 0 to 400) to aid interpretation. Along with substantial day-to-day fluctuations, the peaks on June 22, 2015 and July 13, 2015 are clearly visible.

Table 5 summarizes the indexes obtained on the observation days relevant to this study. Geomagnetic activity was at its peak on DOY 173 (June 22, 2015), but without equally negative effects on TTC. Consequently, although site-specific effects can be ruled out because this behavior was evident across all sites, it is not possible to conclusively attribute the large TTC experienced on DOY 194 to ionospheric disturbances. However, the Kp-index and Ap-index are global indexes, which are not able to describe regional or local variations in ionospheric activity. Although problems in the satellite signals or CLK91 corrections (i.e. orbits, clocks and biases) may have affected ambiguity resolution on that day, no such abnormalities were evident, and the reason for the slow convergence times on this day remains unexplained. Nevertheless, the TTC values of DOY 194 were considered to be nonrepresentative of the dataset and therefore were excluded from the average TTC results in Table 6.

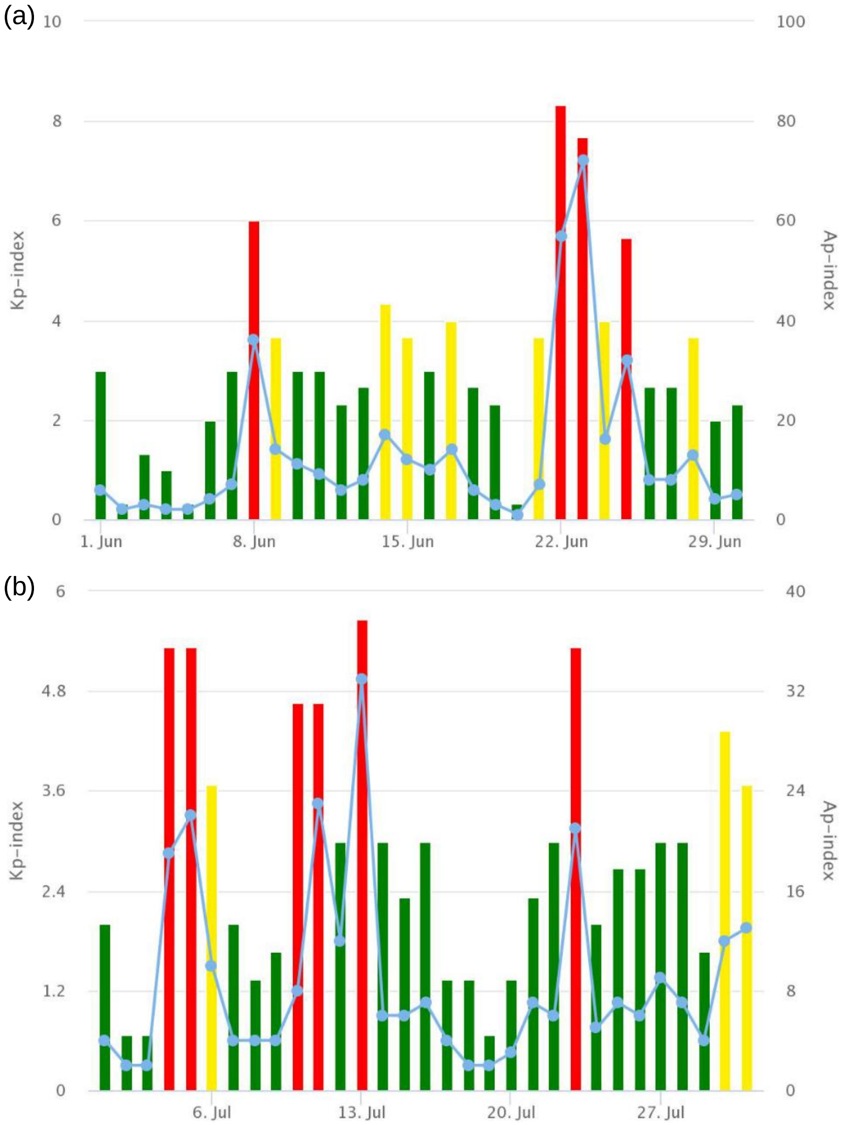

Figure 8. Daily Kp-index (bars) and Ap-index (dots) for (a) June 2015 and (b) July 2015, according to the finalized Kp-index of GeoForschungsZentrum (GFZ) Potsdam. (Data from Space Weather Live 2019.)

Table 5. Kp-index and Ap-index for the observation days considered. (Data from Space Weather Live 2019.)

Date	DOY	Kp-index	Ap-index
June 22, 2015	173	8+	57
June 27, 2015	178	3−	8
July 2, 2015	183	1−	2
July 5, 2015	186	5+	22
July 13, 2015	194	6−	33
July 17, 2015	198	1+	4

Discussion of Simulated AR-RT-PPP Results

Table 6 summarizes the average RMS (1 sigma) as well as TTC results for each coordinate component and position calculation across all 26 sites on the 6 days investigated (excluding DOY 194 for TTC). The average percentage of ambiguity resolution across the entire dataset was 84.3%.

These results are encouraging. RMS values of 0.018 m in East, 0.026 m in North and 0.063 m in Up are generally comparable to the coordinate quality typically expected and achieved using RTK/NRTK (e.g. Edwards et al. 2010; Janssen and Haasdyk 2011), converged (float) PPP solutions (e.g. Harima et al.

2014; Choy et al. 2015b) or the commercial Trimble RTX (PPP) product (e.g. Chen et al. 2011; Leandro et al. 2011). However, although the 84.3% ambiguity resolution success rate is promising, the average TTC was in the range of 40 minutes to 1 hour, i.e. far inferior to standard RTK/NRTK solutions or classical static solutions for medium-length baselines (< 25 km).

Table 6. Summary of results across 26 CORSnet-NSW sites (excluding DOY 194 for TTC), showing RMS values (1 sigma) for each coordinate component, TTC values for each coordinate component and the position solution (Pos).

	East	North	Up	Pos
Avg RMS (m)	0.018	0.026	0.063	−
Min RMS (m)	0.005	0.003	0.006	−
Max RMS (m)	0.049	0.041	0.181	−
Avg TTC (h:mm)	0:54	0:46	0:50	0:41
Min TTC (h:mm)	0:15	0:15	0:15	0:19
Max TTC (h:mm)	4:45	4:30	5:00	1:52

In addition, the variation in TTC was very apparent across the entire dataset. TTC can be good one day (or in one coordinate component) and bad the next (Table 4 and Figures 2-7) – this inconsistency is not desirable when using this technology in practice. Although the average TTC for position was 41 minutes, the TTC of the coordinate components can vary significantly. A minimum TTC of 15 minutes for each coordinate component and 19 minutes for position is promising but was not achieved on a routine basis, negatively affecting the reliability of this technology in practice at this stage.

Because the AR-RT-PPP positioning method is continuing to evolve and improve, the following developments may improve ambiguity resolution and reduce the convergence time to a more favorable level:

- Using multi-GNSS data (this study considered only GPS data) to increase the number of satellites in view and improve satellite geometry (e.g. Li et al. 2015; Ren et al. 2015; Deo and El-Mowafy 2016; Liu et al. 2017b).
- Using triple-frequency measurements from each GNSS constellation (this study considered only dual-frequency GPS data), e.g. by including the L5 signal for GPS (e.g. Geng and Bock 2013; Li et al. 2014a; Elsobeiey 2015).
- Using a high-resolution numerical weather prediction model to improve tropospheric delay modeling (e.g. Jensen and Ovstedal 2008; Wilgan et al. 2017).
- Using a regional ionospheric model generated by a sparse, regional CORS network (this study did not apply any external ionospheric corrections), while still having the advantage of not requiring a local CORS (e.g. Li et al. 2011, 2014b; Nardo et al. 2015).
- Using ionospheric constraints obtained via user-to-user (U2U), machine-to-machine (M2M) or rover-to-rover (R2R) type communication, i.e. if another user is in an area close enough to experience similar ionospheric delays, then the ionospheric delay already estimated by the neighboring rover can be used to allow fast convergence times by the new user (Collins et al. 2012). Although this method may seem unconventional, with the progress in the precise positioning industry it may not be long before this type of mechanism becomes feasible.
- Reverting to a classical initialization on a known point (e.g. Mozo et al. 2012).

It is expected that a combination of the aforementioned issues will need to be resolved in order to achieve ambiguity resolution times at an acceptable level (i.e. very few minutes) and a consistent rate (i.e. always) for practical applications. Only then, and once these developments have been incorporated into software packages and made available in a standard format to the user community, will AR-RT-PPP become an optional, but less accurate (0.05 m), alternative to RTK/NRTK positioning. As such, dense CORS networks will remain the gold standard for precise positioning for the foreseeable future.

Result Verification Using Actual Real-Time Data

To verify the results from the simulated AR-RT-PPP solution presented previously, actual real-time data were collected at a 1-second rate for a subset of CORSnet-NSW. This included BATH (DOY 105, April 15, 2014), Ivanhoe (IHOE) (DOY 116, April 26, 2014) and Tibooburra (TBOB) (DOY 106, April 16, 2014) (cf. Figure 1).

GPS-only positioning solutions were generated using the German Federal Agency for Cartography and Geodesy (BKG) Networked Transport of RTCM via Internet Protocol (NTRIP) client (BNC, see Weber et al. 2016) in AR-RT-PPP mode with the CNES CLK9B live stream (CNES 2019), the observation and ephemeris live streams from CORSnet-NSW (NSW Spatial Services 2019), and IGS antenna models (igs08_1745.atx).

Table 7 summarizes the results obtained for these CORSnet-NSW sites, compared with a 24-hour AUSPOS solution for the same day. The table includes the RMS (1 sigma, calculated from the epoch-by-epoch differences to the 24-hour AUSPOS solution used as ground truth) in each coordinate component, the percentage of ambiguity resolution, the time to convergence for position and the total observation length. The real-time AR-RT-PPP results were comparable with the simulated results, showing similar positioning quality, but the TTC values were not yet suitable for most precise positioning applications. It therefore is concluded that the simulated results are representative of the performance that can be obtained in real-time operation.

Table 7. Real-time AR-RT-PPP results for BATH, IHOE and TBOB, showing RMS (1 sigma) in each coordinate component, percentage of ambiguity resolution (Fix), time to convergence (TTC) for position solution and observation length.

Station	DOY (2014)	RMS E (m)	RMS N (m)	RMS Up (m)	Fix (%)	TTC (h:mm)	Observation Length (h:mm)
BATH	105	0.020	0.019	0.047	90.5	1:08	11:23
IHOE	116	0.041	0.029	0.055	95.4	1:00	21:39
TBOB	106	0.025	0.024	0.081	90.4	1:33	15:32

AR-RT-PPP as Potential Fill-In Service for Sparse CORS Networks

The results of this study showed the possible future potential of ARRT-PPP as an alternative, but lower-accuracy, positioning method. However, it also is clear that it is not yet a suitable option for practical applications, primarily due to the long and inconsistent ambiguity resolution times achievable at the moment.

The advantages of AR-RT-PPP include achieving positioning at a level of better than 0.05 m (as evidenced by previous studies and the data presented here), improving convergence times over traditional (float) PPP, and not requiring a connection to a local or regional CORS network (which is particularly useful in remote areas). Because local (RTK/NRTK) corrections are not required, computational efficiency is increased and the feasibility of correction delivery via satellite is higher, i.e. the required global or regional corrections can be broadcast from a geostationary (GEO) satellite requiring a relatively small amount of bandwidth while covering a large footprint.

RTK/NRTK-type corrections typically are updated every second and given in the Observation Space Representation (OSR), i.e. they use GNSS observations of an actual reference station that are transmitted to and applied by the user's rover. AR-RT-PPP or PPP-RTK corrections, on the other hand, can be given in the State Space Representation (SSR), i.e. a functional (and optional stochastic) description of the individual GNSS error components. One important benefit of SSR corrections is the lower bandwidth requirement because the dynamics of different parameters can be utilized to optimize the bandwidth through identifying required parameter ranges and varying update rates. Consequently, these dynamic models (used at the network side) reduce the number of parameters to be sent to the user. A detailed discussion of the benefits and delivery options of SSR corrections was given by Wübbena et al. (2005). Discussions of dynamic models used at the network side were given by, e.g., Odijk et al. (2016).

However, several limitations still remain, primarily the long and inconsistent convergence times needed to resolve ambiguities, currently restricting the use of AR-RT-PPP for practical applications. The convergence time could be minimized to RTK standards through a regional CORS network aiding better prediction of the ionospheric delay.

This leads to the question of whether AR-RT-PPP has the potential to be used as a fill-in service for sparse CORS networks in areas where dense CORS coverage is not justified due to low population density or for economic reasons (such as in developing nations), or in areas with intermittent or lacking mobile internet coverage. Currently, the only advantage that AR-RT-PPP has over RTK/NRTK is that it does not require a local/regional CORS network. This also allows AR-RT-PPP corrections (e.g. precise orbit/clock corrections, phase biases, ionospheric corrections or tropospheric corrections) to be distributed by a satellite-based delivery system, such as a Satellite-Based Augmentation System (SBAS), opening up the use of AR-RT-PPP in areas with intermittent or lacking mobile internet coverage.

However, in today's society, convergence and/or ambiguity resolution times greater than a few minutes will not suffice in practice. The ability to constrain and correctly predict the ionospheric delay remains a key factor in enabling integer ambiguity resolution for PPP (Collins and Bisnath 2011). It therefore is unlikely that AR-RT-PPP using a global or wide-area CORS network will become as effective as short/medium-baseline RTK or NRTK techniques, due to the difficulty in providing sufficiently precise ionospheric corrections for the foreseeable future.

A regional CORS network with an interstation spacing of the order of a few hundred kilometers (and preferably much less), e.g. a subset of CORSnet-NSW sites, has the potential to significantly improve the modeling of the spatial variability of the ionosphere. Because the accuracy requirements for such ionospheric corrections are very challenging, this currently requires a dense, well-distributed CORS network similar to that used for NRTK services. However, such downscaling of PPP from using global to local/regional CORS infrastructure in order to provide high-resolution atmospheric corrections will compromise the unique characteristic of PPP as a global, wide-area precise positioning technique. Hence, further work is required to allow AR-RT-PPP to become a viable solution for providing a fill-in service for sparse CORS networks in precise positioning applications.

Conclusion

This paper investigated the potential of Ambiguity-Resolved Real-Time PPP using six 24-hour datasets spanning a 4-week period, collected at each of 26 CORSnet-NSW sites distributed across New South Wales, Australia. Based on this extensive dataset, involving almost 13.5 million calculated positions, it was found that AR-RT-PPP is achievable, on average providing positioning quality at the few-centimeter level (RMS of 0.018 m in East, 0.026 m in North, and 0.063 m in Up) with an average ambiguity resolution success rate of 84.3%. Although the average time to convergence was in the range of 40 minutes to 1 hour (with a minimum TTC for position of 19 minutes), significant inconsistencies were apparent, with TTC values varying from 15 minutes to 5 hours between the 24-hour datasets (and coordinate components). These simulated real-time results were verified using actual real-time data collected at a subset of CORSnet-NSW sites.

Although the results are encouraging, AR-RT-PPP currently is not able to provide a viable option for practical applications requiring centimeter-level positioning. This is due primarily to the long and inconsistent ambiguity resolution times currently achievable. However, it is expected that ongoing development will improve the speed, quality and reliability of the AR-RT-PPP technique in the future. To become a feasible positioning alternative in practice, it is expected that AR-RT-PPP solutions must be precise and reliable in a few minutes or less. The authors believe that it then will have the potential to provide a fill-in service to RTK/NRTK positioning in remote areas lacking mobile internet coverage or where the establishment of a local CORS network cannot be justified.

Data Availability Statement

Some or all data, models, or code used during the study were provided by a third party (modified RTKLIB software, real-time correction products). Direct requests for these materials may be made to the provider as indicated in the Acknowledgments.

Acknowledgments

Dr Ken Harima of RMIT University, Melbourne, is gratefully acknowledged for providing the modified RTKLIB software used in this study. The International GNSS Service is thanked for providing the real-time correction products required for PPP processing.

References

Altamimi, Z., Collilieux, X., and Métivier, L. (2011). "ITRF2008: An improved solution of the International Terrestrial Reference Frame." *J. Geod.*, 85(8), 457-473. https://doi.org/10.1007/s00190-011-0444-4.

Bisnath, S., and Collins, P. (2012). "Recent developments in Precise Point Positioning." *Geomatica*, 66(2), 103-111. https://doi.org/10.5623/cig2012-023.

Chang, X.-W., Yang, X., and Zhou, T. (2005). "MLAMBDA: A modified LAMBDA method for integer least-squares estimation." *J. Geod.*, 79(9), 552-565. https://doi.org/10.1007/s00190-005-0004-x.

Chen, X., Allison, T., Cao, W., Ferguson, K., Grünig, S., Gomez, V., Kipka, A., Köhler, J., Landau, H., Leandro, R., Lu, G., Stolz, R., and Talbot, N. (2011). "Trimble RTX, an innovative new approach for Network RTK." In *Proc., ION GNSS 2011*, 2214-2219. Manassas, VA: Institute of Navigation.

Choy, S., Bisnath, S., and Rizos, C. (2017). "Uncovering common misconceptions in GNSS Precise Point Positioning and its future prospect." *GPS Solut.*, 21(1), 13-22. https://doi.org/10.1007/s10291-016-0545-x.

Choy, S., Harima, K., Choudhury, M., Rizos, C., and Kogure, S. (2015a). "Real-time Precise Point Positioning using QZSS LEX augmentation corrections in Australia." In *Proc., Int. Symp. on GNSS 2015 (ISGNSS2015)*. Tokyo: Institute of Positioning, Navigation and Timing of Japan.

Choy, S., Harima, K., Li, Y., Choudhury, M., Rizos, C., Wakabayashi, Y., and Kogure, S. (2015b). "GPS Precise Point Positioning with the Japanese Quasi-Zenith Satellite System LEX augmentation corrections." *J. Navig.*, 68(4), 769-783. https://doi.org/10.1017/S0373463314000915.

CNES (French Space Agency). (2019). "The PPP-WIZARD project." Accessed October 21, 2019. http://www.ppp-wizard.net/caster.html.

Collins, P., and Bisnath, S. (2011). "Issues in ambiguity resolution for Precise Point Positioning." In *Proc., ION GNSS 2011*, 679-687. Manassas, VA: Institute of Navigation.

Collins, P., Bisnath, S., Lahaye, F., and Heroux, P. (2010). "Undifferenced GPS ambiguity resolution using the decoupled clock model and ambiguity datum fixing." *Navigation*, 57(2), 123-135. https://doi.org/10.1002/j.2161-4296.2010.tb01772.x.

Collins, P., Lahaye, F., and Bisnath, S. (2012). "External ionospheric constraints for improved PPP-AR initialisation and a generalised local augmentation concept." In *Proc., ION GNSS 2012*, 3055-3065. Manassas, VA: Institute of Navigation.

Deo, M., and El-Mowafy, A. (2016). "Triple frequency Precise Point Positioning with multi-constellation GNSS." In *Proc., Int. GNSS Soc. Symp. (IGNSS2016)*. Sydney, Australia: International GNSS Society.

Edwards, S. J., Clarke, P. J., Penna, N. T., and Goebell, S. (2010). "An examination of Network RTK GPS services in Great Britain." *Surv. Rev.*, 42(316), 107-121. https://doi.org/10.1179/003962610X12572516251529.

El-Mowafy, A., Deo, M., and Rizos, C. (2016). "On biases in Precise Point Positioning with multi-constellation and multi-frequency GNSS data." *Meas. Sci. Technol.*, 27(3), 035102. https://doi.org/10.1088/0957-0233/27/3/035102.

Elsobeiey, M. (2015). “Precise Point Positioning using triple-frequency GPS measurements.” *J. Navig.*, 68(3), 480-492. https://doi.org/10.1017/S0373463314000824.

Elsobeiey, M., and Al-Harbi, S. (2016). “Performance of real-time Precise Point Positioning using IGS real-time service.” *GPS Solut.*, 20(3), 565-571. https://doi.org/10.1007/s10291-015-0467-z.

GA (Geoscience Australia). (2019a). “AUSPOS – Online GPS processing service.” Accessed October 21, 2019. http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/auspos.

GA (Geoscience Australia). (2019b). “Positioning Australia.” Accessed October 21, 2019. https://www.ga.gov.au/scientific-topics/positioning-navigation/positioning-australia.

Gao, Y., and Kongzhe, C. (2004). “Performance analysis of Precise Point Positioning using real-time orbit and clock products.” *J. Global Positioning Syst.*, 3(1-2), 95-100. https://doi.org/10.5081/jgps.3.1.95.

Ge, M., Gendt, G., Rothacher, M., Shi, C., and Liu, L. (2008). “Resolution of GPS carrier-phase ambiguities in Precise Point Positioning (PPP) with daily observations.” *J. Geod.*, 82(7), 389-399. https://doi.org/10.1007/s00190-007-0187-4.

Geng, J., and Bock, Y. (2013). “Triple-frequency GPS precise point positioning with rapid ambiguity resolution.” *J. Geod.*, 87(5), 449-460. https://doi.org/10.1007/s00190-013-0619-2.

Geng, J., Meng, X., Dodson, A. H., and Teferle, F. N. (2010). “Integer ambiguity resolution in Precise Point Positioning: Method comparison.” *J. Geod.*, 84(9), 569-581. https://doi.org/10.1007/s00190-010-0399-x.

Geng, J., Shi, C., Ge, M., Dodson, A. H., Lou, Y., Zhao, Q., and Liu, J. (2012). “Improving the estimation of fractional-cycle biases for ambiguity resolution in precise point positioning.” *J. Geod.*, 86(8), 579-589. https://doi.org/10.1007/s00190-011-0537-0.

Geng, J., Teferle, F. N., Meng, X., and Dodson, A. H. (2011). “Towards PPP-RTK: Ambiguity resolution in real-time Precise Point Positioning.” *Adv. Space Res.*, 47(10), 1664-1673. https://doi.org/10.1016/j.asr.2010.03.030.

Grinter, T., and Roberts, C. (2011). “Precise Point Positioning: Where are we now?” In *Proc., Int. GNSS Soc. Symp. (IGNSS2011)*. Sydney, Australia: International GNSS Society.

Grinter, T., and Roberts, C. (2013). “Real time Precise Point Positioning: Are we there yet?” In *Proc., Int. GNSS Soc. Symp. (IGNSS2013)*. Sydney, Australia: International GNSS Society.

Hadas, T., and Bosy, J. (2015). “IGS RTS precise orbits and clocks verification and quality degradation over time.” *GPS Solut.*, 19(1), 93-105. https://doi.org/10.1007/s10291-014-0369-5.

Håkansson, M., Jensen, A. B. O., Horemuz, M., and Hedling, G. (2017). “Review of code and phase biases in multi-GNSS positioning.” *GPS Solut.*, 21(3), 849-860. https://doi.org/10.1007/s10291-016-0572-7.

Harima, K., Choy, S., Li, Y., Grinter, T., Choudhury, M., Rizos, C., Wakabayashi, Y., and Satoshi, K. (2014). “Performance of real-time Precise Point Positioning using MADOCA-LEX augmentation messages.” In *Proc., XXV FIG Int. Congress (FIG2014)*. Copenhagen, Denmark: International Federation of Surveyors.

Heroux, P., and Kouba, J. (1995). “GPS precise point positioning with a difference.” In *Proc., Geomatics ’95*. Sidney, BC: Natural Resources Canada.

IGS (International GNSS Service). (2019). “Real-time service.” Accessed October 21, 2019. http://www.igs.org/rts/products.

Janssen, V., and Haasdyk, J. (2011). “Assessment of Network RTK performance using CORSnet-NSW.” In *Proc., Int. GNSS Soc. Symp. (IGNSS2011)*. Sydney, Australia: International GNSS Society.

Janssen, V., Haasdyk, J., and McElroy, S. (2016). “CORSnet-NSW: A success story.” In *Proc., Association of Public Authority Surveyors Conf. (APAS2016)*, 10-28. Bathurst, Australia: Association of Public Authority Surveyors.

Jensen, A. B. O., and Ovstedal, O. (2008). “The effect of different tropospheric models on Precise Point Positioning in kinematic mode.” *Surv. Rev.*, 40(308), 173-187. https://doi.org/10.1179/003962608X290979.

Kouba, J. (2015). “A guide to using the IGS products.” Accessed October 21, 2019. http://kb.igs.org/hc/en-us/articles/201271873-A-Guide-to-Using-the-IGS-Products.

Laurichesse, D., Mercier, F., Berthias, J. P., Broca, P., and Cerri, L. (2009). "Integer ambiguity resolution on undifferenced GPS phase measurements and its application to PPP and satellite precise orbit determination." *Navigation*, 56(2), 135-149. https://doi.org/10.1002/j.2161-4296.2009.tb01750.x.

Leandro, R., Landau, H., Nitschke, M., Glocker, M., Seeger, S., Chen, X., Deking, A., BenTahar, M., Zhang, F., Ferguson, K., Stolz, R., Talbot, N., Lu, G., Allison, T., Brandl, M., Gomez, V., Cao, W., and Kipka, A. (2011). "RTX positioning: The next generation of cm-accuracy real-time GNSS positioning." In *Proc., ION GNSS 2011*, 1460-1475. Manassas, VA: Institute of Navigation.

Li, T., Wang, J., and Laurichesse, D. (2014a). "Modeling and quality control for reliable precise point positioning integer ambiguity resolution with GNSS modernization." *GPS Solut.*, 18(3), 429-442. https://doi.org/10.1007/s10291-013-0342-8.

Li, X., Ge, M., Dai, X., Ren, X., Fritsche, M., Wickert, J., and Schuh, H. (2015). "Accuracy and reliability of multi-GNSS real-time precise positioning: GPS, GLONASS, BeiDou, and Galileo." *J. Geod.*, 89(6), 607-635. https://doi.org/10.1007/s00190-015-0802-8.

Li, X., Ge, M., Dousa, J., and Wickert, J. (2014b). "Real-time precise point positioning regional augmentation for large GPS reference networks." *GPS Solut.*, 18(1), 61-71. https://doi.org/10.1007/s10291-013-0310-3.

Li, X., Ge, M., Zhang, H., and Wickert, J. (2013). "A method for improving uncalibrated phase delay estimation and ambiguity-fixing in real-time precise point positioning." *J. Geod.*, 87(5), 405-416. https://doi.org/10.1007/s00190-013-0611-x.

Li, X., Zhang, X., and Ge, M. (2011). "Regional reference network augmented precise point positioning for instantaneous ambiguity resolution." *J. Geod.*, 85(3), 151-158. https://doi.org/10.1007/s00190-010-0424-0.

Liu, T., Yuan, Y., Zhang, B., Wang, N., Tan, B., and Chen, Y. (2017a). "Multi-GNSS precise point positioning (MGPPP) using raw observations." *J. Geod.*, 91(3), 253-268. https://doi.org/10.1007/s00190-016-0960-3.

Liu, Y., Ye, S., Song, W., Lou, Y., and Chen, D. (2017b). "Integrating GPS and BDS to shorten the initialization time for ambiguity-fixed PPP." *GPS Solut.*, 21(2), 333-343. https://doi.org/10.1007/s10291-016-0525-1.

Mozo, A., Calle, J. D., Navarro, P., Piriz, R., Rodriguez, D., and Tobias, G. (2012). "Demonstrating in-the-field real-time precise positioning." In *Proc., ION GNSS 2012*, 3066-3076. Manassas, VA: Institute of Navigation.

Nardo, A., Drescher, R., Brandl, M., Chen, X., Landau, H., Rodriguez-Solano, C., Seeger, S., and Weinbach, U. (2015). "Experiences with Trimble CenterPoint RTX with fast convergence." In *Proc., European Navigation Conf. (ENC2015)*. Prague, Czech Republic: European Global Navigation Satellite Systems Agency.

NOAA (National Oceanic and Atmospheric Administration Space Weather Prediction Center). (2019). "Alerts, watches and warnings." Accessed October 21, 2019. https://www.swpc.noaa.gov/products/alerts-watches-and-warnings.

NSW Spatial Services. (2019). "CORSnet-NSW." Accessed October 21, 2019. http://www.corsnet.com.au/.

Odijk, D., Khodabandeh, A., Nadarajah, N., Choudhury, M., Zhang, B., Li, W., and Teunissen, P. J. G. (2017). "PPP-RTK by means of S-system theory: Australian network and user demonstration." *J. Spatial Sci.*, 62(1), 3-27. https://doi.org/10.1080/14498596.2016.1261373.

Odijk, D., Zhang, B., Khodabandeh, A., Odolinski, R., and Teunissen, P. J. G. (2016). "On the estimability of parameters in undifferenced, uncombined GNSS network and PPP-RTK user models by means of S-system theory." *J. Geod.*, 90(1), 15-44. https://doi.org/10.1007/s00190-015-0854-9.

Ren, X., Choy, S., Harima, K., and Zhang, X. (2015). "Multi-constellation GNSS Precise Point Positioning using GPS, GLONASS and BeiDou in Australia." In *Proc., Int. GNSS Soc. Symp. (IGNSS2015)*. Sydney, Australia: International GNSS Society.

Rizos, C., Janssen, V., Roberts, C., and Grinter, T. (2012). "Precise Point Positioning: Is the era of differential GNSS positioning drawing to an end?" In *Proc., FIG Working Week 2012*. Copenhagen, Denmark: International Federation of Surveyors.

Space Weather Live. (2019). "The aurora and solar activity archive." Accessed October 21, 2019. https://www.spaceweatherlive.com/en/archive.

Takasu, T. (2013). "RTKLIB: An open source program package for GNSS processing." Accessed October 21, 2019. http://www.rtklib.com/.

Takasu, T., and Yasuda, A. (2009). "Development of the low-cost RTK-GPS receiver with an open source program package RTKLIB." In *Proc.*, *Int. Symp. on GPS/GNSS 2009*. Daejeon, South Korea: Chungnam National Univ.

Teunissen, P. J. G., and Khodabandeh, A. (2015). "Review and principles of PPP-RTK methods." *J. Geod.*, 89(3), 217-240. https://doi.org/10.1007/s00190-014-0771-3.

Verhagen, S. (2005). "On the reliability of integer ambiguity resolution." *Navigation*, 52(2), 99-110. https://doi.org/10.1002/j.2161-4296.2005.tb01736.x.

Wang, Z., Li, Z., Wang, L., Wang, X., and Yuan, H. (2018). "Assessment of multiple GNSS real-time SSR products from different analysis centers." *ISPRS Int. J. Geo-Inf.*, 7(3), 85. https://doi.org/10.3390/ijgi7030085.

Weber, G., Mervart, L., Stürze, A., Rülke, A., and Stöcker, D. (2016). *BKG Ntrip Client (BNC), version 2.12*. Frankfurt, Germany: Federal Agency for Cartography and Geodesy (BKG).

Wilgan, K., Hadas, T., Hordyniec, P., and Bosy, J. (2017). "Real-time precise point positioning augmented with high-resolution numerical weather prediction model." *GPS Solut.*, 21(3), 1341-1353. https://doi.org/10.1007/s10291-017-0617-6.

Wübbena, G., Schmitz, M., and Bagge, A. (2005). "PPP-RTK: Precise Point Positioning using state-space representation in RTK networks." In *Proc.*, *ION GNSS 2005*, 2584-2594. Manassas, VA: Institute of Navigation.

Zhang, B., Teunissen, P. J. G., and Yuan, Y. (2017). "On the short-term temporal variations of GNSS receiver differential phase biases." *J. Geod.*, 91(5), 563-572. https://doi.org/10.1007/s00190-016-0983-9.

Zumberge, J. F., Heflin, M. B., Jefferson, D. C., Watkins, M. M., and Webb, F. H. (1997). "Precise Point Positioning for the efficient and robust analysis of GPS data from large networks." *J. Geophys. Res.*, 102(B3), 5005-5017. https://doi.org/10.1029/96JB03860.