Positioning Accuracy of Single Frequency GNSS PPP by CLAS Comparing with MADOCA Products

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Abstract

In this paper, we present the single frequency PPP algorithms based on our GR models with applying CLAS (Centimeter Level Augmentation Service) data from Japan Quasi-Zenith-Satellite-System (QZSS), comparing with the positioning results applying the MADOCA (Multi-GNSS Advanced Demonstration tool for Orbit and Clock Analysis) Products which had been developed by JAXA (Japan Aerospace Exploration Agency) and are provided by GPAS (Global Positioning Augmentation Service Corporation). Throughout the numerical experiments the total 3DMMS error by applying CLAS is approximately 0.28 [m], in contrary with the total 3DMMS error by applying MADOCA Products is being approximately 0.52 [m].

1 Introduction

In this paper, we implement the satellite orbits and clocks correction data from the CLAS [1] or MADOCA Products [2]-[3] into our PPP algorithms. Additionally, Ionosphere delay is obtained from CLAS or GIM. and Tropospheric delay is obtained from CLAS or Saastamoinen model.

First of all, we review the previous PPP algorithms based on Global navigation satellite system Regression models (referred as GR models) which have been developed in [4]-[5]. By presenting GR equations according to [4]-[5], we derive single frequency PPP algorithms. Then, we show the experimental results of positioning accuracy of using CLAS with comparing MADOCA Products.

2 Measurement Model

Similarly to [5], we only describe the case of L1 frequency GNSS Regression (GR) models for the observed positioning data consisting of L1 carrier phases and pseudoranges based on C/A code due to simpler description and the commercial usage of positioning. Namely, we consider the following fundamental measurements of L1 band carrier phases $\Phi_{L1,u}^p(t)$ and the pseudoranges $\rho_{CA,u}^p(t)$ based on C/A codes, respectively, as follows:

$$\begin{aligned} \rho_{CA,u}^p(t) &= r_u^p(t, t - \tau_u^p) + c[\delta t_u(t) - \delta t^p(t - \tau_u^p)] \\ &\quad + \delta I_u^p(t) + \delta T_u^p(t) + \delta b_{CA}^p + d_{rel}^p \\ &\quad + \Delta p_{ant} + e_{CA,u}^p(t), \end{aligned} \quad (1)$$

$$\begin{aligned} \Phi_{L1,u}^p(t) &= \lambda_1 \varphi_{L1,u}^p(t) \\ &= r_u^p(t, t - \tau_u^p) + c[\delta t_u(t) - \delta t^p(t - \tau_u^p)] \\ &\quad - \delta I_u^p(t) + \delta T_u^p(t) + \delta b_{L1}^p + d_{rel}^p \\ &\quad + \Delta p_{ant} + \lambda_1(N_{L1,u}^p + \Delta \phi_{L1,u}^p) \\ &\quad + \lambda_1 \varepsilon_{L1,u}^p(t). \end{aligned} \quad (2)$$

In (1)-(2), $r_u^p(t, t - \tau_u^p)$ is the geometric distance between the receiver u at the time t and the satellite p at the time $t - \tau_u^p$ (τ_u^p denotes the travel time from the satellite p ($p = 1, \dots, n_s$) to the receiver u). Namely, $r_u^p(t) \equiv r_u^p(t, t - \tau_u^p) = \|u(t) - s^p(t - \tau_u^p)\|$, where $u \equiv [x_u, y_u, z_u]^T$ and $s^p \equiv [x^p, y^p, z^p]^T$ are the user (unknown) and satellite positions, respectively. Also, c ($\approx 2.99792458 \times 10^8$ [m]) denotes the speed of light, (δt_u) and (δt^p) are the receiver and satellite clock errors respectively, (δI_u^p) is the Ionosphere delay, (δT_u^p) is the Tropospheric delay, $f_1 (= 1575.42$ [MHz]) and λ_1 are the central frequency and the wave length of the L1 carrier wave, (δb_{CA}^p) and (δb_{L1}^p) are the code bias and the phase bias respectively for the satellite p . (d_{rel}^p) is relativistic delay [m]. (Δp_{ant}) is antenna phase center offsets (PCO) and antenna phase center variation (PCV) [m]. $(N_{L1,u}^p)$ denotes integer ambiguity between the satellite p and the receiver u , $(\Delta \phi_{L1,u}^p)$ is the phase wind up correction and e and ε denote measurement errors.

Then, we take the 1st order Taylor series approximation around the previous estimated value $u = \hat{u}$ and $s^p = \hat{s}^p$ such that we have the GR equations [5]:

$$\begin{aligned} \rho_{CA,u}^p &\cong g_u^p(u - s^p) \\ &\quad + c(\delta t_u - \delta t^p) \\ &\quad + \delta I_u^p(t) + \delta T_u^p(t) + \delta b_{CA}^p \\ &\quad + d_{rel}^p + \Delta p_{ant} + e_{CA,u}^p(t), \end{aligned} \quad (3)$$

$$\begin{aligned} \Phi_{L1,u}^p &\cong g_u^p(u - s^p) \\ &\quad + c(\delta t_u - \delta t^p) \\ &\quad - \delta I_u^p(t) + \delta T_u^p(t) + \delta b_{L1}^p \\ &\quad + d_{rel}^p + \Delta p_{ant} \\ &\quad + \lambda_1(N_{L1,u}^p + \Delta \phi_{L1,u}^p) + \lambda_1 \varepsilon_{L1,u}^p(t) \end{aligned} \quad (4)$$

where,

$$g_{\hat{u}}^{\hat{p}} \equiv \left[\frac{\partial r_u^p}{\partial \hat{u}} \right]_{u=\hat{u}, s^p=\hat{s}^p}^T = \frac{(\hat{u} - \hat{s}^p)^T}{\|\hat{u} - \hat{s}^p\|}.$$

The parameters in GR models; (3)-(4) are provided from CLASLIB(SSR2OSR) and MADOCA Products. The satellite position (s^p) and clock errors (δt^p) are obtained by CLASLIB(SSR2OSR) or MADOCA Products. Ionosphere delay (δI_u^p), Tropospheric delay (δT_u^p), the code bias (δb_{CA}^p), the phase bias (δb_{L1}^p) for the satellite p , the relativistic delay (d_{rel}^p), respectively, and the antenna phase center variation (ant, Δp_{ant}) are obtained from CLASLIB(SSR2OSR). Finally, the receiver position u , receiver clock error (δt_u) and the interger ambiguity ($N_{L1,u}^p$) are estimated by applying the Kalman filters.

Also, we have the following vector regression equation:

$$y_t = H_t x_t + v_t \quad (5)$$

where,

$$y_t \equiv \begin{bmatrix} \rho_{CA,u}^p \\ \Phi_{L1,u}^p \end{bmatrix}, \quad H_t \equiv \begin{bmatrix} G_{\hat{u}}^{\hat{p}} & \mathbf{1} & O \\ G_{\hat{u}}^{\hat{p}} & \mathbf{1} & \lambda_1 I \end{bmatrix},$$

$$x_t \equiv \begin{bmatrix} u \\ c\delta t_u \\ N_{L1,u} \end{bmatrix}, \quad v_t \equiv \begin{bmatrix} e_{CA,u}^p \\ \varepsilon_{L1,u}^p \end{bmatrix}.$$

where, $\mathbf{1} \equiv [1, 1, \dots, 1]^T$: $n_s \times 1$ vector and $O \equiv [0, 0, \dots, 0]^T$: $n_s \times n_s$ matrix. where n_s is the number of satellites corresponding to the focusing satellite system. Also define the $n_s \times 3$ matrix, and I is the $n_s \times n_s$ matrix identity as follows:

$$G_{\hat{u}}^{\hat{p}} \equiv \begin{bmatrix} g_{\hat{u}}^{\hat{p}1} \\ g_{\hat{u}}^{\hat{p}2} \\ \vdots \\ g_{\hat{u}}^{\hat{p}n_s} \end{bmatrix}, \quad I \equiv \begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 \end{bmatrix}. \quad (6)$$

And then, Kalman filter is applied to the observation equation (5) for GNSS PPP implementation.

3 QZSS(Quasi-Zenith Satellite System)

The QZSS (Quasi-Zenith Satellite System) is a regional space-based positioning system that uses a constellation of satellites placed in multiple orbital planes. The system covers regions in East Asia and Oceania centering on Japan and is designed to enable users in the coverage area to receive QZS (Quasi Zenith Satellite) signals from a high elevation angle at all times [6].

3.1 CLAS

CLAS use Japan's GNSS-based control stations data to calculate correction information, and utilizing the L6 signal of QZS to broadcast corrections for the Japanese homeland and the surrounding ocean. This technology can be accomplished with centimeter level error.

3.1.1 CLASLIB(SSR2OSR)

CLASLIB(CLAS Test Library) is an open source software tool to provide for CLAS. We can get CLASLIB from QZSS website [7]. SSR2OSR is contained in CLASLIB. SSR2OSR is a conversion utility to make offset values of observations from Compact SSR (State Space Representation). The following measurement models is used SSR2OSR. From (3)-(4):

$$\begin{aligned} \rho_{CA,u}^p &\cong g_{\hat{u}}^{\hat{p}}(u - s_{brd}^p) \\ &\quad + c(\delta t_u - \delta t_{brd}^p) \\ &\quad + s_{CLAS}^p - \delta t_{CLAS}^p + \text{PRC1} + e_{CA,u}^p(t), \end{aligned} \quad (7)$$

$$\begin{aligned} \Phi_{L1,u}^p &\cong g_{\hat{u}}^{\hat{p}}(u - s_{brd}^p) \\ &\quad + c(\delta t_u - \delta t_{brd}^p) \\ &\quad + s_{CLAS}^p - \delta t_{CLAS}^p + \text{CPC1} + \lambda_1 N_{L1,u}^p \\ &\quad + \lambda_1 \varepsilon_{L1,u}^p(t). \end{aligned} \quad (8)$$

where,

$$\begin{aligned} \text{PRC1} &= \delta I_u^p(t) + \delta T_u^p(t) + \delta b_{CA}^p \\ &\quad + d_{rel}^p + \Delta p_{ant}, \\ \text{CPC1} &= -\delta I_u^p(t) + \delta T_u^p(t) + \delta b_{L1}^p \\ &\quad + d_{rel}^p + \Delta p_{ant} + \lambda_1 \Delta \phi_{L1,u}^p. \end{aligned}$$

The parameters in SSR2OSR models; (7)-(8) are provided from Broadcast Ephemeris. The satellite position (s_{brd}^p) and clock errors (δt_{brd}^p) are obtained by Broadcast Ephemeris, Orbit correction (s_{CLAS}^p) and Clock correction (δt_{CLAS}^p) are obtained by CLAS. Orbit correction and Clock correction are component in the line of sight from the receiver to the satellite [m]. (PRC1) is pseudo range correction as OSR for CA [m] and (CPC1) is carrier range correction as OSR for L1 [m].

3.2 MADOCA

JAXA has developed Multi-GNSS orbit and clock estimator called MADOCA. Estimate satellite orbit and satellite clock from about 100 reference stations that is call MGM-net(Multi GNSS Monitor Network), and multi GNSS support. MADOCA product provide the two method; Real-time or Offline products. We use the Offline products.

4 EXPERIMENTAL RESULTS

We have carried out the experiments of using the GPS data (see Table 1) from the antennas, and the coordinates of their true positions in the WGS-84 system are listed in Table 2 which are obtained by GNSS Earth Observation Network System.

Table 1: Experimental Conditions

Date	February 5, 2019
Data1(GPST)	(06:00'20~06:59'59)
Data2(GPST)	(07:00'20~07:59'59)
Data3(GPST)	(18:00'20~18:59'59)
Data4(GPST)	(19:00'20~19:59'59)
Location	Tsukuba1, Japan (GEONET)
Antenna(Ant)	TPSCR.G5 GSI
Receiver	TRIMBLE NETR9
Epoch interval	1 [s]
Elevation angle mask	15 [deg.]
Measurement Data	C/A code, L1 carrier-phase

Table 2: True positions

X [m]	Y [m]	Z [m]
-3957162.3949	3310203.4909	3737752.3012

We have carried out experiments to compare the estimation accuracy of CLAS and MADOCA Products (Table 3).

Table 3: Experimental methods

	MADOCA-PPP	CLAS-PPP
Orbit correction	MADOCA(final)	CLAS(ORB)
Clock correction	MADOCA(final)	CLAS(CLK)
Ionosphere delay	GIM(IGS-final)	CLAS(Iono)
Troposphere delay	Saastamoinen model + Chao mapping function	CLAS(Trop)

Fig. 1: Positioning Errors at Data1

Fig. 2: Positioning Errors at Data2

Fig. 3: Positioning Errors at Data3

Fig. 4: Positioning Errors at Data4

Table 3 : RMS-ERRORS

			RMS [m]	
Data1	CLAS	E	0.0987	0.0915
		N	0.0790	
		U	0.0957	
	MADOCA Products	E	0.6128	0.4713
		N	0.3455	
		U	0.4140	
Data2	CLAS	E	0.4564	0.3286
		N	0.2581	
		U	0.2214	
	MADOCA Products	E	0.9135	0.6078
		N	0.3577	
		U	0.3821	
Data3	CLAS	E	0.1197	0.5181
		N	0.1178	
		U	0.8816	
	MADOCA Products	E	0.3657	0.5658
		N	0.7214	
		U	0.5535	
Data4	CLAS	E	0.0328	0.1628
		N	0.1283	
		U	0.2490	
	MADOCA Products	E	0.6836	0.4221
		N	0.2054	
		U	0.1578	

Figs.1-4 shows the positioning errors with the local level axes (East, North and Upper), where the solid red lines show the errors for using CLAS and the solid blue lines show the errors for using MADOCA Products. The errors were computed by difference between the estimated positions and the corresponding positions in the coordinates of Table 3. We can observe from Figs.1-4 that the positioning quality is considerably improved by using CLAS. The statistics of the positioning results are summarized in Table 3, where RMS errors are shown for using CLAS and MADOCA Products.

5 Conclusions

We have presented PPP algorithms with applying CLAS. When applying CLAS, the positioning accuracy is better than one applying MADOCA Products. Namely, throughout the numerical experiments in the section 5, the total 3DMMS error by applying CLAS is approximately 0.28 [m], in contrary with the total 3DMMS error by applying MADOCA Products is being approximately 0.52 [m].

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