Positioning Accuracy of Single-Frequency GNSS PPP based on GR Models by using CLAS

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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). Throughout the numerical experiments by using the single frequency (L1-band, only) measurement data for the static position, we have very accurate positioning results; namely the total 3D-RMS errors by applying CLAS is approximately 0.13 [m], which is the superior positioning result achieved as a single frequency GPS measurements.

1. Introduction

In this paper, we present single frequency (L1 only) GNSS high accuracy Precise Point Positioning (PPP) algorithms based on GNSS regression models (GR models)[1,2] with using CLAS (Centimeter Level Augument Service) data[3,4] and show the positioning results. Throughout the numerical experiments by using the single frequency GPS L1-band measurement data for the static position, we will show the very accurate positioning results in the Section 5, namely, approximately the total 3D-RMS (root mean square) error is 0.13 [m].

GPS in the United States is well known as Global Navigation Satellite System (GNSS), but several national organizations are constructing similar systems. Japan launched its first quasi-zenith satellite system (QZSS; Michibiki) in 2010, and started its service in Nov. 2018 with 4 satellite systems[5]. QZSS has both complementary and augmentation services. The complementary service enhances availability by using the both US GPS and Japanese QZSS combination. The augmentation service enhances accuracy and integrity. One of the augmentation service is so-called as the Centimeter-Level Augumentation Service (CLAS)[3,4], which utilizes L6 signal of Quasi-Zenith Satellites (QZS) to broadcast error information (corrections) in satellite orbits and clocks derived from the navigation data (: Ephemeris data), and information on ionospheric and tropospheric delays at virtual points arranged in the grid (the points with approximately 60 km intervals) , so that the receiver can use this information to perform positioning with centimeter-level accuracy.

In CLAS, double-frequency signals are assumed to be used, and the specification values are specified for double-frequency positioning[6,7]. However, from the viewpoint of the structure of the corrections, even single-frequency positioning can be used in principle. Therefore, we have attempted to derive the PPP algorithms based on our GR models[1,2] such that we have been showing the high accuracy of positioning results for single-frequency (only L1) by applying the CLAS corrections.

2. Model Equation for Precise Point Positioning

2.1 Measurement Model

Similarly to [2], we only describe the case of L1 frequency GNSS Regression (GR) models for the observed positioning data consisting of L1 carrier phases and pseudo-ranges 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 ΦL1,u(t) and the pseudoranges ρCA,u(t) based on C/A codes, respectively, as follows:

\[
\rho_{CA,u}(t) = r^p_u(t, t - \tau^p_u) + \delta t_u(t) - \delta t^p(t - \tau^p_u) + \delta I^p_u(t) + \delta T^p_u(t) + \delta b^p_{CA} + d^p_{rel} + \Delta_p + e_{CA,u}(t)
\]
where $r_u^p(t,t-t_u^p)$ is the geometric distance between the receiver $u$ at the time $t$ and the satellite $p$ at the time $t-t_u^p$ ($\tau_u^p$ denotes traveling time from the satellite $p$ to the receiver $u$). Namely

\[
\begin{align*}
    r_u^p(t,t-t_u^p) & = \left[ (x_u(t) - x_u^p(t-t_u^p))^2 + (y_u(t) - y_u^p(t-t_u^p))^2 \right]^{1/2}, \\
    & \equiv \left[ (x_u(t) - x_u^p(t-t_u^p))^2 + (y_u(t) - y_u^p(t-t_u^p))^2 \right]^{1/2},
\end{align*}
\]

Also the symbols appeared in (1) and (2) are denoted as:

- $t$: true receiving time at receiver $u$
- $c$: speed of light ($= 2,997,924,58 \times 10^8$ [m/s])
- $\lambda_1$: wave length of the L1 ($= 0.190$ [m])
- $\delta t_u^p$: clock error of satellite $p$ at time $t - t_u^p$ [s]
- $\delta t_u(t)$: clock error of receiver $u$ at time $t$ [s]
- $\delta I_u^p(t)$: Ionosphere delay [m]
- $\delta T_u^p(t)$: Tropospheric delay [m]
- $\delta \Phi_{CA}^p$: C/A code bias for the satellite $p$ [m]
- $\delta \Phi_{P}^p$: carrier phase bias for the satellite $p$ [m]
- $d_{rel}^p$: relativistic delay of radiowave [m]
- $\Delta p_{ant}$: antenna phase center offsets and variation
- $\delta \phi_{L1,u}^p$: phase windup correction [cycle]
- $N_{\lambda u}^p$: integer ambiguity [cycle]
- $e_{\lambda u}^p(t)$: measurement errors of code pseudo range [m]
- $e_{\lambda u}^p(t)$: measurement errors of carrier phase [cycle].

### 2.2 GNSS Linear Regression Model

In (1)-(2), unknown parameters are the receiver 3-dimensional coordinates ($x_u, y_u, z_u$), receiver clock error $\delta t_u(t)$, satellite clock error $\delta t_u^p(t-t_u^p)$, ionospheric refraction effect $\delta I_u^p(t)$, tropospheric refraction effect $\delta T_u^p(t)$, and integer bias $N_{\lambda u}^p$. These unknown parameters are applied to GNSS linear regression (GR) model which is solved by a linear regression equation.

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 [2]:

\[
\begin{align*}
    \Phi^p_{L1,u}(t) & = r_u^p(t, t-t_u^p) + c[\delta t_u(t) - \delta t_u^p(t-t_u^p)] \\
    & - \delta I_u^p(t) + \delta T_u^p(t) + \delta \Phi_{CA}^p + d_{rel}^p \\
    + \Delta p_{ant} + \lambda_1(N_{\lambda u}^p + \delta \phi_{L1,u}^p) \\
    + \lambda_1 e_{\lambda u}^p(t),
\end{align*}
\]

where

\[
\begin{align*}
    \Phi^p_{L1,u}(t) & = r_u^p(t, t-t_u^p) + c[\delta t_u(t) - \delta t_u^p(t-t_u^p)] \\
    & - \delta I_u^p(t) + \delta T_u^p(t) + \delta \Phi_{CA}^p + d_{rel}^p \\
    + \Delta p_{ant} + \lambda_1(N_{\lambda u}^p + \delta \phi_{L1,u}^p) \\
    + \lambda_1 e_{\lambda u}^p(t).
\end{align*}
\]

### 3. CLAS and CLASLIB

#### 3.1 Centimeter-Level Augmentation Service

CLAS is a service that estimates satellite orbit and clock errors and local atmospheric delay in State-Space Representation (SSR) [8] using data from multiple Continuously Operating Reference Stations (CORS) in GNSS Earth Observation Network System (GEONET) in Japan, and broadcasts these correction data from QZS to the whole of Japan using L6 signals. The target satellite systems include GPS, Galileo, and GLONASS (Schedule) as well as QZSS. This method can be called PPP in the sense that it enables positioning without directly acquiring observation data of nearby CORS, but it is called PPP-RTK because observation data of CORS in Japan are used for generating correction data.

#### 3.2 CLAS Test Library and SSR2OSR

CLAS Test Library (CLASLIB) is an open source software developed based on RTKLIB and GSILIB as a reference data generation tool for those considering implementation algorithms for CLAS-enabled products. It consists mainly of 2 tools: SSR2OSR, which decodes L6 signals, i.e., converts the correction amount from the SSR to the observation space representation (OSR) at a positioning point, and outputs the positioning result by PPP-RTK. The L6 signals used in CLASLIB and this tool can be obtained from the QZSS website [9,10]. In this paper, however, we use only SSR2OSR and perform positioning by our own PPP algorithms base on GR-models in Section 2, which had been developed in [1,2].

#### 3.3 Apply to GR model

Applying the correction value output by the SSR2OSR to the GR model (5), (6), these equations can be expressed as follows:

\[
\begin{align*}
    \rho_{CA,u}^p & \equiv g_u^p(u - s_{rel}^p) + c[\delta t_u - \delta t_u^p] \\
    & + \delta \Phi_{CL}^p + \delta \Phi_{UCL}^p + \delta \Phi_{UCL}^p + \delta \Phi_{CA,CL}^p \\
    & + d_{rel}^p + \Delta p_{ant} \\
    & + \epsilon_{CA,u}^p.
\end{align*}
\]
\[ \Phi_{0,1,u} = g\left( u - s_{brd}^{r} \right) + \left( \delta_{t,u} - \delta_{brd}^{r} \right) + \lambda_{1} N_{1,1,u}^{p} + \delta s_{CL}^{p} - \delta t_{CL}^{p} - \delta t_{u,CL}^{p} - \delta T_{u,CL}^{p} + \delta t_{CL}^{u,CL} + \Delta \Delta_{pant} + \lambda_{1} \Delta \phi_{L,1,u}^{p} + \lambda_{1} \varepsilon_{L,1,u}^{p}, \] (8)

where the position of the satellite \( p \): \( s_{brd}^{r} \) and the clock error of the satellite \( p \): \( \delta_{brd}^{r} \) are obtained from the navigation data (Ephemeris).

In the case of post-processing, multiple effective ephemeris exist at the same time, and the accuracy cannot be obtained unless the same ephemeris is used in the CLAS correction data generating process (can be confirmed by IODE, and will necessarily be the same ephemeris for real-time processing). In the case of general single-frequency GPS positioning, group delay correction \( \delta t_{brd}^{p} = \delta t_{brd}^{p} - T_{GD} \) (for L1 bands) is performed, but \( T_{GD} \) is not used in CLAS.

In (7) and (8), the following quantities are provided as the OSR correction values distributed by CLAS (Be output by SSR2OSR from CLAS).

\[
\begin{align*}
\delta s_{CL}^{p} : & \text{LOS error of } \delta s_{brd}^{r} \\
\delta t_{CL}^{p} : & \text{range dimension error of } \delta t_{brd}^{r} \\
\delta I_{u,CL}^{p}(t) : & \text{Ionosphere delay} \\
\delta T_{u,CL}^{p}(t) : & \text{Tropospheric delay} \\
\delta \phi_{C,A,CL}^{p} : & \text{C/A code bias} \\
\delta \phi_{L,1,CL}^{p} : & \text{carrier phase bias.}
\end{align*}
\]

The estimated value of \( \phi_{C,A,CL}^{p} \), \( \Delta \Delta_{pant} \), \( \Delta \phi_{L,1,u}^{p} \) are not the correction values distributed by CLAS, but SSR2OSR outputs the value calculated accurately by the built-in model. Therefore, these values may be used, or the values calculated by the built-in model of the own positioning program may be used.

These estimated values are subtracted from both sides in (7), (8), then these terms are eliminated. Therefore, the unknown values are the three-dimensional coordinate \(( x_{u}, y_{u}, z_{u} ) \), receiver clock error \( \delta t_{u}(t) \), and integer bias \( N_{1,1}^{p} \).

Therefore, define new observables as follows.

\[
\begin{align*}
\tilde{\phi}_{C,A,CL}^{p} & \equiv \phi_{C,A,CL}^{p} + g\sigma_{brd}^{p} + c\delta t_{r}^{p} \\
& - \delta s_{CL}^{p} + \delta t_{CL}^{p} - \delta I_{u,CL}^{p} - \delta T_{u,CL}^{p} - \delta \phi_{C,A,CL}^{p} \\
& - \delta t_{CL}^{u,CL} - \Delta \Delta_{pant} - \lambda_{1} \Delta \phi_{L,1,u}^{p}, \quad (9)
\end{align*}
\]

Then, the measurement equations in (7) and (8) are expressed by

\[
\begin{align*}
\tilde{\phi}_{C,A,CL}^{p} & \equiv g\left( u - s_{brd}^{r} \right) + c\delta t_{u} + e_{C,A,CL}^{p}, \quad (11)
\tilde{\phi}_{L,1,u}^{p} & \equiv g\left( u - s_{brd}^{r} \right) + c\delta t_{u} + \lambda_{1} N_{1,1,u}^{p} + \lambda_{1} \varepsilon_{L,1,u}^{p}, \\
& (12)
\end{align*}
\]

where,

\[
\begin{align*}
y_{t} & \equiv \begin{bmatrix} \hat{\phi}_{C,A,u}^{p} \\ \hat{\phi}_{L,1,u}^{p} \end{bmatrix} : \text{observation vector} \\
H_{t} & \equiv \begin{bmatrix} G_{u}^{p} & 1 \\ \lambda_{1} I_{n_{s}} \end{bmatrix} : \text{measurement matrix} \\
x_{t} & \equiv \begin{bmatrix} \hat{\phi}_{u}^{p} \\ \hat{\phi}_{L,1,u}^{p} \end{bmatrix} : \text{state vector} \\
v_{t} & \equiv \begin{bmatrix} e_{C,A,u}^{p} \\ \lambda_{1} \varepsilon_{L,1,u}^{p} \end{bmatrix} : \text{measurement noise vector}
\end{align*}
\]

Here, it is assumed that the observed quantities of the \( n_{s} \) satellite have been obtained, and \( \tilde{\phi}_{C,A,u}^{p}, \hat{\phi}_{L,1,u}^{p}, \hat{\phi}_{L,1,u}^{p} \) and \( I_{n_{s}} \) is the \( n_{s} \times 1 \) vector, \( O \) is the zero matrix of \( n_{s} \times n_{s} \), and \( G_{u}^{p} \) is the \( n_{s} \times 3 \) gradient matrix shown below.

\[
G_{u}^{p} \equiv \begin{bmatrix} g_{1}^{p} \\ g_{2}^{p} \\ \vdots \\ g_{n_{s}}^{p} \end{bmatrix}
\]

4. Kalman Filtering for PPP Positioning by applying CLAS

Now we have get the measurement equations in (13) and then we will applying the recursive estimation of the unknown states \( x_{t} \) by applying the Kalman filter. Therefore we should examine to \( r \) the proper dynamical models for the states of \( x_{t} \), especially of \( u_{t} \), which are depended on the occasions of the user positions. We have already proposed and examined many cases of movements of the user in [11–14], similarly to Singer’s models[15]. Also several state models for the clock errors \( \delta t_{u} \) are considered in [16].

5. Experimental Results

The positioning performances of the method described above are carried out by using the received data from GEONET (GNSS Earth Observation Network System) which are provided by the Geospatial Information Authority of Japan (GSI). The properties of the observation data used are described in Table 1.

In these experiments, we use the following state equation, namely the user position is static, therefore we use the model: \( u_{t+1} = u_{t} \). Also we apply the model of the receiver’s clock error is assumed as the first order markov model such as \( \delta t_{u,t+1} = \alpha \delta t_{u,t} + \varepsilon_{t_{u,t}} \).

Therefore we have following state equation:

\[
x_{t+1} = F_{t} x_{t} + w_{t},
\]

where
Table 1: Conditions for observed data

| 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     | Tsukuba, Japan (GEONET) |
| Antenna(Ant) | TFSKR,G5 GSI |
| Receiver     | TRIMBLE NETR9 |
| Epoch interval | 1 [s] |
| Satellite System | GPS |
| Measurement Data | C/A code, L1 carrier-phase |
| Elevation angle mask | 15 [deg.] |

Table 2: Correction items and correction methods

| correction item | correction method |
|-----------------|-------------------|
| Orbit correction| use CLAS correction $\delta s_{CL}$ |
| Clock correction | use CLAS correction $\delta t_{CL}$ |
| Ionosphere delay | use CLAS correction $\delta I_{CL}$ |
| Troposphere delay | use CLAS correction $\delta T_{CL}$ |
| Satellite H/W bias | use CLAS correction $\delta b_{CL}$ |
| Phase Wind-up | use CLASLIB model $\Delta \varphi_{L,1,1}$ |
| General relativistic delay | use CLASLIB model $\Delta \varphi_{rel}$ |
| Solid Earth tide | use positioning software model (IERS) |
| Antenna PCO/PCV ($\Delta p_{ant}$) | no correction in calculation |
| (\Delta p_{ant}) | PCO correction to F3 solution |

Fig. 1: Positioning errors at data1

\[
F_i \equiv \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 & 1 & 0 \\ 0 & 0 & \alpha \end{bmatrix} : \text{state transition matrix}
\]

\[w_t : \text{process noise.}\]

For accurate estimation by Kalman filtering, it is necessary to properly set covariance matrices of the observation noises, the process noises, and initial values of states.

Table 2 shows the existence and distribution of various corrections. The first four items correspond to the correction amounts distributed from CLAS, and the following two items use the model of SSR20SR. The last earth solid tide was calculated and corrected by the positioning program, because it was considered to be a non-negligible value although it was not specified in the above equation. On the other hand, the correction of ocean tidal load deformation, polar motion tide, and antenna PCV was omitted.

Figures 1 - 4 show the positioning errors in the ENU coordinate system in time series. Table 3 shows the RMS value of the error for one hour in each case.
The positioning error was calculated by (estimated values – true values) using the precise analysis result (F3 solution) provided by GSI (Geospatial Information Authority of Japan) as “daily coordinate value” [17] as the reference (true value). Since the F3 solution is the coordinate value of the antenna bottom surface, the antenna phase center offset was corrected by the antenna PCO/PCV data, which is also published.

Compared with our previous results in [18] and [19], the accuracy is generally improved by optimizing the ephemeris selection, removing abnormal satellites, correcting the solid earth condition, and correcting the receiver PCO.

For reference, Table 3 reprints the RMS error of single-frequency MADOCOA in [18]. Since MADOCOA broadcasting data does not include ionospheric delay correction, it is necessary to estimate by some model or obtain from another data source. We used GIM (IGS-Final) data and their accuracy is said to be around 0.4[m]. Therefore, it would be difficult for MADOCOA to achieve high accuracy with single-frequency unless precise ionospheric delay correction is provided.

| Table 3 Positioning errors (RMS[m]) |
|------------------------------------|
| E/N/U  | MADOCOA | 3D (in[18]) |
|--------|---------|-------------|
| Data1  | E 0.051 | 0.163 | 0.471 |
|        | N 0.048 |        |       |
|        | U 0.148 |        |       |
| Data2  | E 0.041 | 0.084 | 0.608 |
|        | N 0.038 |        |       |
|        | U 0.062 |        |       |
| Data3  | E 0.041 | 0.129 | 0.566 |
|        | N 0.059 |        |       |
|        | U 0.107 |        |       |
| Data4  | E 0.040 | 0.132 | 0.422 |
|        | N 0.064 |        |       |
|        | U 0.109 |        |       |

6. Conclusions

We discussed the use of CLAS correction data in single-frequency GNSS precision point positioning (PPP). We also added some CLAS correction functions to the single-frequency mode of our GNSS PPP programs, and evaluated the positioning errors from GEONET points shown in Table 2. From Table 3, we can say that the positioning accuracy of 3D-RMS was approximately 13 [cm] (Horizontal: Approx. 7 [cm], Vertical: Approx. 11 [cm]), these results are good because we only used lowest-cost single-frequency GPS measurements, comparing with the results appeared in [7], where they used measurement data from high-cost multi-frequencies and multi-GNSS systems.

In the future, it will be examined whether the accuracy can be further improved by the use of ambiguity resolution.

In addition, it is assumed that single-frequency positioning is often performed by inexpensive receivers and antennas such as smartphones and car navigation systems, rather than the receivers and antennas for surveying used at GEONET points. It is a future task to evaluate the observation data in such cases and improve the accuracy.

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