Design of GNSS PPP-RTK Assistance System and its Algorithms for 5G Mobile Networks*

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5th Generation (5G) mobile communication technology plays the role of a typhoon-eye among world economic superpowers. In a whirlwind of international cutthroat competition, Global Navigation Satellite System (GNSS) precise positioning is said to be the first application of 5G mobile communication services. 5G brings super-low latency and super-large capacity for data transmission. In this situation, we design a new GNSS PPP-RTK assistance system using these 5G excellences, based upon the heritage of precise positioning techniques utilizing Quasi-Zenith Satellite System (QZSS). In the comparison to the existing system, this design makes the horizontal accuracy from several centimeters to almost one centimeter, and makes the convergence time from one minute to a few seconds. These are the highest performances as the unidirectional assistance of real-time GNSS positioning for mass-market applications which should be implemented into the smart society which we have been actively building today.

1. Introduction

European Commission (EC) published GNSS Market Report, which is widely cited in the international community of GNSS area[1]. According to this report, the world’s people have 7 billion GNSS devices for Location Based Service (LBS). The LBS devices adopt Third Generation Partnership Project (3GPP) standards[9].

In this paper, we show the design of GNSS PPP-RTK assistance system for 5G mobile networks and its algorithms for the first time in the world. PPP-RTK can be said to be a method of Precise Point Positioning (PPP) with very fast convergence, based on Real-Time Kinematic (RTK) networks [2,3]. There are past papers which described about PPP-RTK algorithms [4,5]. They are, however, not systems for 5G mobile network and include accumulated programmatic inefficiency. We reveal theoretically essential meaning as system requirements and describe a principally operational flow, utilizing the heritage of application demonstrator for QZSS [7,8], and this content is quite useful for social implementation of the most advanced positioning infrastructure.

2. 5G Mobile Network

5G mobile network is standardized in the 3GPP organization, which made the standards of 4th Generation (4G)/Long Term Evolution (LTE). Various regions of the world are launching 5G mobile services today. The 5G technology consists of both Enhanced LTE (eLTE) and New Radio (NR), which uses entirely novel techniques. The 3GPP made the international agreement for adopting GNSS PPP-RTK service in the release 16. It requires a precise positioning service with atmospheric correction using carrier-phase measurement and State Space Representation (SSR).

The 3GPP mobile communication platform equips U-plane (User plane) and C-plane (Control plane). In particular, C-plane enables inner control for the network and we can add the priority of service. The assistance data are able to stream through both planes.

The 5G mobile communication system is characterized by the performance of super-low latency and super-large capability. These features are also very useful and quite significant for next-generation precise positioning services.

3. Design Objective

The design objective is the highest performance of GNSS positioning system for mass-market applications using the latest technologies. Therefore our target is not a bidirectional service such as RTK or network RTK method, but a unidirectional service using broadcast channel such as a PPP-type service.

In mobile networks, a bidirectional service needs a huge number of serving tasks, for example, tens of
accuracy of only one L6D satellite channel (1695bps) of QZSS. The 5G’s super-speed contributes to dramatically minimize the convergence time into a few seconds. The proposed design will check it by experiments.

4. Error Models
The PPP-RTK assistance system identifies the errors through the algorithms and extracts distributed elements as follows.

\[
\delta \ell_p, \delta s^p, \delta I_p^k, \delta t_k, \delta b^p, \delta \rho^p_k,
\]

where \(\delta I_p^k\) is the ionospheric correction, \(\delta t_k\) is the tropospheric correction at the reference station \(k\), \(\delta b^p\) is code-phase bias, and \(\delta \rho^p_k\) is carrier-phase bias of signal-in-space (SIS) for respective signals.

4.1 Satellite Errors
Satellite errors consist of the orbit error and the clock error as follows.

(1) Satellite clock error
The total ranging error by satellite and station clocks is represented as \(c\delta t = c(\delta t_k - \delta t^p)\). As might be expected, the assistance system corrects \(-c\delta t^p\) and the station corrects \(c\delta t_k\) as the responsibility of respective parts.

(2) Satellite orbit error
The coordinates \(s^p\) of the satellite \(p\) and the coordinates \(u_k\) of the station \(k\) are respectively denoted by

\[
s^p = [x^p \ y^p \ z^p]^T, \tag{4}
\]

\[
u_k = [x_k \ y_k \ z_k]^T, \tag{5}
\]

where the coordinate system is Earth-Centered Earth-Fixed (ECEF).

The orbit error \(\delta s^p_k\) on the line-of-sight from the satellite \(p\) to the station \(k\) is represented as formula (6), where \(\tilde{s}\) is a satellite position which is calculated from the broadcast ephemeris data.

\[
\delta s^p_k = \left( \frac{u_k - s^p}{\|u_k - s^p\|} \right) \left( u_k - s^p - \left( u_k - \hat{s}^p \right) \right). \tag{6}
\]

Meanwhile, RTCM 10403.3 presents the orbits in the SSR form of radial, along-track, and cross-track components[10], therefore they must be transformed into the ECEF.

4.2 SIS Biases
SIS biases consist of code-phase bias \(\delta b^p\) and carrier-phase bias \(\delta \rho^p_k\) as the relative delay errors from a base signal bias. The base signals are taken as L1 C/A for GPS/QZSS and E1C for Galileo as of today. \(n = 2\) or 5 for the second band.

(1) Code-phase bias
For using dual band, \(\delta b^p_C\) is defined as \(\delta b^p_C = [\delta b^p_{C1} \delta b^p_{Cn}]^T\) and respective elements are such that

\[
\delta b^p_{C1} = b^p_{C1} - b^p, \tag{7}
\]

\[
\delta b^p_{Cn} = b^p_{Cn} - b^p, \tag{8}
\]
where $b_{C1}^r$ is the reference bias of the base signal.

(2) Carrier-phase bias
Also $\delta b_{C1}^p$ is defined as $\delta b_{L1}^p \equiv \{\delta b_{L1}^p \, \delta b_{Ln}^p\}^T$ and respective elements are such that

$$\delta b_{L1}^p = b_{L1}^p - b_{C1}^r, \quad \delta b_{Ln}^p = b_{Ln}^p - b_{C1}^r.$$

(9) (10)

4.3 Atmospheric Errors
The atmospheric errors consist of the ionospheric error and the tropospheric error for centimeter positioning.

(1) Ionospheric error
The ionospheric error $\delta I_p^k$ is modeled as the slant ionospheric delay such that

$$\delta I_p^k = \delta I_{L1,k}^p + \delta I_{Ln,k}^p. \quad (11)$$

There are other models of the vertical ionospheric error using spherical harmonic or ball crown harmonic functions. Today’s practical PPP-RTK systems, however, adopt slant ionospheric model, because of actual implementations in Japan, South Korea, Europe and North America[13].

(2) Tropospheric error
The tropospheric error $\delta T_k$ is modeled using the vertical zenith tropospheric model at the station $k$ such that

$$\delta T_k \equiv [\delta T_{H,k} \, \delta T_{M,k}]^T, \quad (12)$$

where $\delta T_{H,k}$ is the hydrostatic component, $\delta T_{M,k}$ is the moisture component. We apply Saastamoinen’s tropospheric model $Z(h,t)$ and Neil’s mapping function $M(E_k^p)$, and $E_k^p$ is an elevation angle of the satellite $p$ at the station $k$. $h$ is the height above the sea level, $t$ is the clock time [11,12]. The slant tropospheric error $\delta T_k^p$ is calculated from the zenith vertical tropospheric error $\delta T_k$ as follows.

$$\delta T_k^p = M(E_k^p)Z(h,t)\delta T_k$$

$$= \left[ \begin{array}{cc} Z_H(h,t) & 0 \\ Z_H(0,t) & Z_M(h,t) \end{array} \right] \delta T_k$$

$$= M_H(E_k^p) Z_H(h,t) \delta T_{H,k}$$

$$+ M_M(E_k^p) Z_M(0,t) \delta T_{M,k}.$$ (13)

4.4 Station Residual Errors
The station residual error $e_{f,k}^p$ which the assistance system does not distribute, is described as formula (14) where $f$ is the signal code or the signal frequency of carrier-phase. The right side includes the parameters calculated by physical theories and measurement in advance[8].

$$e_{f,k}^p = m_k^p + e_{A,f,k} + e_{E,k} + e_{R,k} + e_{D,f,k}. \quad (14)$$

where

- $m_k^p$ : station multipath error,
- $e_{A,f,k}$ : antenna phase center difference,
- $e_{E,k}$ : earth tide error,
- $e_{R,k}$ : carrier phase wind up error,
- $e_{D,f,k}$ : station residual error.

5. Model Integration
We describe the observation equation and configure the Kalman filter to generate the most accurate correction parameters.

5.1 Observation Equation
The observation equation is as follows. The pseudorange $\rho_{C1,k}$ and $\rho_{Cn,k}$ of signal code C1 and Cn ($n = 2$ or 5) respectively, are described as equation (15) (16), where $r_k^p$ is the geometric range.

$$\rho_{C1,k} = r_k^p + \delta s_k^p + c(\delta t_k - \delta t_p^p) + \delta I_p^k + \delta T_k^p + \delta b_{C1,k},$$

(15)

$$\rho_{Cn,k} = r_k^p + \delta s_k^p + c(\delta t_k - \delta t_p^p) + \frac{f_{L1}}{f_{Ln}} \delta I_p^k + \delta T_k^p + \delta b_{Cn,k}.$$ (16)

The phase-ranges $\Phi_{L1}^p$ and $\Phi_{Ln}^k$ with signal frequency $L1$ and $Ln$ ($n = 2$ or 5) respectively, are represented as formula (17) (18).

$$\Phi_{L1,k} = r_k^p + \delta s_k^p + c(\delta t_k - \delta t_p^p) - \delta I_p^k + \delta T_k^p + \delta b_{L1,k} + \lambda_{L1}N_{L1,k}^p + e_{L1,k},$$

(17)

$$\Phi_{Ln,k} = r_k^p + \delta s_k^p + c(\delta t_k - \delta t_p^p) - \frac{f_{L1}}{f_{Ln}} \delta I_p^k + \delta T_k^p + \delta b_{Ln,k} + \lambda_{Ln}N_{Ln,k}^p + e_{Ln,k},$$ (18)

where $N_{L1,k}^p, N_{Ln,k}^p$ are wave number integer biases of satellite-to-receiver, and $\lambda_{L1}, \lambda_{Ln}$ are the wave length of $L1$-band and $Ln$-band respectively ($n = 2$ or 5).

6. System Design
In this section, we show the design and the algorithms as the system requirement for 5G GNSS PPP-RTK assistance system using the Kalman filter. $u_{p3,k}$ is an average of the F3 solutions, which are provided from Geospatial Information Authority (GSI) of Japan, as the nationally-authorized reference position of the GEONET station $k$. GEONET is the national Continuously Operating Reference Station (CORS) network. The displacement of the station $k$ from the reference position is represented such that

$$\delta u_k = u_k - u_{F3}.$$ (19)

It means to fit with the temporal epoch coordinates of Japanese Geodetic Datum 2011 (JGD2011), that is the basis of transformation to the reference epoch coordinates of JGD2011, the right national coordinate system which is required in the practical
market, for example, to build the smart cities as the national projects.

The precise estimate \( \hat{\delta}_k \) of the phase-range can be calculated such that

\[
\hat{\delta}_k = \Phi_{L,1,k} - \{\delta^p_k + c(\delta t_k - \delta t^p) - \delta T^p_k + \delta T^p_k\} + \delta\hat{T}_{L,1} + \lambda_{L,1} N^p_{L,1,k} + \delta e_{L,1,k}.\tag{20}
\]

The hat symbol means the optimal estimate parameter of respective valuables.

### 6.1 Observation Dimension

We have to check the dimension \( n_y \) of the observation space. The system nominaly uses 25 stations per a network of the assistance system. 12 satellites are typically received. The respective satellites are used as 2 signals with 2 channels such as code and carrier-phase. Therefore,

\[
n_y = 25 \times 12 \times 2 = 1,200 \text{ dimensions.} \tag{21}
\]

The whole land of Japan is divided to 12 networks as Fig.1, therefore the total dimension is such that

\[
n_y^{\text{Japan}} = 1200 \times 12 = 14,000 \text{ dimensions.} \tag{22}
\]

The dimensions is practically time-variant depending on operations.

### 6.2 State Equation

We design to optimize the areal networks respectively, and make a model of one network using all stations in the network. From formula (15)-(18), we configure the state equation represented as formula (23) and (24).

\[
\begin{align*}
\dot{\theta}_{t+1} &= F_t \theta_t + G_t w_t, \\
y_t &= H_t \theta_t + v_t. 
\end{align*} \tag{23, 24}
\]

The observation vector and the state vector, where all components are written as sub-vector, are rather complicated and therefore they can be represented as only summarized sets of sub-vector.

\[
\begin{align*}
y_t &\equiv [\hat{\delta}_{C,1,k}^p; \hat{\delta}_{N,1,k}^p; \Phi_{L,1,k}^p; \Phi_{L,n,k}^p]^T, \\
\theta_t &\equiv [\delta^p t_k; \delta^{p^p} t_k; \delta^{s^p} t_k; \delta^{T^p}_k; \delta^{T^p}_k; N^p_{L,1,k}; N^p_{L,n,k}; \delta T_k; m^p_k]^T, \\
E[w_t] &= 0, \quad E[w_tw_t^T] = Q_{\delta^p t_k}, \\
E[v_t] &= 0, \quad E[v_tw_t^T] = R_{\delta^p t_k}. 
\end{align*} \tag{25-28}
\]

where \( w_t \) and \( v_t \) is independent Gaussian white noise, \( \delta^p t_k \) is the Kronecher’s \( \delta \)-function, and \( N^p_k \) is defined as \( N^p_k \equiv [N^p_{L,1,k}; N^p_{L,n,k}]^T \). The state vector does not include \( \delta^p_{C,t_k} \) and \( \delta^p_{T_k} \), and these parameters are calculated out of the Kalman filtering optimization.

### 6.3 Computability

We need to check the dimension \( n_y \) of the state space. \( n_s \) satellites and \( n_k \) stations are used per region which one computational task covers.

In spite of being the state vector element, \( N^p_{L,1,k} \) and \( N^p_{L,n,k} \) do not become independent dimension such that

\[
\begin{align*}
\delta^{u_k} t_k &\equiv 3n_k, \quad \delta^{t^p} t_k \equiv n_s, \quad \delta^{s^p} t_k \equiv 3n_s, \\
\delta^{u_k} t_k &\equiv n_s n_k, \quad \delta^{T^p}_k \equiv n_s, \quad t_k \equiv n_k, \quad m^p_k \equiv n_s n_k.
\end{align*}
\]

Therefore, the total dimension for Japan is

\[
n_y^{\text{Japan}} = 688 \times 12 = 8,256 \text{ dimensions}. \tag{32}
\]

Because of \( n_y > n_\theta \), the computation is possible, and the system is able to give the solutions.

### 6.4 Kalman Filtering

#### (1) Update operation

The filtering and prediction, the Kalman gain \( K_t \), and the estimated error covariance \( \Sigma_t \) are equipped such that

\[
\begin{align*}
\hat{\theta}_{t+1|t} &= F_t \hat{\theta}_{t|t}, \\
\hat{\theta}_{t|t} &= \hat{\theta}_{t|t-1} + K_t[y_t - H_t \hat{\theta}_{t|t-1}], \\
K_t &= \Sigma_{t|t-1} H_t^T [H_t \Sigma_{t|t-1} H_t^T + R_t]. 
\end{align*} \tag{33-35}
\]

#### (2) Initial conditions

The initial conditions for the Kalman filter are provided into formula (36) from the navigation messages from GNSS, the station positions given in advance, and the precise ephemerides from the expertized agencies of the GNSS provider countries through the internet.

\[
E[\theta_0] = \bar{\theta}_0, \quad Var[\theta_0] = \Sigma_0. \tag{36}
\]

### 7. Assistance Service

The assistance system generates \( \hat{\theta}_t \) through the above algorithms and extracts distributed elements.

\[\delta^{p^p} t_k, \delta^{s^p} t_k, \delta^{T^p}_k, \delta^{T^p}_k, \delta T_k.\]

The hat symbol means the optimal estimate parameter of respective valuables.

#### 7.1 Atmospheric Grid

The atmospheric errors \( \delta^{p^p} t_k \) and \( \delta T_k \) are transformed into receiver-known positions, because the receivers do not know the station position \( k \). Therefore the grid positions \( k^a \) are defined. This method has the below merits.

(1) Independent from changing station network
(2) No need to publish the station positions
In particular, item (2) may be important for the countries to concern the national security.
The PPP-RTK technique uses the grid set, which covers its service area. The grid function transforms the station position \( k \) to the grid position \( k' \) using interpolation calculation\[8\]. The ionospheric and tropospheric corrections are respectively transformed from the station position \( k \) to the grid position \( k' \) by interpolation calculation such that

\[
\hat{\delta}I_p^k = G_I(\hat{\delta}I_p^k),
\]

\[
\hat{\delta}T_k^k = G_T(\hat{\delta}T_k),
\]

where \( G_I \) is the transform function for the ionospheric correction, and \( G_T \) is the transform function for the tropospheric correction respectively.

7.2 Distribution

The PPP-RTK corrections are distributed shown as Table 1. \( \Delta t_{QZ} \) is the interval time of the existing system\[8\] and \( \Delta t_{5G} \) is by this design using the 5G platform.

| Correction                  | Symbol | \( \Delta t_{QZ} \) | \( \Delta t_{5G} \) |
|-----------------------------|--------|---------------------|---------------------|
| Satellite clock correction  | \( \hat{\delta}t^p \) | 5 s                 |                     |
| Satellite orbit correction  | \( \hat{\delta}s^p \) |                     |                     |
| SIS code-phase bias         | \( \hat{\delta}b_G^p \) | 30 s                |                     |
| SIS carrier-phase bias      | \( \hat{\delta}b_L^p \) |                     |                     |
| Ionospheric correction     | \( \hat{\delta}I_k^p \) |                     |                     |
| Tropospheric correction    | \( \hat{\delta}T_k \) |                     |                     |

In a typical assistance system, the corrections are simply extracted from its sequence at the timing of 5 or 30 second interval. These interval timings come from the RTCM standard\[10\].

The practical system distributes the parameters of User Range Accuracy (URA)\[8\] and proposes an authentication message for anti-spoofing\[6\].

8. Experiments

The experiments of the designed assistance system and its algorithms, were carried out. The observation data were sent from 25 stations of GEONET per one region of approximately 200 by 200 kilometers. In the experiments, we used typical positioning algorithms described in the QZSS specification\[8\], and measured the accuracy and the convergence time of the positioning result using the GNSS PPP-RTK assistance system based on the QZSS CMAS\[14\] for application demonstrator in 2011-2018 before that the practical service CLAS commenced.

8.1 Positioning Accuracy

The measured point was Tokyo-metropolitan Authorized Reference Point 10A58 near the Emperor Palace in Central Tokyo. The dual frequency signals of GPS were utilized in the experiment. The receiver was the Mitsubishi LEXR receiver with software. In this case, we used only GPS constellation for evaluating the algorithms. Tables 2, 3 and Figs.2, 3 show the test result of horizontal and height accuracies.

**Table 2 Test conditions of positioning accuracy**

| No | Item                | Content               |
|----|---------------------|-----------------------|
| 1  | Point               | 10A58                 |
| 2  | Positioning Terminal| LEXR/Software         |
| 3  | Date                | November 27th         |
| 4  | Time                | 14:22:49 - 14:29:59   |

**Table 3 Test result of positioning accuracy**

| No | Item   | 2D   | Height | Unit |
|----|--------|------|--------|------|
| 1  | Standard deviation | 0.71 | 1.15   | cm   |
| 2  | Bias   | 0.93 | 0.64   | cm   |
| 3  | RMSE   | 1.01 | 1.32   | cm   |

![Fig. 2 Test result of horizontal accuracy](image1.png)

![Fig. 3 Test result of height accuracy](image2.png)

The accuracy 1.01 cm DRMS in horizontal direction and 1.32 cm RMS in vertical direction were obtained. Furthermore, the fix rate was 99.5%. In this case, the criteria of fixing depended on the build-in function in this commertial receiver.

We can evaluate these are an equivalent level to the result of network RTK GNSS positioning method.

8.2 Convergence Time

The convergence time is defined in this paper as a time from the beginning of positioning to 100% of
ambiguity fixing in all test cases. Table 4 is the test conditions, and Fig.4 shows the test result.

Table 4 Test conditions of convergence time

| No | Item     | Content         |
|----|----------|-----------------|
| 1  | Average  | 10 cases        |
| 2  | Receiver | 7 GEONET stations |
| 3  | Region   | Kanto           |
| 4  | Date     | February 4th    |

Fig. 4 Test result of convergence time

The convergence time of 2.8 seconds was obtained. The experiment applied by post-processing and simulation.

The existing system needs at least 30 seconds for transmitting the all correction data due to the capacity of only one L6D channel (1695bps) of the satellite. Using the 5G platform, we can ignore the transmitting time, and realize very fast fixing.

Super-latency 5G mobile communication significantly contributes to shortening of the convergence time.

8.3 Experimental Summary

In the comparison with the existing system[8], this design makes the 2D RMSE from 3.57 cm to 1.01 cm, the height RMSE from 6.13 cm to 1.32 cm. Furthermore, it makes the convergence time from 60.0 s to 2.8 s. It can be said the highest performance as the unidirectional assistance of real-time GNSS positioning today.

| Performance | Existing System | Proposed Design | Unit |
|-------------|-----------------|-----------------|------|
| Accuracy 2D | 3.57            | 1.01            | cm   |
| Height      | 6.13            | 1.32            | cm   |
| Convergence time | 60.0          | 2.8             | s    |

9. Conclusion

In this paper, we show the design of a new GNSS PPP-RTK assistance system using the 5G excellences, based on the QZSS demonstrator’s heritage. In the comparison with the existing system, this design makes the horizontal accuracy from several centimeters to almost one centimeter, the convergence time from one minute to a few seconds. This is the highest performance as the unidirectional assistance system of real-time GNSS positioning for mass-market applications which should be implemented into the next-generation smart-society.

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