S & M 3217

Key Technologies of Spatiotemporal Information Service Based on Satellite Navigation Augmentation System

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(Received October 31, 2022; accepted February 16, 2023)

Keywords: spatiotemporal information, high precision positioning, satellite navigation augmentation system

Considering the problems of the spatiotemporal information service of the satellite navigation augmentation system (SNAS) and greater needs from high-tech fields, we present network real-time kinematic (RTK) and precise point positioning real-time kinematic (PPP)–RTK positioning methods. We studied spatiotemporal information services and regulatory technology, and designed a SNAS service management platform that realizes the functions of regional spatial data dissemination based on SNAS and uses measurement monitoring, measurement locale setting, and historical trajectory analysis. From the results of the sample test and analysis, we established that users can directly receive high-precision network RTK services based on regional data. PPP-RTK accuracy tests were carried out using a car, and the test results show that the accuracy of determining the horizontal position and elevation was at the level of centimeters in an open environment, indicating that this method could provide reliable positioning services.

1. Introduction

A satellite navigation augmentation system (SNAS) is designed to use the BeiDou navigation satellite system (BDS), global positioning system (GPS), global navigation satellite system (GNSS), and Galileo satellite navigation and positioning systems to correct satellite navigation and positioning errors by uniformly distributing continuous tracking facilities for navigation satellites on the ground and providing real-time, all-weather, highly reliable, centimeter-level high-precision location services for society.(1–3)

Spatiotemporal information and positioning and navigation services have become important new components of infrastructure. These services are used in meteorological forecast analysis, water pipeline maintenance, survey engineering, safety monitoring, and other fields, and focus on serving traditional surveying and mapping users such as survey engineers.(4,5) With the Beidou-3 global satellite navigation system providing comprehensive services, SNAS is now

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https://doi.org/10.18494/SAM4220

ISSN 0914-4935

facing a new situation: the newly revised “Surveying and Mapping Law” has expanded the system for managing reference stations,(6) and the relevant departments of the state have also strengthened the supervision of SNAS. With this as the background for the current development of the 5G information technology industry, SNAS can provide high-precision location services for high-tech fields such as unmanned driving technology, the Internet of Things, and big data, all of which can promote its transformation from the realm of “professional service” to “public service”.

We discuss herein the methods and technical research on positioning based on SNAS. We investigated and analyzed the problems in the user supervision service of SNAS for a specific city. We also studied user supervision technologies, such as real-time service based on a local coordinate system, developed a SNAS service management platform, and verified that the accuracy of a field positioning test meets current requirements.

2. Methods and Research on Positioning Based on SNAS

SNAS includes several reference stations using the GNSS, system monitoring stations, the platform, and data transmission links. A diagram of the high-precision positioning structure based on SNAS is shown in Fig. 1.

The computation can be divided into four steps: first, the reference stations using GNSS receive satellite navigation signals to generate original observation data and then send these data to the service platform through the data transmission links. Second, system monitoring stations receive the satellite navigation signals and augmentation service data of the platform to calculate positioning data and send the original observation, augmentation service, and positioning data to

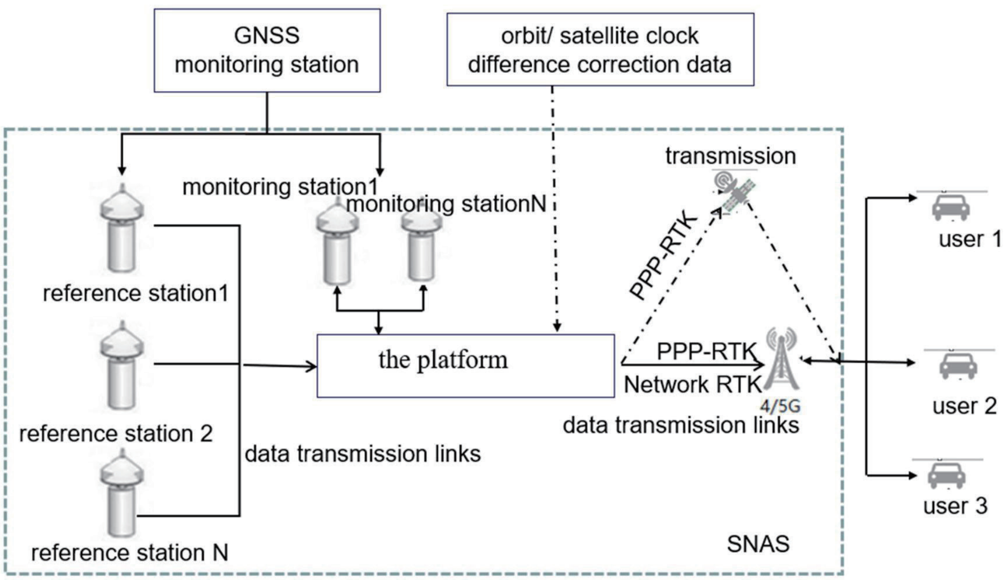


Fig. 1. Diagram of the high-precision positioning structure based on SNAS.

the platform through the data transmission links. Third, the data transmission links support data transmission between the reference stations, the system monitoring stations, users, and the platform. Finally, the platform processes data and generates augmentation service data to provide high-precision positioning services for users.

SNAS can provide network real-time kinematic (RTK) and precise point positioning real-time kinematic (PPP-RTK) positioning methods or a single position on demand. The SNAS that provides the PPP-RTK positioning method uses the global/regional GNSS reference station network to provide corrections for satellite orbits and satellite clock bias, and also provides data services. In addition, the GNSS observation data acquired by the system monitoring stations are not involved in the augmentation service data solution of SNAS.

2.1 Methods of positioning based on SNAS

Currently, there are two main popular technical methods of positioning: the network RTK and PPP-RTK methods.

2.1.1 Network RTK positioning method

The network RTK positioning method is shown in Fig. 2.[7,8] The computation can be divided into three steps.[9,10] First, after receiving data, the baseline in the GNSS reference station network is computed and the double-difference integer ambiguity is resolved. Second, the ionospheric delay, tropospheric delay, and synthesis error for each baseline are calculated using the GNSS observations, the double-difference integer ambiguity, and the known accuracy of

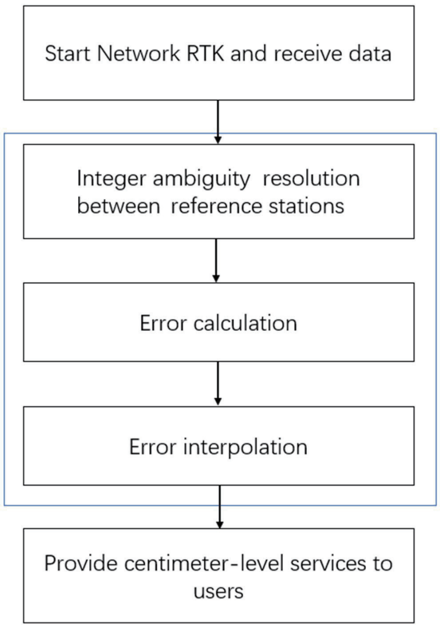


Fig. 2. Network RTK positioning method.

each reference station for each baseline. Finally, according to the approximate coordinates sent by the user, the differential correction information of the network RTK user is determined by interpolation to provide real-time cm-level positioning services for the network RTK user. The process is expressed by

$$\begin{cases} \lambda \cdot \Delta\nabla \varphi_{ij}^{pq} = \Delta\nabla \rho_{ij}^{pq} - \lambda \cdot \Delta\nabla N_{ij}^{pq} + \Delta\nabla Trop_{ij}^{pq} + \varepsilon_{ij}^{pq} \\ \Delta\nabla P_{ij}^{pq} = \Delta\nabla \rho_{ij}^{pq} + \Delta\nabla Trop_{ij}^{pq} + \gamma_{ij}^{pq}, \end{cases} \tag{1}$$

where $\Delta\nabla$ is the double-difference operator, ρ is the distance from the station to the satellite, N is the integer ambiguity, T_{rop} is the tropospheric delay error, ε is the carrier phase observation noise, γ is the pseudo-range observation noise, the superscripts p and q are the observation and reference satellites, respectively, and the subscripts i and j are the reference stations.

2.1.2 PPP-RTK positioning method

The PPP-RTK positioning method is the real-time processing of the reference stations using GNSS, realizes the separation and modeling of full-state satellite navigation and positioning augmentation service data, such as the precise satellite orbit, clock bias, phase/code deviation, and ionospheric/tropospheric atmospheric delay, broadcasts the augmentation service data to positioning users in a one-way broadcast communication mode, and supports real-time high-precision positioning technology with multiprecision and multilevel absolute positioning of a large range of users of massive data.[11,12]

Using the real-time pseudo-range and phase observation data transmitted by the reference stations using GNSS, the original observation equation for multiple frequencies is constructed, and the correction data (for example, satellite orbit, clock bias, tropospheric delay for the reference stations) are obtained by solving Eq. (2).[13]

$$\begin{cases} P_{r,f}^{s} = \rho_r^s + m_r^s \cdot T_r + \mu_f I_{r,1}^s + c \cdot \left[dt_r - dt^s + b_{r,f} - b_{r,f}^s \right] \\ L_{r,f}^{s} = \rho_r^s + m_r^s \cdot T_r - \mu_f I_{r,1}^s + c \cdot \left[dt_r - dt^s \right] + \phi_{r,f} - \phi_{r,f}^s + \lambda_f N_{r,f}^s, \end{cases} \tag{2}$$

where the superscript s represents the satellite, the subscript r represents the reference stations using GNSS, the subscript f represents the satellite frequency, P is the pseudo-range observation, L is the phase observation, ρ is the distance from the station to the satellite, m is the tropospheric projection function, T is the tropospheric zenith delay, u is the ratio of the wavelength of frequency f to the wavelength of the first frequency, c is the propagation speed of light in vacuum, dt_r is the receiver clock bias, dt^s is the satellite clock bias, $b_{r,f}$ is the pseudo-range hardware delay of the receiver, $b_{r,f}^s$ is the pseudo-range hardware delay of the satellite, $\phi_{r,f}$ is the phase offset of the receiver, $\phi_{r,f}^s$ is the phase offset of the satellite, λ_f is the wavelength of frequency f, and $N_{r,f}^s$ is the integer ambiguity between the satellite and the receiver.

The ionospheric and ionospheric delays of the reference stations using GNSS for the region are modeled by Eqs. (3) and (4).

$$STEC_{IPP} = STEC_0^{'} + \frac{dSTEC}{d\phi}\Delta\phi_{IPP} + \frac{dSTEC}{d\lambda}\Delta\lambda_{IPP} + \frac{1}{2}\frac{d^2STEC}{d^2\phi}\Delta\phi_{IPP}^2$$
$$+\frac{1}{2}\frac{d^2STEC}{d\phi d\lambda}\Delta\phi_{IPP}\Delta\Delta\lambda_{IPP} + \frac{1}{2}\frac{d^2STEC}{d^2\lambda}\Delta\lambda_{IPP}^2, \quad (3)$$

where $STEC_{IPP}$ is the total ionospheric oblique electron content at the satellite puncture point, $\Delta\phi_{IPP}$ is the latitude difference between a point and the central puncture point, $\Delta\lambda_{IPP}$ is the longitude difference between a point and the central puncture point, $STEC_0^{'}$ is a constant term for ionospheric delay polynomial fitting, $\frac{dSTEC}{d\phi}$ and $\frac{dSTEC}{d\lambda}$ are the first derivatives of ionospheric delay in latitude and longitude, respectively, and $\frac{d^2STEC}{d^2\phi}$, $\frac{d^2STEC}{d\phi d\lambda}$, and $\frac{d^2STEC}{d^2\lambda}$ are the second derivatives of ionospheric delay in latitude and longitude.

$$ZWD = ZWD_0 + \frac{dZWD}{dx}x + \frac{dZWD}{dy}y + \frac{d^2ZWD}{dxdy}x \cdot y + \frac{dZWD}{dh}h, \quad (4)$$

where ZWD is the tropospheric wet delay for the zenith, ZED_0 is a constant term for tropospheric delay polynomial fitting, x, y, and h refer to plane coordinates and elevation for the reference stations using GNSS, $\frac{dZWD}{dx}$, $\frac{dZWD}{dy}$, and $\frac{dZWD}{dy}$ are the first derivatives of tropospheric delay at x, y, and h, respectively, and $\frac{d^2STEC}{d^2\phi}$, $\frac{d^2STEC}{d\phi d\lambda}$, and $\frac{d^2STEC}{d^2\lambda}$ are the second derivatives of tropospheric delay at the plane.

Finally, the platform sends the regional delay model parameters and correction data to users in the coverage area through the communication base station to complete the PPP-RTK positioning service.

2.2 Technical research on positioning services based on SNAS

By collecting network data, reading the literature, interviewing relevant personnel such as industry authorities, associations, enterprises and institutions, and scientific research institutes, we visited the company to investigate the emerging fields and the public's demand for GNSS. We found that the reference stations had problems, such as the urgent need for positioning services based on SNAS using the Beidou-3 data, spatial data service capacity needs to be improved, and a better supervision of users. In response to these problems, research on spatiotemporal information services and regulatory technology is being carried out and the SNAS service supervision platform is being developed to improve the capabilities of the system to provide service.

2.2.1 Establishing spatial data and dissemination service technology

According to laws and regulations, relevant national requirements, and the actual development needs of a city, projection schemes have been designed. Using the collected data, the projection deformation numbers were calculated according to the length deformation equations. According to the principle that length deformation should not exceed the limit over the largest proportion of the area, analysis and optimization are carried out across different dimensions to establish spatial data for urban development.

The equations for length deformation are

$$S = D(1 - \frac{H_m}{R_n} + \frac{y_m^2}{2{R_m}^2}), \tag{5}$$

$$\Delta S = D(-\frac{H_m}{R_n} + \frac{y_m^2}{2{R_m}^2}), \tag{6}$$

where D is the horizontal distance of side length, y_m is the approximate average of the two endpoints of the abscissa, R_n is the curvature radius of the ellipsoidal surface arc truncation, R_m is the average curvature radius of the ellipsoidal surface at the midpoint of the side length, and H_m is the average elevation of the side length higher than the reference ellipsoid. These parameters are all expressed in units of meters.

The dissemination service technology based on SNAS supports the addition, query, management, modification, and deletion of solution services, and user job source nodes realize the control of user job services and sources. This new benchmark will be applied to high-precision location services.

2.2.2 Measurement monitoring

The technology described herein enables the monitoring of a user's operation location, unit, status, online duration, number of satellites used, login time, and other information. According to the situation, RTK users can be disconnected to strengthen supervision. At the same time, the total fixed rate of users is calculated to evaluate the quality of service of the system.

2.2.3 Measurement locale setting

To achieve the purpose of user control of the area of operation, the technical research on file uploading, adding, querying, managing, modifying, and deleting for the operation area is performed. In addition, an electronic fence setting has been realized.

2.2.4 Historical trajectory analysis

The SNAS service supervision platform can query the historical trajectory of a specific RTK account at different times, download and display the trajectory map, which is convenient for the management department to query and manage the records of the user terminal, and analyze big data on the basis of the location to assess the development trends of urban construction.

3. Experimental Results and Analysis

3.1 Network RTK positioning

Twelve GNSS control points were selected evenly across the entire city. The network RTK test was carried out using representative types of GNSS receivers commonly used at home and abroad, and the measured coordinate system and GNSS control point results were analyzed. At the same time, we analyzed the convergence and communication times of the network RTK to test the functionality, applicability, and usability of the satellite navigation and positioning reference service supervision platform and provide a basis for its official use.

Using the differential information released by the satellite navigation and positioning reference service system, real-time dynamic positioning measurements were carried out at the same test point. At each point, four sets of positioning were carried out. The average value of multiple positioning of each group was used to examine the accuracy of the inner and outer compliance of the test points.

The accuracy of both the inner compliance of the detection points and the external compliance between the positioning results and the known results at each detection point was measured on the basis of neutral errors. The methods of calculating the values are shown in the "technical standard for urban surveying using satellite positioning system".(14)

Observation, data processing, and accuracy evaluation must be carried out for the points. From the results of the analysis of an example, the internal compliance medium error was 12 mm, and the external compliance medium error was 24 mm, both of which are less than the technical requirements.

In addition to the evaluation of the accuracy of GNSS control points, the results of the user supervision service system platform were compared with those of the Trimble Pivot system. As shown in Table 1, the accuracy reached the centimeter level.

3.2 PPP-RTK positioning

On the basis of three reference stations using GNSS (15) and the positioning reference service supervision platform, the positioning effect of the PPP-RTK positioning terminal mounted on a vehicle in the urban environment was evaluated. The distribution of the reference stations using GNSS is shown in Fig. 3. The car equipped with a PPP-RTK terminal and test environments is shown in Fig. 4.

Table 1
Results of accuracy evaluation for network RTK positioning.

Name of points	N/mm	E/mm	U/mm
t01	6	6	15
t02	1	4	11
t03	2	1	5
t04	2	2	2
t05	6	5	7
t06	5	2	6
t08	1	3	5
t09	4	8	5
t10	3	1	8
t11	6	5	3
t12	5	8	2
t13	7	4	2

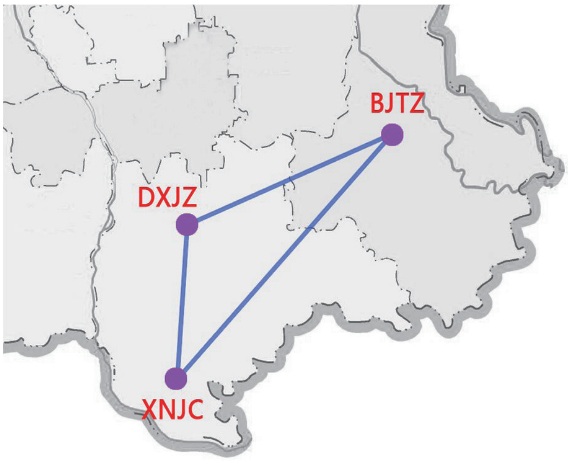
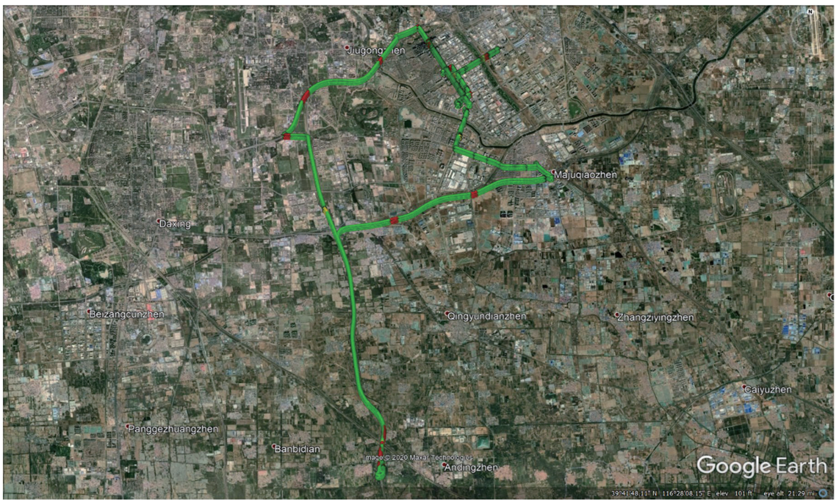


Fig. 3. (Color online) Distribution of the reference stations using GNSS.

(a)

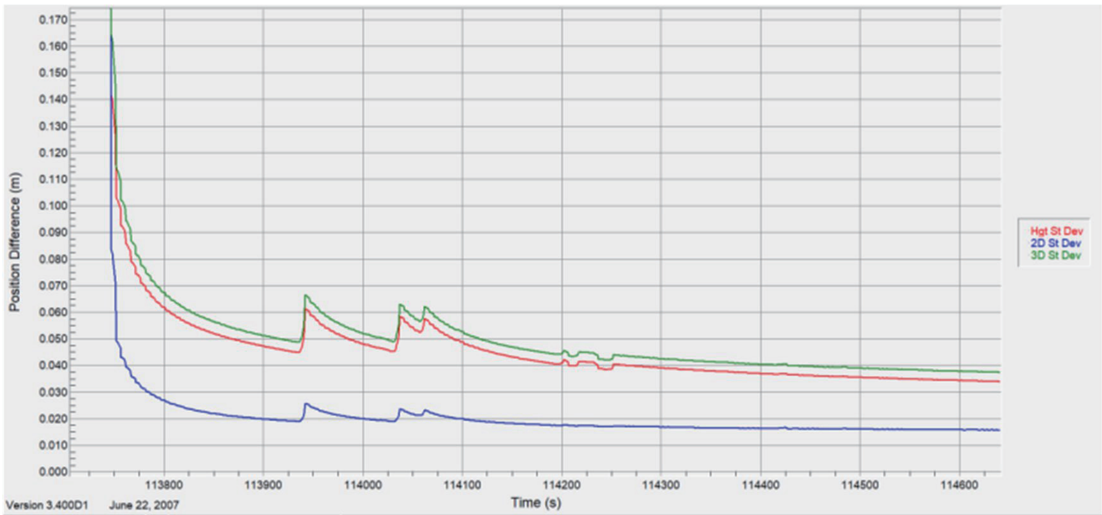
(c)



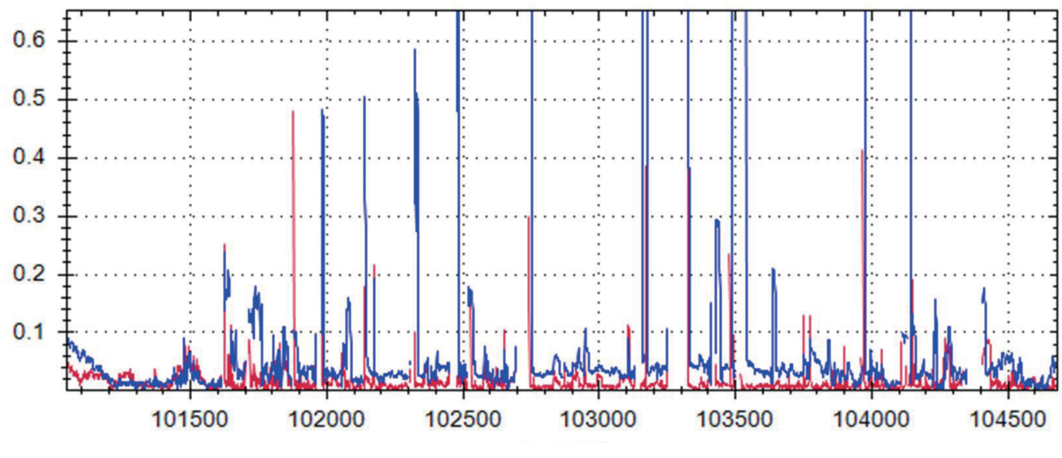
(b)

Fig. 4. (Color online) (a) Car equipped with test terminal, (b) its trace over, and (c) a test environment.

PPP-RTK static and dynamic accuracy tests were carried out. The results are shown in Fig. 5. In Fig. 5(a), the red line is the standard deviation in elevation, the blue line is the standard deviation in horizontal position, and the green line is the standard deviation in three-dimensional position. After about 50 s after powering on the terminal, the horizontal accuracy converges to less than 5 cm, the horizontal accuracy is stable within 2 cm after 400 s, and the elevation accuracy is stable within 5 cm. A few small fluctuations in the middle may be caused by fluctuations in the environment, which is normal. The blue line in Fig. 5(b) refers to the PPP-RTK dynamic accuracy; the positioning accuracy at the centimeter level can be guaranteed in normal open areas, but it is significantly reduced in the case of multiple paths and obstructions.



(a)



(b)

Fig. 5. (Color online) Results of tests of PPP-RTK (s) static and (b) dynamic accuracies.

4. Conclusions

According to the requirements of the new surveying and mapping method for SNAS combined with the new demand for high-precision positioning, the user supervision problems existing in SNAS were analyzed, key technologies such as the real-time acquisition of local coordinate systems and historical query tracks were studied, and a user supervision platform was developed. After the Beijing case test, we conclude that the accuracy of the field positioning test meets the requirements and the needs of the user supervision service. The system described herein can provide users with network RTK and PPP-RTK services. It is necessary to test the stability of the two services by considering more scenarios, which will be the focus of subsequent research.

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