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Multi-Level High Precision LBS Architecture Based on GNSS CORS Network, A Case Study of HNCORS

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ABSTRACT With the rapid development of the ground infrastructure as CORS and mobile communication stations, the high precision LBS expand from the limited fields to the public. The comprehensive LBS platforms which meet the demands such as multi-precision level, massive user and desirable scalability, become critical for the public applications. In this paper, a new high precision LBS architecture based on GNSS CORS network is presented. The platform is deployed in the cloud computational environment. It is divided into two parts: data processing and allocation system individually. The virtual grids differential corrections are involved to optimize the real-time CORS stations data processing. Besides, the API/SDK module is introduced as a new service mode, which integrates the meter, decimeter, centimeter level LBS applications, respectively realized by the coordinates, pseudo range and carrier phase differential. With the daily needs of HNCORS network, the platform "SoBDS" is established. The experiments for decimeter level example shows that, the platform could support one million users, and it is compatible and scalable. The real-time positioning accuracy is $\pm$0.425m and $\pm$0.436m in east and north. The total accuracy is $\pm$0.612m and $\pm$0.773m in horizontal and vertical direction.

INDEX TERMS Global positioning system, global navigation satellite system, continuously operating reference stations, location based service platform, RTCM protocol, application programming interface, software development kit.

I. INTRODUCTION

The Global Navigation Satellite System (GNSS) Continuously Operating Reference Stations (CORS) network indicates the establishment of the high precision navigation and positioning geospatial reference frame [1]. The CORS network have become the critical infrastructure for real-time precise positioning [2], especially for the precision which is better that one meter and even higher [3], [4]. Meanwhile, the Location Based Service (LBS) platform is turned out to be the media between the CORS agency and users. How to design and realize powerful and desirable LBS platform is one of the most important topic to expand the public applications for the CORS agencies.

The development of high precision LBS platform could be divided into 3 stages. During the earliest stage, the main target of the platform is to be compatible for the high precision positioning algorithm such as network Real-time Kinematic (RTK). The famous GNSS manufacturer (Trimble, Leica, Topcon, etc.) or even college and institutes, developed their own real-time CORS network data processing software with the supplementary Management and Service Platform (MSP) [5]–[8]. With these software, the CORS agencies could be able to provide the precise

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LBS services. In the second stage, the target is focus on how to improve and optimize the service managements. The regional CORS agencies, designed and developed the individualized MSP. For instance, the Plate Boundary Observatory from UNAVCO [9], the GAPS and CSRS-PPP from Natural Resources Canada [10], the JENOBA and GPSDATA Real-time Service from GeoNET in Japan [11]. In China, a lot of the regional CORS agencies have also developed the MSP based on Trimble Pivot Software, such as the Gansu CORS [12] and HeBei CORS [13]. The charging management system was designed for the Henan CORS [14]. The typical architecture for city level systems were discussed in literature [15], [16]. Meanwhile, some of the auxiliary functions were integrated into the MSP [17], such as the coordinate transformation, ionospheric and tropospheric monitoring, etc. For Hunan CORS, the MSP was developed to improve the daily maintenance with the location big data [18], [19]. One of the most important characteristics of the second stage is that the applications of CORS are principally oriented to the geospatial fields, especially for the surveying and mapping. For the latest stage, the aims of the CORS agencies are to meet the demands of LBS service for public applications. For the massive concurrent user condition and scalability, the cloud computation technology was introduced to the LBS platform. The cloud computational LBS platform oriented to the mobile terminals were discussed in reference [20]–[22], which effectively improved the performance under massive users condition. With combination of the reference location nodes and cloud computation, the LBS service PinPtr [23], could transform the coordinates from the relative to absolute reference frame. A cloud computational environment, which is scalable and Internet Service Provider (ISP) oriented, is proposed in reference [24]. The Internet of Things (IoT) cloud model is proposed based on the mobile LBS [25]. It uses the real-time user location info to promote the network efficiency instead of collecting info blindly. For the high precision LBS, the cloud computation is introduced for better scalability and computation efficiency. Some CORS agencies established the cloud computation resource pool, which are individually used for basic management, data processing, application developing and visualization for better utilization [26]. Huang proposed the augmented network RTK architecture with Iaas, Paas and Saas for massive user condition [27]. Similarly, some other thoughts based on grids were presented for massive concurrent users. Manurung *et al.* [28] developed the GNSS receivers as the mobile CORS station using cloud server to improve the RTK performance. The experiments proved the effectiveness in Indonesia where the number of stations are not dense enough. Cheng presented the concept GridGNSS relies on the IPv6 system [29]. It would realize the totally sharing and exchanging of GNSS observation, storage, knowledge, experts and computation resources. According to these concepts, case study with the grids pseudo range observables shows that the accuracy could reach the decimeter level [30]–[32]. In Hao's study [33], the decimeter level positioning by pseudo range differential was realized for the HNCORS network. Moreover, the Application Programming Interface (API) and Software Development Kit (SDK) for the pseudo range differential is designed and tested. While how to expand the decimeter level to both the meter and centimeter level LBS services, and integrate the 3 tpyes of precision level LBS services into a comprehensive platform, is still need to be discussed.

As mentioned above, the LBS platform experienced the development from the conventional to high precision [34], [35], from simple to comprehensive architecture, from specialized fields to the public [36], [37], from the limited computation resources to cloud computation. However, these progress still cannot meet the increasing public demands. These demands could be summarized as 3 aspects.

1) The massive concurrent users condition is one of the most critical factor. The classical positioning algorithm cannot supports the massive users condition in public applications. For example, the Virtual Reference Station (VRS) algorithm [38]–[40], which models the virtual observables for each user, is obviously not suitable for the massive concurrent user condition.
2) The comprehensive platform which is scalable is needed urgently. The desirable platform is expected to be scalable not only to the computation resource but also to all the precision level from meters to centimeters LBS services.
3) The convenience for the further application development. The LBS is usually integrated into the variable application system as one of the highlights. Unfortunately it is obviously not easy for the developer to exactly understand the basic theory as differential positioning.

Therefore, a novel high precision LBS service platform architecture based on CORS network is presented in this paper. First of all, the traditional integrated system is replaced by data processing and allocation system individually. The allocation system is deployed based on the cloud server which could be extended according to the system loading. Secondly, the virtual grids differential is involved to optimize the real-time CORS stations data processing. It is expected to improve the performance under massive concurrent user condition and scalability for the multi-level of LBS services. Finally, the API/SDK module is designed to be a new service mode, which would be useful for the application system developers.

The contents in this paper are organized as follow. In the first section Introduction, the research background is discussed and summarized. The second section shows the architecture of the presented LBS platform, especially for the improvement compared to the classical ones. In third section, the key technology as the virtual grid differential and the API/SDK mode are discussed detailed, respectively supporting the meter, decimeter and centimeter level LBS services. In the final experiments and results section, the load tests and precision tests are carried out to show the performance with case study on the SoBDS platform, which have been realized in HNCORS network.

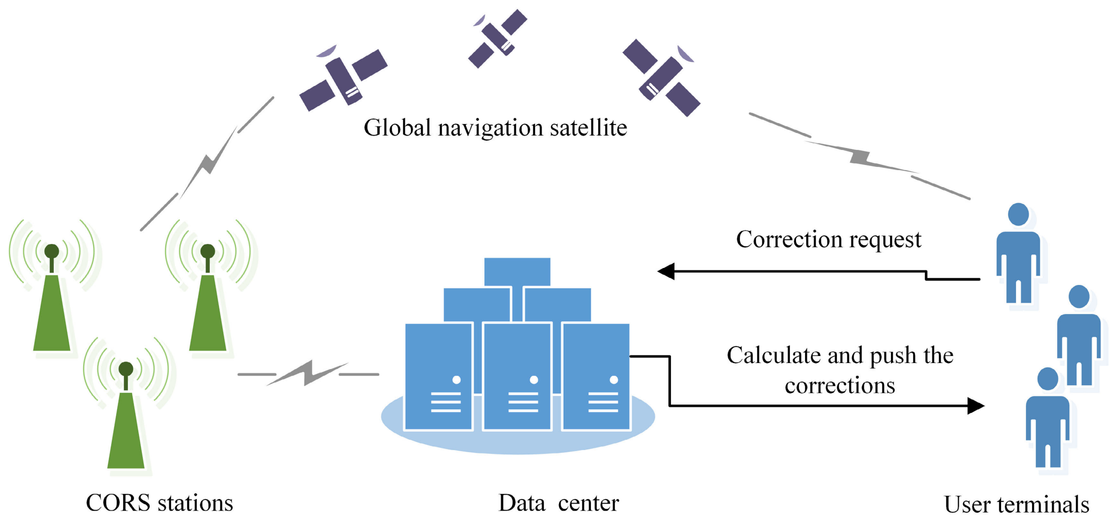

FIGURE 1. The components of high precision LBS based on CORS.

II. ARCHITECTURE

A. HIGH PRECISION LBS COMPONENTS

The high precision LBS platform is based on the CORS network, which is shown in Fig.1. A typical platform consists of 4 parts: the GNSS satellites, the ground CORS stations, the data processing center and user terminals.

The GNSS satellites mainly include GPS satellites from the United States, GLONASS from Russia, GALILEO from Europe, and BDS satellites from China [41], [42]. The satellites continuously transmit radio signals to the ground, including pseudo range and carrier phase observables.

The CORS station mainly includes antennas, receivers and internet equipment and other auxiliary device as cables. The stations are built at monument with the precise three dimension coordinate which is known. It continuously receives the signals from the GNSS satellites, and transmit them to the data processing center via internet.

The data center mainly consists of servers, routers, firewall and real-time data processing software. The software model the spatial error with the real-time observations and precise coordinates of wild CORS stations. And then it transmits the error corrections to the user terminals.

The user terminals is in varied forms, such as the geodetic GNSS receivers, handheld device, pad computer or even smart phones [43], [44]. Generally, the user terminals consists of 2 parts: the signal receiver and computing unit.

The most popular precise positioning technology is VRS [45]. Compared to the typical Master Auxiliary station (MAX or iMAX) [7], Flăchen-Korrektur Parameter (FKP) or Nearest algorithm, it works better in sparse station network and lower latitude area which often suffers from the ionospheric disturbance. According to the VRS algorithm. It models a virtual station nearby the user terminal. It is supposed that they share the similar spatial correlated error which could be well corrected by differential. For one time differential, the user terminal receives the GNSS observables and calculate the approximate location. And then the approximate location is sent to data processing center via internet. The real-time network processing software uses both the CORS stations observables and approximate coordinate to model the virtual observations at the approximate location. With the virtual observables and its own observations, the user terminal could achieve the precise location info by differential [46]. In this paper, the improvement is carried out based on the typical VRS algorithm.

B. HIGH PRECISION LBS PLATFORM ARCHITECTURE

The high precision LBS platform in this paper still contains 4 components mentioned above. While the data processing center and user terminals are improved as Fig.2. The data processing center and user terminals are further divided into 5 parts: the data processing server, virtual grids observation set, data allocation server, software system and user terminals.

The data processing server receives the observations from CORS stations and model the error as virtual stations. When processing the real-time observations, it no longer interact with the user terminals but generates virtual observations in regular or irregular grids. All the virtual station observations construct the virtual observation set. Actually, most of the real-time network processing software (such as the Trimble Pivot, Leica Spider, Topcon Topnet, South NRS) support this typical VRS algorithm.

The virtual grids corrections set can be classified into 3 types: the coordinate, pseudo range and carrier phase, respectively to the meter, decimeter and centimeter level positioning. The 3 precision levels often refer to different costs of user terminal, user groups or scenarios. The coordinate differential directly corrects the geographic coordinates from the GNSS positioning chips. Its accuracy is about 1 to 3 meters,

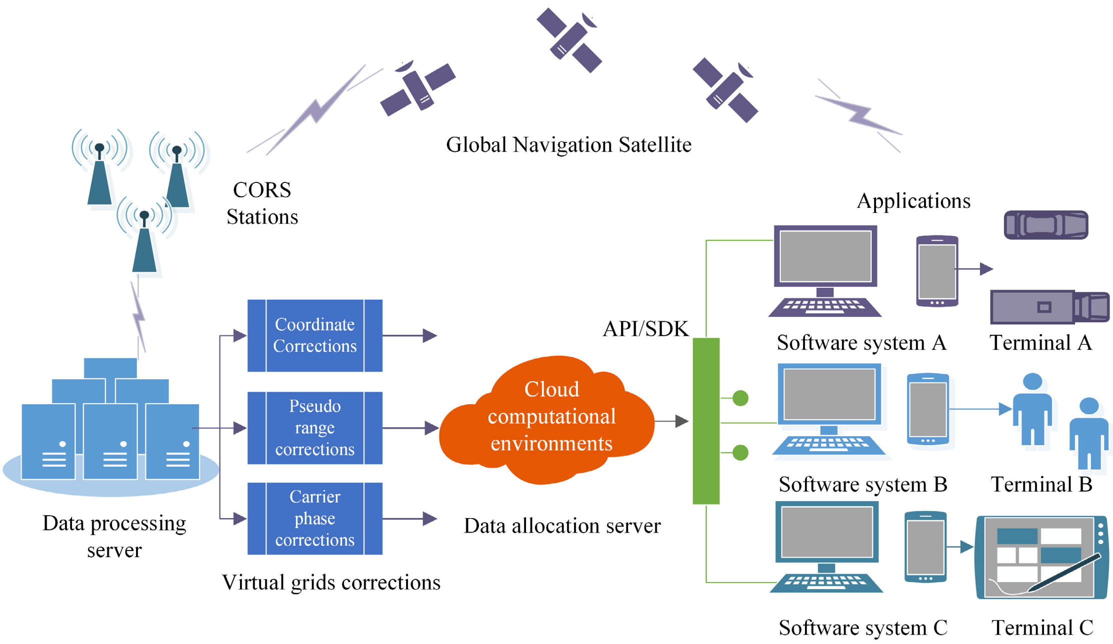

FIGURE 2. The architecture of LBS platform.

which often applied to the devices can not provide the original observables such as mobile phones. The virtual pseudo range observation is usually applied to the devices can provide the pseudo range observations. Compared to the devices supports providing carrier phase observables, the pseudo range devices has a great advantage in costs. The virtual carrier phase data actually consists both of the pseudo range and carrier phase observables. Thus, its accuracy is the best of all, which is always applied in the geography, surveying and mapping fields. The corresponding devices are often the geodetic or RTK GNSS receivers.

The data allocation server is the bridge between the virtual observations and user terminals. It is a Ntrip client in essence. It provide the functions as identity verification, service management, load balancing, grid switching, etc. The identity verification relies on the Ntrip protocol to verify terminal username and password. Only the terminal successfully verified can access for the virtual observations. The service management integrates user registration, service application, service renewal, charge management, geographical fence, etc. The load balancing is introduced for massive user conditions. On one hand, it assigns the user to the IP ports which provide the corresponding precision level services. On another hand, it assigns the users to the idle server. For example, if an user applies for decimeter level positioning, it would be assigned to the pseudo range IP ports, and then assigned to the idle server. The data allocation server should be deployed in cloud computation environment, which could be scaled according to the user number.

The user terminal is further modified as a software system and user terminal. The software system relies on the high precision LBS API and SDK. The API, which is oriented to the various software system design and development, is provided by the platform. Taking the meter level LBS as an example, it provides developer with functions as terminal management, real-time and historical location queries, geographic fences, intelligent alarms and statistical analysis. The SDK is mainly oriented to the user terminals in both IOS and Android style. For the devices could provide original GNSS observations, the SDK integrates the functions as acquirement, differential processing and export the final location info. For instance of centimeter level application, the developers usually hope to realize the application as geographic information collection. The functions as acquirement, differential and export the centimeter level location info integrated in SDK is ready for developers. The more attention could be paid on how to analyze the precise location with other geographic information but not realizing the positioning. The API and SDK can reduce the costs of high precision positioning application and improve the efficiency for system development.

III. KEY TECHNOLOGY

A. VIRTUAL GRIDS DIFFERENTIAL

For virtual grids differential, the corrections are generated at the priori defined grids center. At first, the district of the CORS network is divided into regular grids at a equivalent interval, or irregular polygon areas. Based on the approach presented in literature [33] for pseudo range differential, It has been expanded from the to both the coordinate and carrier phase domain. For instance, the coordinate differential, it is calculated by difference between the nearby CORS stations priori precise coordinates and their coordinates determined by pseudo range observables. Then the reverse

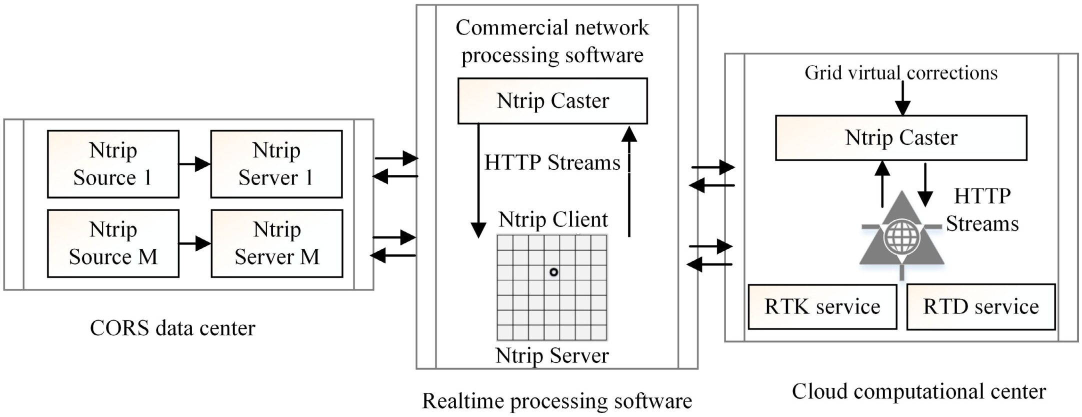

FIGURE 3. The flowchart of the grids virtual observation generation.

distance weighted interpolation (RDWI) method is introduced to estimate the coordinate correction at the center of grids. The RDWI method takes the reciprocal of the distance from the CORS stations to the grid center as the weights, which considers the impact of the relative geometry between CORS stations and grid center. The RDWI method is shown in Eq.(1):

$$\left.\begin{array}{c} V_u = \sum_{i=1}^{n} \varphi_i V_i \\ \varphi_i = S_i/S, \quad (i = 1, 2, 3, \ldots, n) \\ S_i = 1/d_i \\ S = \sum_{i=1}^{n} S_i \\ d_i = \sqrt{(x_i - x_u)^2 + (y_i - y_u)^2} \end{array}\right\} \tag{1}$$

In Eq.(1), the V_u is the correction value for the grid center u, V_i is the coordinate correction value for the ith CORS station, φ_i is the ith CORS station interpolation coefficient, and the d_i is the center point distance from the ith CORS station to grid center u.

Different from the simple approach presented in [33] for pseudo range, the carrier phase virtual observables could be generated with the commercial network processing software. Because these software are based on the Ntrip protocols, the trigger could be designed to generate carrier phase observations, which is shown in Fig.3.

There are 5 steps during the carrier phase correction generation.

1) Simulate the grid center points as a Ntrip client to sent requests to the network processing software.
2) The network processing software would identify of the grid center client, then calculates and generates the grid virtual observations at the grid center.
3) Establish the connection between the network processing software caster and grid client, and transfer the virtual observations to the grid center client.
4) Establish the data connection between the processing and the cloud allocation server, push the virtual observations to the cloud server.
5) The allocation server integrates the grid virtual observations products and sent them to the user terminals.

For the centimeter level LBS service, the positioning accuracy is relative sensitive to the horizontal and vertical distance between the user terminal and grid center. Thus, the distance and elevation of the grids should not be too large. It is suggested that, the grids interval should be designed to get the balance between the accuracy and computation load.

B. API/SDK SERVICE MODE

API/SDK is one of the most critical factors to facilitate the high precision application development. As well as corrections, there are 3 types of API/SDK: coordinate, pseudo range and carrier phase, respectively corresponding to the meter, decimeter and centimeter level LBS services.

1) COORDINATE DIFFERENTIAL WITH API/SDK (METER LEVEL SERVICE)

The coordinate differential API/SDK relies on the conventional TCP/IP protocol or the protocols based on TCP/IP (such as JT/T808, GT06, etc) to transmit the terminal location info to the cloud server. For the protocol JT/T808, each message record is composed by 5 parts as Id bit 1, header, body, check code and Id bit 2. The longitude, latitude and timestamp records are respectively starting at the eighth, twelfth and twenty-first bytes in DWORD type. The cloud server completes correction with the nearest grids center corrections, and finally returns the corrected precise location with API. The data flow is shown in Fig.4.

The coordinate differential includes 3 parts: user terminal, cloud server and virtual grid coordinate corrections. Taking vehicle application as an example, the application usually includes the software system and positioning terminal. The software system is used for the vehicle tracking, trajectory query, allocation, management and interaction. The positioning terminal is not necessary to export the satellite original observables but just the location coordinate of the vehicle, so its price is cheap. Meanwhile, the SDK deployed in the positioning terminal send the location info to the cloud server. The cloud server would finished the grid searching and differential correction, and then feedback the corrected

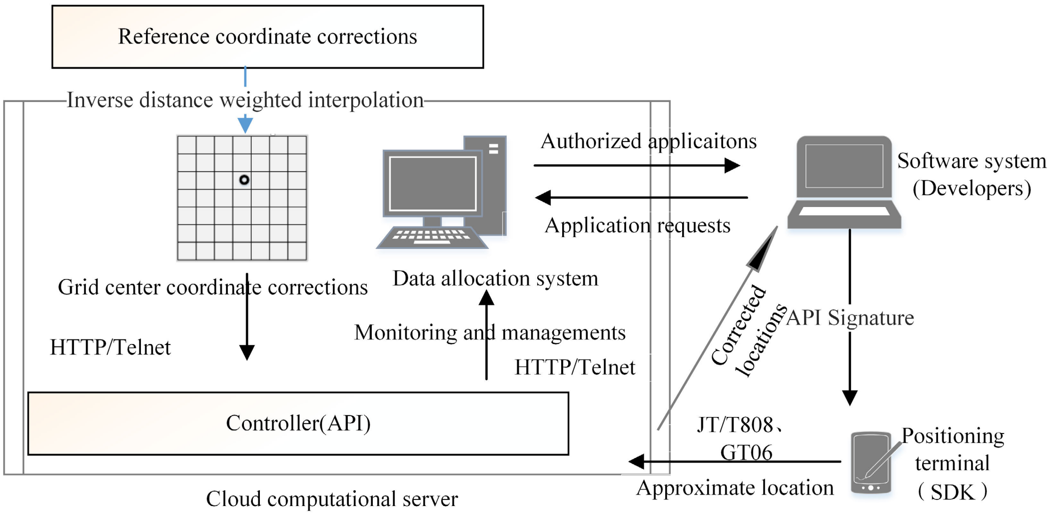

FIGURE 4. The dataflow of coordinate differential with API/SDK.

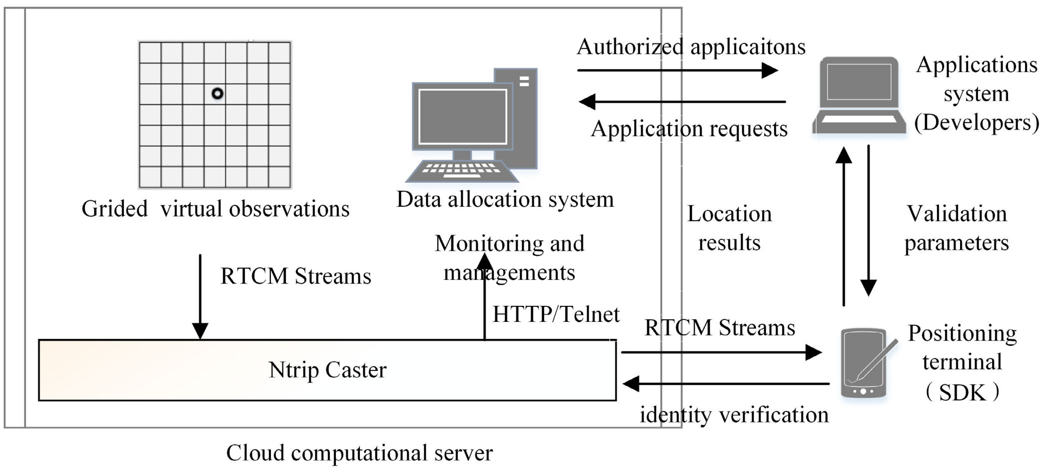

FIGURE 5. The flowchart of pseudo range differential with API/SDK.

location to the software system. The authorized software system receives the corrected location info. Moreover, the historical location info, device info, geographic fences, map service could be called back to realize the vehicle monitoring and management.

2) PSEUDO RANGE DIFFERENTIAL WITH API/SDK (DECIMETER LEVEL SERVICE)

The pseudo range differential API/SDK is oriented to virtual grid pseudo range corrections. Due to the fact that the positioning terminal price is relative moderate, the pseudo range correction is the most popular among the 3 precision level LBS. To ensure the stability and compatibility, as well as simplifying the difficulty in application realization, the identity verification and grid searching is improved based on Ntrip protocol. Moreover, the data type of the correction is the (Radio Technical Commission for Maritime services) RTCM 3.2 format [47]. The flowchart is shown in Fig.5.

In Fig.5, the pseudo range differential contains 8 steps.

1) The developers make the proposal for applications, and then apply for the service API/SDK authorization.
2) The SDK deployed in user terminals send the identification request to software system. If successful, more parameters as location, intervals would be returned.
3) Then the SDK could apply for the grid information (grid parameters and mount point).
4) The SDK finished the parameter setting of itself, then request for the virtual grid pseudo range corrections from the cloud server.
5) The cloud server validates the identity of the terminal, and then creates the grid virtual observation data stream connection.
6) The SDK realize the differential between the grid virtual observation and its own observables, then finish high precision coordinate calculation.
7) The SDK send back the high precision coordinates to the software system.

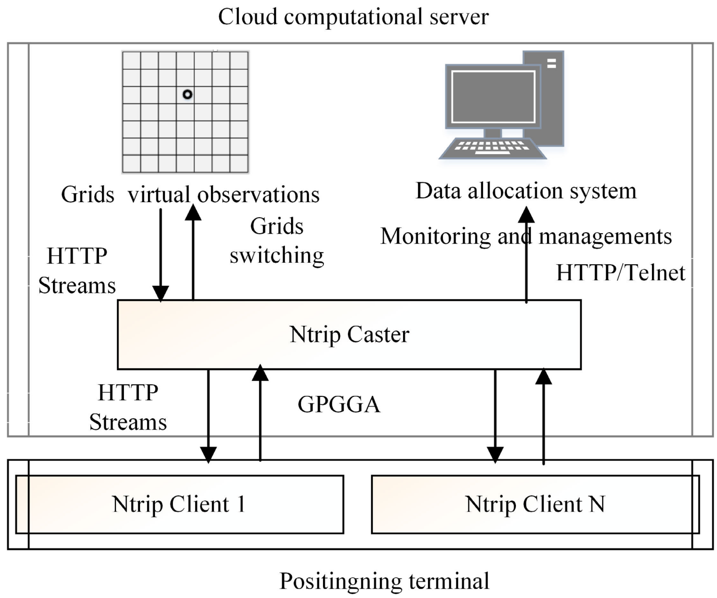

FIGURE 6. **The flowchart of the carrier phase differential with API/SDK.**

8) The SDK searches the grid information according to the location result, and repeat step 2 if the grid need to be switched.

For pseudo range differential with API/SDK, the service requests, differential processing, parameter configuration, grid searching and switching are all initiated by terminal SDK. Different from the procedure in reference [33], how the application system interacts with the data allocation system is had to be also considered here. It is worthy to note that the current supported pseudo range corrections includes the C/A and P code of GPS L1 band, the C/A code of GLONASS L1 band, and the C/A code of BDS band B1. All these corrections are transmitted to the users typically with the RTCM3.2 format with the Multiple Signal Message 4 (MSM4) records. The developers just need to callback SDK to realize software systems and App, which significantly reduces the difficulties. The developers could put more attention into the application itself, which can also greatly mitigate the load of the cloud platform server.

3) CARRIER PHASE DIFFERENTIAL WITH API/SDK (CENTIMETER LEVEL SERVICE)

The carrier phase differential API/SDK both compatible for the carrier phase and pseudo range observations, which are principally used with professional geodetic or surveying GNSS equipment [48], [49]. In the condition of the few concurrent users, the traditional network RTK technology is quite enough. While virtual grid technology works better in another two conditions. The first one is the massive concurrent users. The second one is due to the local policy. Sometimes the precise station coordinates or quasi geoid models are seem to be protected and not transmitting via internet. With the dense grid virtual stations, there would be another approach to realize the real-time normal height surveying. It just needs to change the vertical datum from ellipsoid to normal height, by adding the height anomaly to the virtual ellipsoid height of the VRS. For better compatibility of platform services, the virtual grid observations or corrections is provided in standard RTCM3.2 format. The current supported virtual observables include the C/A, P code and phase of GPS L1 and L2 band, the GLONASS L1 and L2 band, and the BDS band B1 and B2 band [50]. Thus the user terminal need not to make any change and could be greatly compatible to the other previous version. The flowchart of the carrier phase differential is shown in Fig.6.

In Fig.6, the Ntrip Client plays the role as a client in the Ntrip protocol which is integrated in the SDK. It is usually represented as a GNSS receiver. The Ntrip Client sends service requests to the Ntrip Caster server via the internet. While the service request is listened by data allocation system deployed in cloud server, the cloud server would keep tracking the approximate location returned by user terminals in GPGGA and NMEA-0183 format. If the user terminal stride cross a grid boundary, the Ntrip Caster in server would finished the grid switching and send the virtual observables at new grid center. The virtual grid observation data is returned to the user in RTCM3.2 format with the Multiple Signal Message 4 (MSM4) records. Then the user terminal uses its own and the virtual observations to complete the differential and achieves centimeter level location info.

IV. RESULTS AND DISCUSSION

The Hunan Continuously Operating Reference Stations (HNCORS) finished the first stage construction and started providing the high precision location services in 2011. In 2016, the HNCORS began to be compatible with the

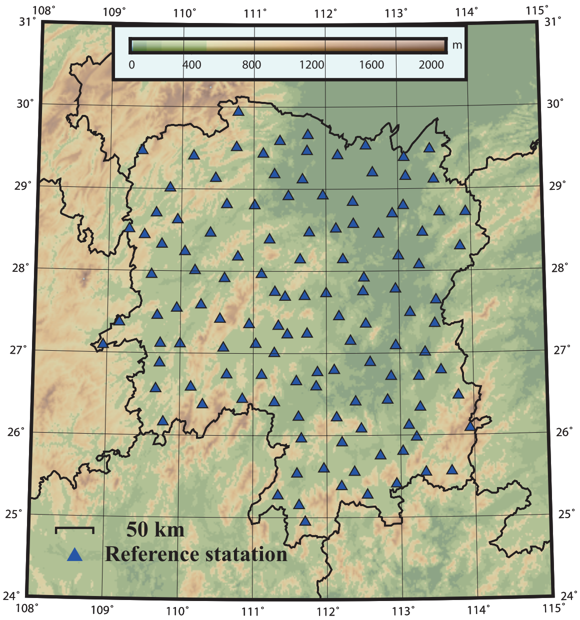

FIGURE 7. The HNCORS stations map. The blue triangle indicates a CORS station.

BDS system. There are 122 stations in HNCORS network, which is shown in Fig.7.

In August 2017, HNCORS finished the establishment of the high precision LBS platform "Solution with BeiDou Satellite system (SoBDS)" with the architecture presented above. The platform "SoBDS" provides the multi-level high precision real-time LBS service from meter to centimeter level.

A. HIGH PRECISION LBS PLATFORM SoBDS (WWW.SoBDS.COM)

The platform SoBDS mainly consists of 2 parts: data and business system. As mentioned above, the data system is in charge of the CORS stations data processing, allocation and communication. While the business system is the front system which is in charge of the service management.

The data system is used to realize the whole data communication and interaction among the users, software system, user terminals, allocation servers, and processing servers. At first, the data request is initiated by the user terminal. The server finishes the authentication and responds to the request. The user terminal also need to realize the differential with virtual grid observations (or corrections) and its own observables, and send back the results to the software systems. While the software system provide the high precision LBS service to users.

The business system of platform SoBDS is applied for user service application, system management, platform maintenance, etc. The function structure of business system is shown in Fig.8.

The business system consists of 3 parts: portal, customer center and management backstage. The portal includes 2 parts: the home page and WeChat public media. It is the window for platform introduction, news and even advertisements. The customer center is the main tool for the customer to manage the services, which could be both by Web browser and App in smart phones. The management backstage is for the platform manager in the Web style.

The experiment are carried out respectively to the aspects as the system load and precision tests. Considering that the number meter level user of HNCORS is relative rare and the centimeter level user is mainly from the surveying and mapping field, which is not so representative, the decimeter level application is introduced here.

B. SYSTEM LOAD TESTS

The system load tests are carried out to evaluate the computational capability of the platform. Different from the load tests of literature [33], the tests in this paper are carried out respectively for the data processing and allocation systems instead of single tests on local server. The purpose of data processing system test is to understand the relationship between the virtual grid density and system computation load. It is carried out in intranet environment. The testing server is DELL R9, with 2 cpus (E7-4809, 2.1 GHz basic frequency), 16 cores and 32G memory. By continuously increasing the density of the grids, the changes in the CPU and memory of the server are recorded. The data allocation system tests focuses on the relationship between the number of concurrent users and the server load. It is tested with the cloud server, the Aliyun elastic compute service (ECS). The system parameter is as follow, 24 cpus (Intel Skylake Xeon Platinum 8163 2.5GHz), 24 cores, 96G memory 20Gbps intranet bandwidth and 400 million pps. By increasing the number of concurrent users, the simulator finishes the steps as identity verification, accessing the server, receiving the virtual observations and differential. Meanwhile, the cpu and memory load parameters are recorded continuously. The tests results is shown in Fig.9.

In Fig.9(1), the horizontal axis is the size of grids. In this area, the distance of $1°$, $30'$ and $2'$ are about 85km, 50km and 3km respectively. In Fig.9(2), the horizontal axis is concurrent user number, and the vertical axis is the CPU and memory usage ratio. It is not difficult to find in Fig.9(1), the cpu load of the data processing system is gradually increasing when the grid size reduces. The most sharply growth of the cpu load is happened when the grid size reduce from $30' \times 30'$ to $12' \times 12'$ and $6' \times 4'$ to $6' \times 2'$. According to these grids number, virtual observation stream number increases from 84 to 518 and from 3416 to 6826. The increasing ratio are 51.6% and 99.8% respectively, which indicates that the cpu load is mainly affected by grid size. In contrast to CPU, memory is not varied significantly when the grid size changes. During the memory tests, the memory load is always below the 20%, which indicates that the huge memory is not necessary for grids algorithm.

It can be seen from Fig.9(2), the CPU load increases gradually as the number of concurrent users increases. The CPU load growth law is about increasing 10% every 10000 more

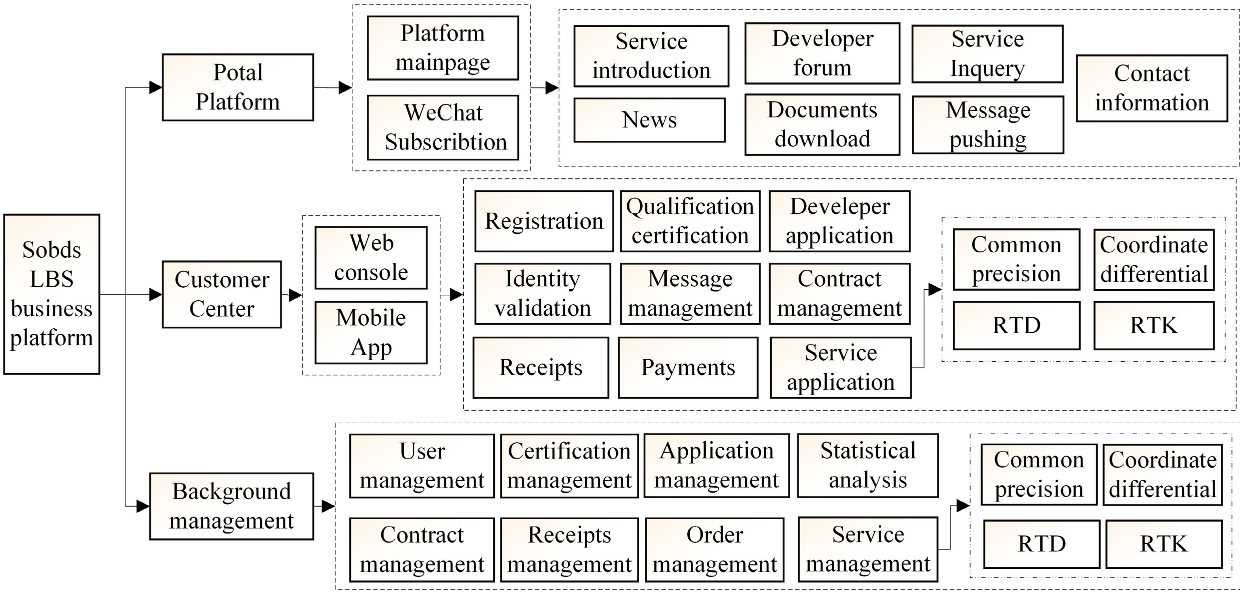

FIGURE 8. The function structure of platform SoBDS.

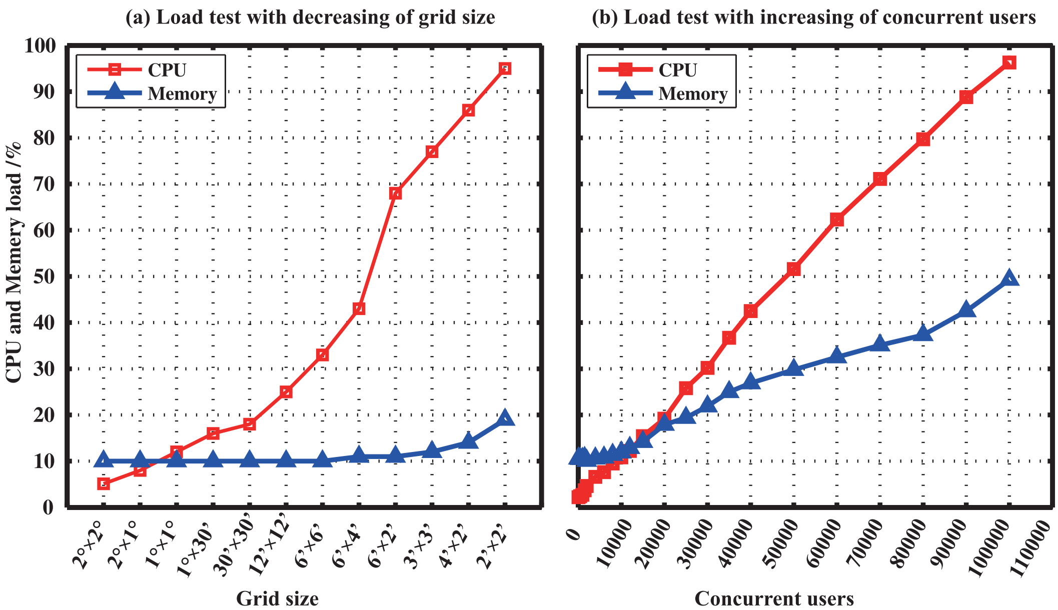

FIGURE 9. The load test results for decimeter level application.

concurrent users access for services. When the user number increases to 100000, the CPU load reaches 96.3%. For memory load test of data allocation system, the similar situation happens compared to the data processing system. Even if the concurrent user increases to 100,000, the memory is still below 50%. At present, the user number of the HNCORS is about 2100, the maximal daily concurrent user number is about 200 (9.5% to the total user). It indicates that, the maximal user number could reach more than 1,050,000 with the cloud server configuration. It is supposed to be enough for the potential users for the next 3 years. It is need to be noted that, the system computation capability could be further upgraded and extended with the cloud server for more users.

C. POSITIONING PRECISION TESTS

The precision tests are carried out on the decimeter level application as load tests. Due to the fact that the decimeter level is based on the pseudo range differential, it does not considering the carrier phase observation at all. All the solutions are float but not ambiguity fixed. And the accuracy is definitely weaker compared to the network RTK positioning. During the tests, the accuracy is represented with the Root Mean Square Error (RMSE) as Eq.(2),

$$\sigma = \sqrt{\frac{\sum_{n=1}^{N} \Delta_i^2}{n-1}} \tag{2}$$

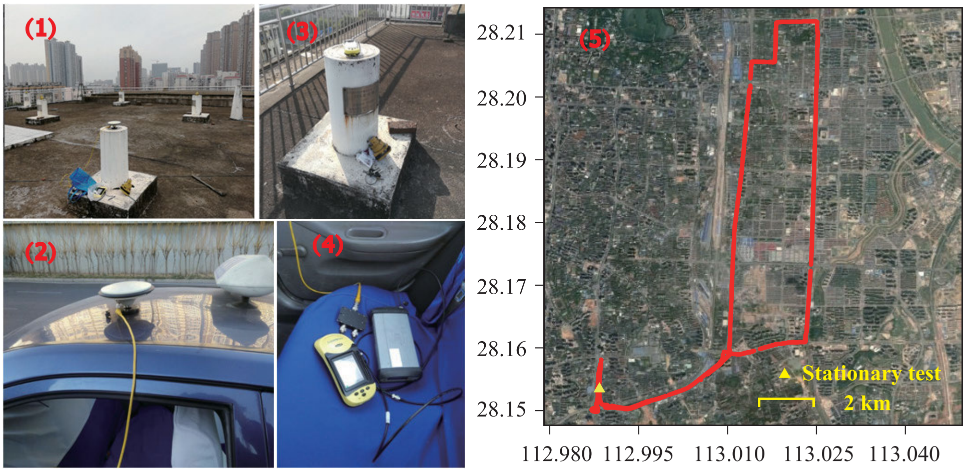

FIGURE 10. The precision tests for decimeter level application.

In Eq.(2), the Δ_i is the difference between the positioning results and the real coordinate results at a epoch in certain direction [51], [52]. The n is the number of observation epochs. For stationary tests, the RTK positioning results of the GNSS monument is seem to be the real location. For moving tests, the coordinate from Trimble geodetic GNSS receiver solved by precise data processing software is taken as the reference. With the precise priori coordinates and the real-time positioning results at every epoch (in latitude/longitude/height or x/y/z format), the external accuracy indicator is achieved. Both the stationary and moving tests were carried out in Changsha, China, which is shown in Fig.10. In Fig.10, the subfigure (1) and (3) is the situation for stationary tests. It is carried out with the monument on the top of building. The subfigure (2) and (4) shows how the moving tests carried out. The moving tests trajectory is shown in subfigure (5) of Fig.10.

1) STATIONARY PRECISION TESTS

The stationary precision tests involve an handed GNSS device (Huachen CC20 made in China) and a smart phone to provide the Wifi communication. During the tests, the difference between the handed GNSS device and prior precise location coordinates is taken to be analyzed. In reference [33], one of the test points with less than 800 epochs, is eliminated because it is from the preparation period. The error time series at 3 testing points is shown in Fig.11.

In Fig.11(1), (2) and (3), the testing points P1, P2 and P3 are respectively carried out in morning, afternoon and evening. The tests last 15, 12 hours and 23 minutes, which is corresponding to 53975, 43779 and 1341 epochs. Due to the packet loss, the final successfully resolved epochs are 52899, 41677 and 1284, respectively to resolving ratio 98.00%, 95.20% and 95.75%. The main reasons for packet loss might be the quality of the user observation condition, CORS network stations and communication [53]. For stationary tests, the quality of communication is the main reason, because the observation condition is desirable

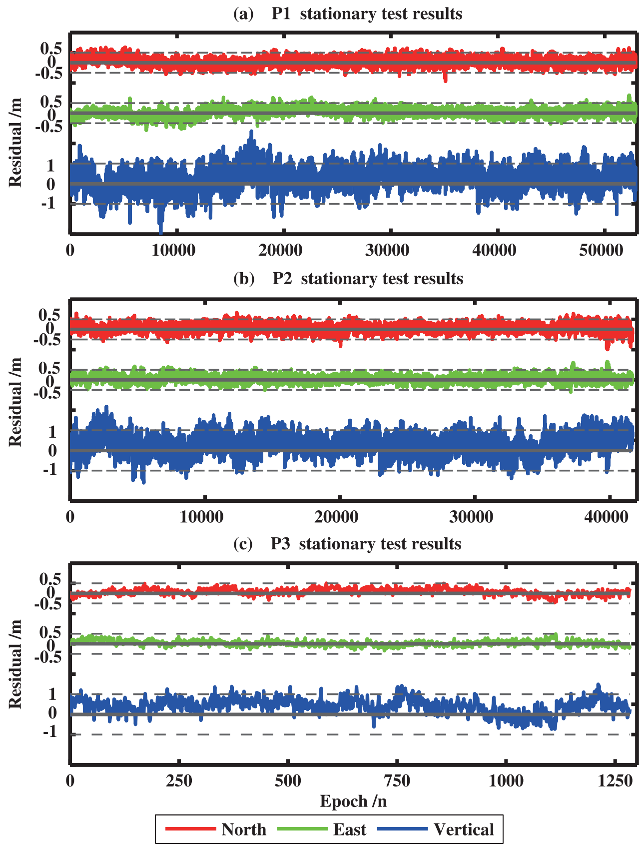

FIGURE 11. The error time series of stationary tests at 3 testing points.

on the top of building. On one hand, the real-time positioning requires the synchronization between the virtual grid observation and user terminal observables. If the grid observations is delayed, the positioning cannot be realized. On another hand, the grid observations are transmitted via 3G/4G internet. If the quality of internet is not good enough, the positioning is also impossible. The location results are shown in Table.1, respectively for north, east and vertical directions.

TABLE 1. The error statistics of precision tests.

No.	Testing Point	Grid pseudo range differential /m			Horizontal RMS/m
		North	East	Vertical	
1	Stationary: P1	0.436	0.433	0.742	0.615
2	Stationary: P2	0.447	0.407	0.732	0.605
3	Stationary: P3	0.415	0.365	0.684	0.553
4	Moving: T1	0.405	0.537	0.933	0.673

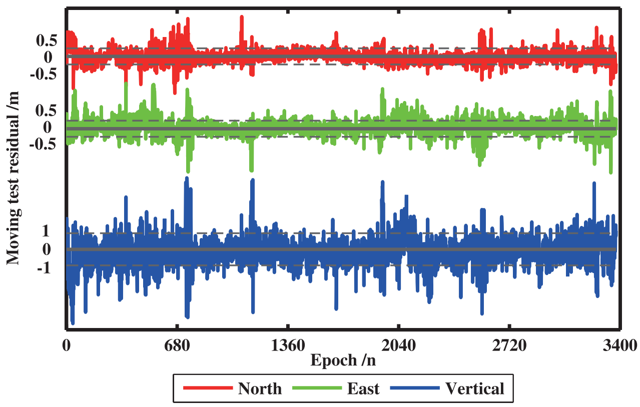

FIGURE 12. The error time series of moving tests.

It can be found out that in Table.1, the accuracy of all the test points is desirable on north and east directions. The error epochs which is greater than ±0.5m is only 1.1% and 0.83% to the total epochs. While in vertical direction, the error epochs which is greater than ±0.5m is 5.91%. It indicates that the accuracy in vertical direction is weaker than horizontal, which conforms to the general characteristics of GNSS positioning.

2) MOVING PRECISION TESTS

The moving tests are carried out by zeros baseline approach. An antenna is attached on the top of vehicle as is shown in Fig.10(2). With a signal divider, a Trimble R9 type GNSS receiver and a handed receiver are both connected to the antenna as is shown in Fig.10(4). Both the recording interval of two receivers are set to be 1Hz. The length of moving test trajectory, which is about 20.9km, is shown in Fig.10(5). The moving tests includes 2 critical steps. At first, record the observables with Trimble R9 type GNSS receiver. Meanwhile, record the real-time location results from handed receiver. Secondly, calculate the precise location results from Trimble GNSS receiver. The location results would be taken as the reference to be analyzed with real-time location results from handed receiver. The error time series of moving test is shown in Fig.12.

The moving tests started at 2017/12/26, 10:00AM. The moving test lasts about an hour, 3664 epochs in total. The successfully resolved epochs number is 3375, which is 92.11% to the total epochs. It is clearly shown in Fig.10(5), the packet loss happens near the intersections or flyovers. With analysis on the observations, it can be found out that the reason for packet loss is different from the stationary tests. It is mainly caused by the observation conditions, where it is almost impossible to capture the signals from satellites. The moving test error statistics is shown as the No.4 item in Table.1. As well as the stationary tests, the RMSE in north and east is better than vertical direction. The epochs of error which is greater than ±0.5m is about 15.7% and 26.6% to total epochs. While for the vertical direction, the error epochs which is greater than ±1m is about 21.5%. The epochs with better accuracy mainly happens in the middle of the test (from epochs 680 to 2500), where the cars were mainly travel on the highway, expressway or the flyover. The observation conditions are desirable for the satellite positioning, which leads to the better accuracy. In this period, the error epochs which is greater than ±0.5m is about 11.0% and 19.7% to total epochs respectively in north and east. While for the vertical direction, the error epochs which is greater than ±1m is about 17.9%. It indicates that the observation condition is one of the critical factor for precise satellite positioning.

V. CONCLUSION

In this paper, a multi-level high precision LBS architecture, which support the meter, decimeter and centimeter level LBS services, is presented. The platform is deployed in the cloud computational environment to improve the scalability. And the virtual grids differential is introduced to optimize the real-time CORS stations data processing, which makes it be able to solve the problem of concurrent users. Moreover, the API/SDK module is designed as a new service model to achieve the better efficiency on multiple precision level LBS developments. With the daily needs of HNCORS network, the platform "SoBDS" is established, which integrates the meter, decimeter, centimeter level LBS applications with respectively coordinate, pseudo range and carrier phase differential. The experiment results for decimeter level example shows that, the platform could support one million users, and it is also compatible and scalable. The real-time positioning accuracy is ±0.425m and ±0.436m in north and east. The total accuracy is ±0.612m and ±0.773m in horizontal and vertical direction. In future, how to optimize the grid and cloud server parameters (such as the density or load balancing) with artificial intelligent algorithm might be one of the research interest.

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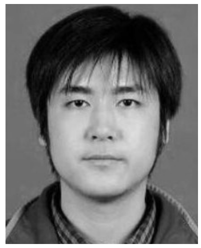

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