Positioning and Timing Test Campaign Based on China Area Positioning System (CAPS)

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Abstract: With high performance ground atomic clock and satellite retransferring feature, CAPS achieved higher positioning and timing precision than traditional GNSS. Positioning and timing high-performance verification test has been conducted by National Time Service Center (NTSC in Xi'an, China) in Xi'an city Shaanxi province. Test results show that, (1) the accuracy of the code phase timing and the carrier phase timing with single GEO satellite are better than 5 ns and 0.5ns, respectively; (2) the accuracy of the code phase positioning and the carrier phase positioning with 1 IGSO and 3 GEO satellites are better than 1.5 meters and 0.5 meters respectively. The results indicate the ability of high-precision positioning and timing of CAPS.

Keywords: China Area Positioning System (CAPS), positioning and timing, test campaign

1. Introduction

With the development of science and technology, many fields need more accurate real-time positioning and timing service, such as space target interception and strike need nanoseconds level timing and decimeter level positioning accuracy. Traditional GNSS can not meet the requirement. With C-band radio frequency, China Area Positioning System (CAPS), a novel regional satellite navigation system proposed by Chinese Academy of Sciences (CAS), can provide the high-performance positioning and timing service based on carrier phase. GNSS use satellite special-developed for navigation to broadcast navigation signal generated onboard to users [1,4], while in CAPS, the satellite transponder without onboard atomic clock is used as navigation satellite. It aims to transparently transfer the navigation signal generated on the ground.

For working on C-band, the wavelength of the CAPS and GPS L1 signal is 7.84 cm and 19.04 cm, respectively, therefore, the precision of CAPS carrier-phase measurement would be theoretically higher than GNSS [2].

In this paper, the CAPS architecture, principle and the features are introduced, the timing and positioning test is described, and test results will be showed.

2. System Architecture

CAPS consists of the space segment, the ground segment and the user segment.

2.1 Space Segment

The space segment includes four GEO communication satellites (transponder) and an inclined geosynchronous orbit (IGSO) satellite (transponder) at present. Table 1 shows the orbit locations of the four communication satellites.

Table 1. 4 GEO communication satellite resources

NUM	Satellite	Location	Available Frequency	EIRP
1	APSTAR 7	76.5°E	3826±18MHz	39dBW
2	ChinaSat 12	87.5°E	3826±18MHz	40dBW
3	ChinaSat 10	110.5°E	3826±18MHz	44dBW
4	Measat2	148°E	3700~4200MHz	41dBW

The ascending node of the IGSO satellite is 95°E and the orbital inclination angle is 55°. All of the satellite transponders operate on C-band.

2.2 Ground Segment

The ground segment mainly realizes the generation, maintenance and transmission of the system time, the precision orbit observation and determination of each satellites and the navigation signal transmission and reception processing. It is mainly divided into three parts:

(1) Time and frequency reference generation and maintenance center is mainly composed of high-performance atomic clock group, time and frequency integrated equipment, two-way comparison equipment of high-precision time and frequency signal, time and frequency signal distribution network. It provides high stability and accuracy time and frequency signals and time code information for system.

(2) The satellite orbit observation and determination center are made up of the orbit observation and determination main station located in Xi'an and the secondary stations located in Changchun, Xuyi, Kashgar, Sanya, and Kunming. It mainly realizes precise forecasting and determination of the GEO satellites and IGSO satellite orbits and provides highly reliable precise ephemeris data.

(3) The navigation signal controlling center consists of four ground stations with 13-meter aperture antenna, one ground station with 16-meter aperture antenna,

navigation message and virtual clock data processing and management equipment and supporting equipment. It mainly realizes the generation of virtual atomic clock, the generation and transmission of satellite uplink navigation signals, the reception and processing of satellite downlink navigation signals and high-precision ranging.

2.3 User Segment

Multiple types of user receivers including pseudo-random code user receivers and carrier-phase user receivers have been developed by NTSC, which can provide high precision positioning, timing and velocity measurement (PVT) services for users. The carrier-phase high-precision PVT user receiver is shown in figure 1.

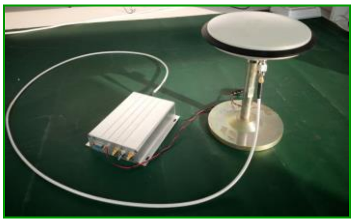


Figure 1. carrier-phase high-precision PVT user receiver

3. Basic Principle

CAPS is different from GNSS in that the navigation signal is generated on the ground and up loaded to the communication satellites. [3] And then the navigation signal is broadcasted to users by the satellite transponder. The basic principle of CAPS based on communication satellites transfer mode is shown in figure 2 as below.

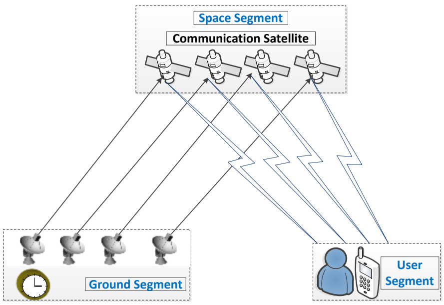


Figure 2. The basic principle of CAPS based on the communication satellite transponder

The figure 2 shows that CAPS adopts commercial geostationary orbit (GEO) communication satellites to form a navigation constellation. The navigation signal and the navigation message are generated on the ground and re-transferred to users via satellite. Therefore, the range which is measured by user receiver is that the signal path from the ground station to satellite including the time delay of satellite transponder and plus the path from the satellite to the receiver. The range can be expressed as:

$$\rho = c \cdot (\tau_{uplink} + \tau_{transp}) + \rho_{down} = c \cdot \tau_{Vclk} + \rho_{down} \tag{1}$$

where ρ is the range of the whole loop , ρ_{down} is the range from the satellite to the user receiver, τ_{uplink} is the time delay from the ground station to satellite, τ_{transp} is the time delay of the satellite transponder, c is the speed of light.

Compared with GNSS, there is an additional uplink path from the ground station to the satellite in the signal transmission path of CAPS. However, the pseudo-range used for positioning and timing is the measurement between the satellite and the users.[3] Hence, this additional uplink distance must be known to user for PVT services. A method called "Virtual Atomic Clock" is proposed to solve this additional uplink.[6] The modems on ground station transmit the ranging signal and receive it, and the real-time measurement ranging data is used to build the "virtual atomic clock" model to predict the uplink delay τ_{uplink} and the satellite transponder time delay τ_{transp}. The virtual clock correction includes the uplink atmospheric delay, satellite receiving and retransfer delay.[3] The model will be broadcasted to users in the navigation message. From the perspective of the user terminal, the CAPS users obtain PVT service by passively receiving navigation signals, which is almost as same as the way that of GNSS users. There is only a difference in calculation method of the pseudo-range from the satellite to the user receiver which will be explained in detail below.

3.1 Single-Satellite Time Service Principle

The precise position coordinates (X_u, Y_u, Z_u) is known to a static user, precise time measurement or synchronization can be achieved by observing only one satellite (x_s, y_s, z_s).[8] The principle of single-satellite time service of the CAPS is shown in figure 3.

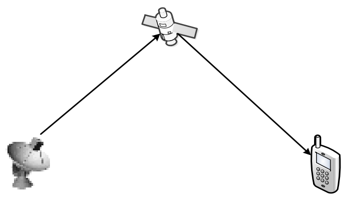


Figure 3. Single-satellite time service of the CAPS

The unknown amount Δt_u is defined as the clock difference between the system clock and the user clock. ρ is the pseudo-range from the ground station to the user which is measured by receiver directly, the observation equation is:

$$\sqrt{(X_u - x_s)^2 + (Y_u - y_s)^2 + (Z_u - z_s)^2} + c \cdot \Delta t = \rho - c \cdot \tau_{Vclk} \tag{2}$$

The satellite position (X_u, Y_u, Z_u) can be obtained from the broadcast ephemeris in the navigation message, and τ_{Vclk} is the time delay from the ground station to the satellite and the satellite transponder time delay. τ_{Vclk} can be calculated from the "virtual atomic clock" model.

3.2 Positioning Principle

Similar to GNSS, CAPS utilizes time of arrival (TOA) ranging to determine user position.[4] By making TOA measurement to at least four satellites, three-dimensional positioning can be achieved [4]. When using the CAPS system to determine user position, it is necessary to simultaneously observe four or more satellites to obtain the user coordinate and receiver's clock error. Pseudo-range measurements can be done by observing the tracking the satellite, and the observation equations are:

$$\| S_j - u \| + c \cdot \Delta t_u = \rho_j - c \cdot \tau^j_{Vclk} \tag{3}$$

where j refers to different satellites and their corresponding signal transmitting ground stations, S indicates the satellite coordinate, u is the position of the user receiver, Δt_u is the clock difference between the user clock and the system clock, ρ_j is the pseudo-range from the ground station j to the user, τ^j_{Vclk} is the time delay from the ground station j to satellite j and its transponder time delay. When j=1,2,3,4, the equation (3) can be expanded into the following set of equations in the unknowns x_u, y_u, z_u and Δt_u:

$$\begin{aligned}
\sqrt{(x_u - x_s^1)^2 + (y_u - y_s^1)^2 + (z_u - z_s^1)^2} + c \cdot \Delta t &= \rho_1 - c \cdot \tau^1_{Vclk} \\
\sqrt{(x_u - x_s^2)^2 + (y_u - y_s^2)^2 + (z_u - z_s^2)^2} + c \cdot \Delta t &= \rho_2 - c \cdot \tau^2_{Vclk} \\
\sqrt{(x_u - x_s^3)^2 + (y_u - y_s^3)^2 + (z_u - z_s^3)^2} + c \cdot \Delta t &= \rho_3 - c \cdot \tau^3_{Vclk} \\
\sqrt{(x_u - x_s^4)^2 + (y_u - y_s^4)^2 + (z_u - z_s^4)^2} + c \cdot \Delta t &= \rho_4 - c \cdot \tau^4_{Vclk}
\end{aligned} \tag{4}$$

Where x_s^j, y_s^j, z_s^j denote the jth satellite's position in three dimensions which can be obtained from the broadcast ephemeris in the navigation message. τ_{Vclk}^j can be calculated by the "virtual atomic clock" model in the navigation message. ρ_j is the measurement pseudo-range of the receiver. Hence, x_u, y_u, z_u and Δt_u can be calculated.

3.3 System Features

The main features of CAPS is that the navigation signals and navigation messages are generated and uplinked directly to the satellite from the ground control station, before being downlinked and broadcasted to users via the communication satellite transponder[5].CAPS does not require the on-board atomic clock and use a higher stability atomic clock group in the ground station[2].Therefore, the complicated on-board technique can be greatly simplified and the system can be easily and flexibly built at a low cost. In addition, the constellation of CAPS can be flexibly selected by renting the transponders on the communication satellites. [9]
Furthermore, CAPS uses C-band frequencies for navigation. Therefore, the error caused by the ionosphere and multi-path effect is smaller and the precision of carrier-phase measurement is higher than that of the GNSS. These features hold the promise of achieving PVT service with a relatively high accuracy.

4. Test and Analysis

Timing and positioning test had been carried out in NTSC in August 2017, with receiver used 4-Hz sampling frequency.

4.1 Test campaign

The basic structure of CAPS receiver is almost like the GPS receiver. The main difference is timing and positioning algorithm and the radio frequency. For no anti-multipath antenna, the antenna was installed on a 40-meter high tower to reduce the multipath effects. The figure 4 shows the basic frame of the test.
The single-satellite timing test was performed by observing a GEO satellite. The timing error data was collected by the counter SR620. The 1PPS signal from the atomic clock in the ground station is used as the opening signal of the counter, and

the output 1PPS signal of the receiver was used as the closing signal. The output of the counter is the timing error of the CAPS system.

The constellation type of 4 GEO satellites cannot provide 3D positioning because the GEO satellites are all located in orbit over the equator.[3] Therefore, when IGSO satellite is available, positioning tests can be performed by using 3 GEO satellites and 1 IGSO satellite.

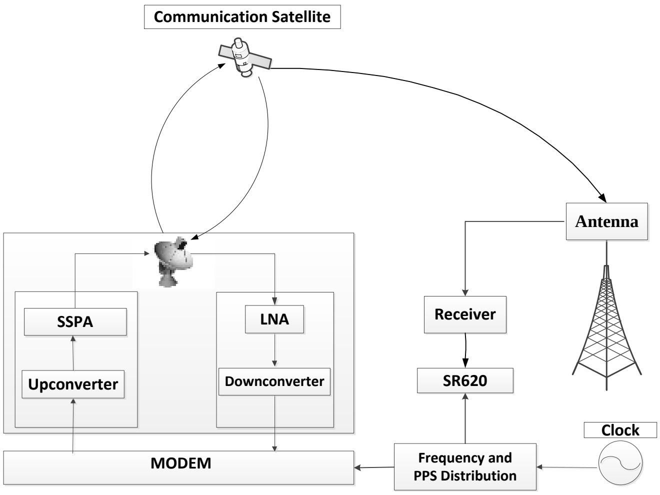


Figure 4. The frame of the test

4.2 Test results and analysis

The communication satellite APSTAR 7 was selected to performed the single-satellite timing test. The timing results based on the code measurement and the carrier measurement are illustrated in figure 5. The standard deviation of the single-satellite timing errors based on the code measurement is 0.3028 ns, while the result base on carrier measurement is 0.1566 ns. It can be seen that the timing errors based on the carrier measurement is smaller than the code measurement.

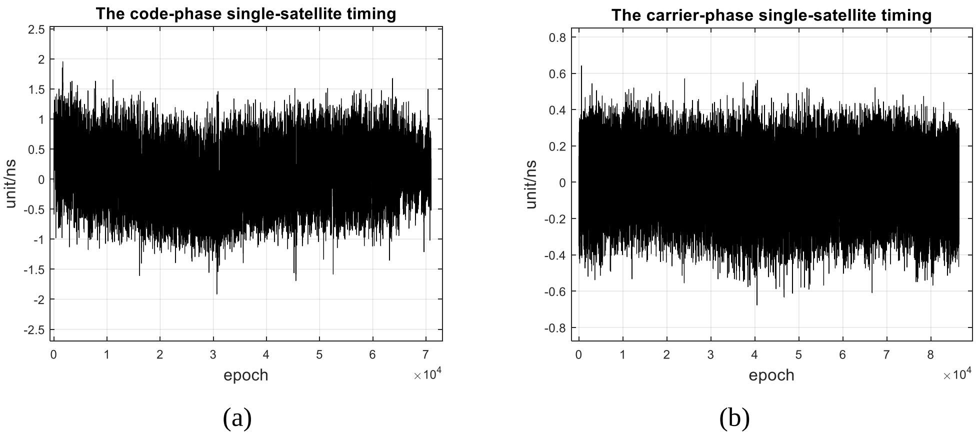
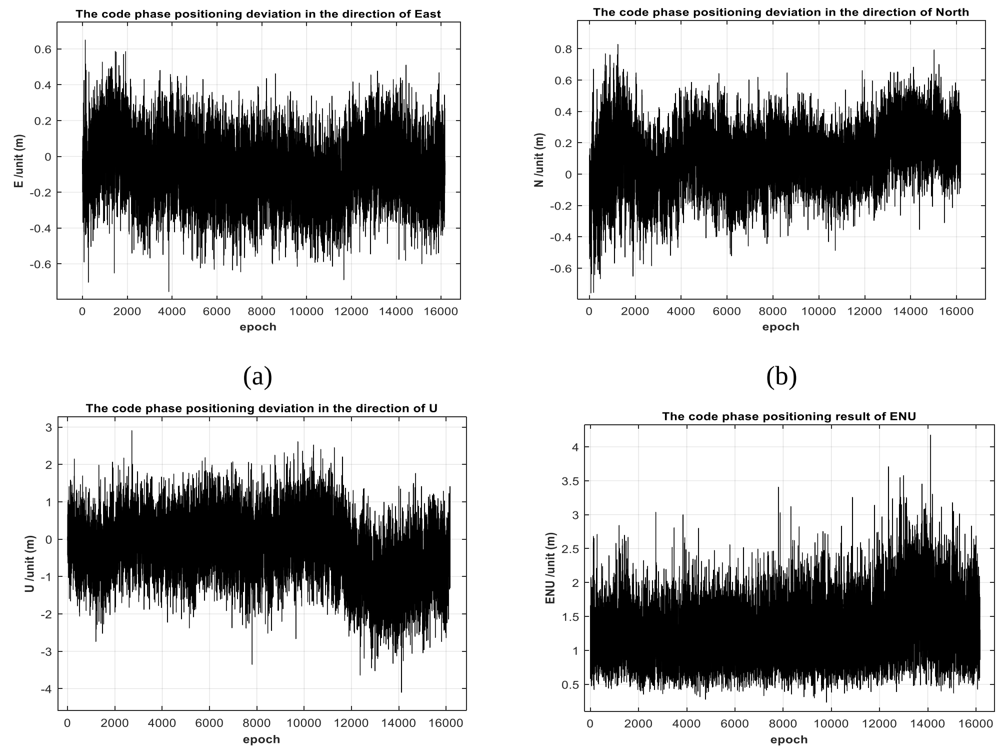


Figure 5. The single-satellite timing error of the CAPS based on the code phase measurement (a) and the carrier phase measurement (b).

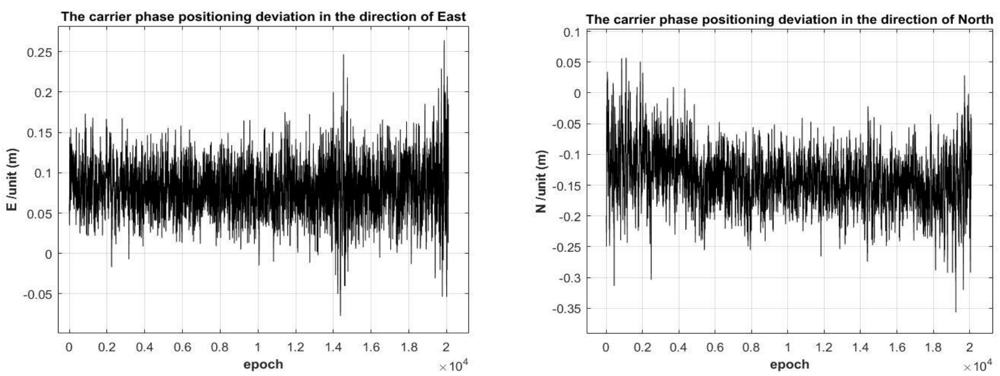
The positioning errors in the east, north and vertical components and synthetic ENU for the static positioning based on the code measurement are illustrated in figure 6, while the corresponding results for the carrier-phase measurement are shown in figure 7 respectively. It can be seen that the positioning result in the east-west component is much better, both for the code-phase and for the carrier-phase measurements. This is mainly because of the distribution of the current CAPS constellation. It can be seen that there is a slow fluctuation in the positioning results based on the code measurement from figure 6. This is caused by the multipath error. Although the multipath effect can be reduced by placing the antenna position, it is still difficult to eliminate.



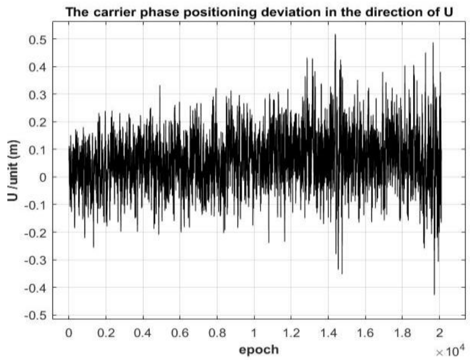
(a) (b)

(c) (d)

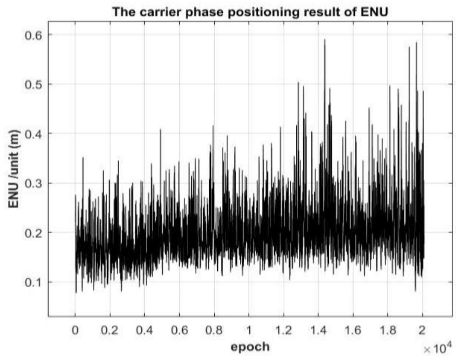
Figure 6. The positioning error in the east (**a**), north (**b**) and vertical (**c**) components and synthetic ENU (d) for the CAPS static positioning based on the code measurement.



(a) (b)



(c)



(d)

Figure 7. The positioning error in the east (**a**), north (**b**) and vertical (**c**) components and synthetic ENU (d) for the CAPS static positioning based on the carrier measurement.

The root mean square (RMS) of those positioning errors results are shown in Table 2. The accuracies of the positioning based on the code measurement are about 0.1876 m, 0.2128 m, 0.8749 m and 1.3391 m in the east-west, north-south and vertical components and synthetic, respectively, while the corresponding results based on carrier measurement are about 0.0867 m, 0.1462 m, 0.1150 m and 0.2058 m. The standard deviations of the positioning results are shown in Table 3.

Table 2. RMS of the positioning errors

RMS/m	East-West	North-South	Vertical	Synthetic
Code Measurement	0.1876	0.2128	0.8749	1.3391
Carrier Measurement	0.0867	0.1462	0.1150	0.2058

Table 3. Standard deviation of the positioning errors

STD/m	East-West	North-South	Vertical	Synthetic
Code Measurement	0.1741	0.1848	0.8317	0.4452
Carrier Measurement	0.0306	0.0440	0.0971	0.0565

5. Conclusion

CAPS is a regional navigation system based on commercial communication satellite transfer mode which is proposed and built by Chinese Academy of sciences. It operates on C-band and it is a technical experiment and validation platform. According to the principle, verification tests and the analysis, the following conclusions can be drawn:

(1) Based on the architecture and the principle of the CAPS, this novel system has obvious advantages include: (a) higher precision because of C-band; (b) no need of on-board atomic clock; (c) short construction period; (d) low investment.

(2) The precision of CAPS single-satellite timing is about 0.3028 ns and 0.1566 ns based on the code measurement and the carrier measurement, respectively.

(3) The accuracy of CAPS static positioning based on the code measurement and the carrier measurement is about 1.34 m and 0.2 m, respectively. The static positioning precision of CAPS is higher than GPS. The positioning error in the east-west component is smaller because of the distribution of the constellation. CAPS also has a number of disadvantages. For example, the PDOP of CAPS is not good as that of GNSS. The navigation signal is retransferred by satellite transponder which will destroy the continuity of carrier. The CAPS is still in the development and some of the disadvantages may be overcome. In addition, higher positioning accuracy can be achieved by improving the orbital accuracy or by using precise ephemeris for data post-processing.

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