A Positioning System based on Communication Satellites and the Chinese Area Positioning System (CAPS) *

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Abstract The Chinese Area Positioning System (CAPS) is a positioning system based on satellite communication that is fundamentally different from the 3"G" (GPS, GLONASS and GALILEO) systems. The latter use special-purpose navigation satellites to broadcast navigation information generated on-board to users, while the CAPS transfers ground-generated navigation information to users via the communication satellite. In order to achieve accurate Positioning, Velocity and Time (PVT), the CAPS employs the following strategies to overcome the three main obstacles caused by using the communication satellite: (a) by real-time following-up frequency stabilization to achieve stable frequency; (b) by using a single carrier in the transponder with 36 MHz band-width to gain sufficient power; (c) by incorporating Decommissioned Geostationary Orbit communication satellite (DGEO), barometric pressure and Inclined Geostationary Orbit communication satellite (IGSO) to achieve the 3-D positioning. Furthermore, the abundant transponders available on DGEO can be used to realize the large capacity of communication as well as the integrated navigation and communication. With the communication functions incorporated, five new functions appear in the CAPS: (1) combination of navigation and communication; (2) combination of navigation and high accuracy orbit measurement; (3) combination of navigation message and wide/local area differential processing; (4) combination of the switching of satellites, frequencies and codes; and (5) combination of the navigation message and the barometric altimetry. The CAPS is thereby labelled a PVT5C system of high accuracy. In order to validate the working principle and the performance of the CAPS, a trial system was established in the course of two years at a cost of about 20 million dollars. The trial constellation consists of two GEO satellites located at E87.5° and E110.5°, two DGEOs located at E130° and E142°, as well as barometric altimetry as a virtual satellite. Static and dynamic performance tests were completed for the Eastern, the Western, the Northern, the Southern and the Middle regions of China. The evaluation results are as follows: (1) land static test, plane accuracy range: C/A code, 15∼25 m; P code, 5∼10 meters; altitude accuracy range, 1∼3 m; (2) land dynamic test, plane accuracy range, C/A code, 15∼25 m; P code, 8∼10 m; (3) velocity accuracy, C/A code, 0.13∼0.3 m s^{-1}, P code, 0.15∼0.17 m s^{-1}; (4) timing accuracy, C/A code, 160 ns, P code, 13 ns; (5) timing compared accuracy of Two Way Satellite Time and Frequency Transfer (TWSTFT), average accuracy, 0.068 ns; (6) random error of the satellite ranging, 10.7 mm; (7) orbit determination accuracy, better than 2 m. The above stated random error is 1σ error. At present, this system is used as a preliminary operational system and a complete system with 3 GEO, 3 DGEO and 3 IGSO is being established.

Key words: astronomy application — satellite navigation — satellite communication — astrometry — astronomic technique

1 INTRODUCTION

In early human history, navigation was aided with pure natural phenomenon – stars, such as the North Star or the Sun. Because visible light is often insufficient in all weather and daytime, the magnetic compass equipped with a lodestone, which is well known as one of Chinese four great inventions, was used as a guide, and navigation by means of natural features lasted thousands of years in history.

In recent time, people created special-purpose aid systems to meet navigational demands, such as light-houses and the inertial navigation system. Significant development of navigation by artificial systems came from the invention of the radio, including the widely used Loran-C system (Gan 2000). Rocket technology has promoted development of the aerospace. Furthermore, the inventions of satellite and the spacecraft enabled the positioning and navigation system to make a start. The 3"G" systems (GPS, GLONASS and GALILEO) and the Chinese Beidou-II Navigation system[1] in completed or development phase around world are being developed as a special satellite positioning and navigation system (Kaplan 1996; Liu 2003; Yuan et al. 2003; Bian et al. 2005). With high accuracy the PVT functions (P: Positioning, V: Velocity, T: Time), the satellite navigation and positioning system was rapidly globalized, and can provide all-weather and real time operational capacity to cover land and sea, and even aerospace (thousands of kilometers up).

Facing challenges from the growing development of the 3"G" navigation systems, we need to develop our own navigation and positioning system, and in following sections, the wide demands will be discussed in detail. There are two key problems in the 3"G" systems: (1) service capabilities through positioning, velocity measurement and time service without communication. With their navigation/communication integrated functions, GEOSTAR and the Chinese Beidou I system, are not able to be developed into the mainstream navigation system due to its limited communication capacity and poor security as an active navigation system (Liu et al. 1999; Yuan et al. 2003; Bian et al. 2005); (2) jamming vulnerability. For example, weak received signal, fixed satellites/frequencies/code, and jamming vulnerable to interference. There are two features to be developed in future: (a) return to nature to seek new navigation aids, e.g. let the navigation system make use of astronomical pulsar stars[2], and also include new barometric and magnetic applications etc. (Sheikh 2005). (b) It has been a long dream in the world to make the satellite system into an integrated system, combining the functions of communication and navigation. We proposed an innovational navigation system, called Chinese Area Positioning System (CAPS), with the capability of integrating the communication satellites including the Geostationary Orbit communication satellites (GEO), the Decommissioned Geostationary Orbit communication satellite (DGEO) and the Inclined Geostationary Orbit communication satellite (IGSO), as well as barometric altimetry technique, as a test of the on-going researches of navigation technology.

2 CAPS: AN OVERVIEW

The CAPS positioning system based on satellite communication is fundamentally different from the 3"G" (GPS, GLONASS and GALILEO) systems, these systems (e.g., GPS) use special-purpose navigation satellites to broadcast on-board navigation information to users (Kaplan 1996; Yuan et al. 2003), basically, the 3"G" systems are passive radio navigation systems. In contrast, CAPS broadcasts navigation messages uploaded from the ground via communication satellite transponders[3], thus, CAPS is passive transceiver mode; see Figure 1. Hereinafter, for convenience, CAPS refers to the satellite Communication and Navigation system and Chinese Area Positioning System, and we will discriminate it only when we discuss the Global Chinese Positioning System (GCPS).

Using communication satellites, CAPS can realize easily the 3"G" function and meet its high technical specification; however, CAPS has three main obstacles: (1) generally, the communication satellite use a crystal clock, rather than an atomic clock, and it is difficult to meet completely the demands of velocity measurement with the precision of $\pm 0.1 \, \mathrm{m \, s^{-1}}$ and the carrier phase measurement; (2) 3-D positioning can not be realized due to the poor dilution of precision (DOP) caused by a satellite constellation that has several GEO communication satellites in the same equatorial plane; (3) the Effective Isotropic Radiated

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[1] Tong K., 2004, Development of China navigation and positioning system *http://ilib.cn/A-gitk200306001.html.*

[2] Pines D. J., 2004, XNAV. *http://www.darpa.mil./baa/baa04-23.htm.*

[3] National Astronomical Observatories of China, CAS, National Time Service Center, CAS, Transponder satellite communication navigation and positioning system, Ai G. X., Shi H. L., Wu H. T. et al., PRC Patent, No. 200410046064.1, 2004.
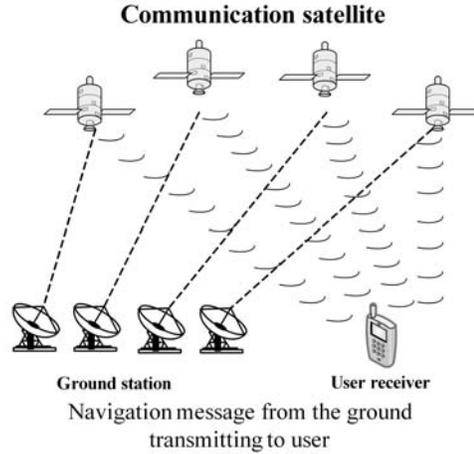
Communication satellite

Ground station   User receiver

Navigation message from the ground
transmitting to user

Fig. 1 CAPS principle.

Power (EIRP) in a communication satellite is generally insufficient. The following sections will discuss how to overcome these drawbacks.

The main features of CAPS are that with the navigation information processed on the ground, we can greatly simplify complicated on-board technique, reduce cost and easily build a positioning infrastructure system. Furthermore, CAPS uses the communication satellites to integrate the navigation and communication function. Using the communication satellites means we can collect continually various error information in order to update synchronously navigation message to the up-link carrier signal, and to improve greatly real-time positioning accuracy and capacity of anti-interference. CAPS is a PVT5C system, meaning it contains the three functions of positioning (P), velocity (V), and Timing (T), as well as five combinations, (1) navigation and communication, (2) positioning and high accuracy orbit determination, (3) navigation message and Wide area/Local area differential system, (4) alterability in satellite, carrier frequency and code, (5) navigation message and barometric altimetry. It will be described in following sections.

2.1 CAPS Positioning (P)

CAPS satellite constellations are composed of several GEOs, DGEOs and IGSOs. At least four satellites are observable for a given user. Navigation message in up-link carrier signal of communication satellite is transmitted to the user via satellite transponders, thus, the user may compute its coordinates and receiver clock error by means of measured pseudo range and assembled navigation message.

The pseudo range equation could be expressed as (Kaplan 1996; Yuan et al. 2003):

$$\rho_{si} = c \times (t_r - t_s^i) = \sqrt{(X_r - X_s^i)^2 + (Y_r - Y_s^i)^2 + (Z_r - Z_s^i)^2} + c \times dt, \qquad (1)$$

where, X_s^i, Y_s^i, Z_s^i (i=1, 2, 3, 4) are the satellite coordinates, the light velocity c is known, the pseudo range ρ_{si} (i=1, 2, 3, 4) is an observed value, (X_r, Y_r, Z_r) are the user coordinates, the clock difference dt for the satellite translated broadcasting signal to receiver is unknown; t_r is the epoch of reception of the satellite signal by the ground station and t_s^i are the epochs of transmission of the signals by the satellite.

If the user only observes the GEO satellite, the above equation is nearly singular and only produces an equipotential curve. To obtain a positioning solution, the Earth ellipsoid plane equation is needed, which is the intersection of the equipotential curve and spherical surface. Thus, the set of pseudo range equations needs one more equation:

$$\sqrt{(X_r / (a+h))^2 + (Y_r / (a+h))^2 + (Z_r / (a+h))^2} = 1, \qquad (2)$$

where, a, b are the Earth ellipsoid radii and h, the user altitude. In this case, 3-D positioning may be obtained by using more than 3 GEO and barometric altimetry.

For measuring the time difference between the arrival times, at the recevier antenna, of signals from the different satellites, this system adopts the same time difference method as the other existing satellite navigation systems. Now, for the other satellite navigation systems, the range signal and navigation message are generated on-board, with the time and frequency referred to the atomic clock on-board, so the ground observation system has to maintain the time synchronization among satellite atomic clocks. In contrast, in our system, the satellites are not equipped with atomic clocks; the range signal and navigation message are produced on the ground and then transferred via the satellite; the time and frequency reference are the group of ground atomic clocks.

When the user uses the pseudo range intersecting method for positioning, the clock time of transmitting signal on board (time that down-link signal leaves the satellite transponder) can not be directly, but indirectly generated, it will have no effect on the satellite as a ranging reference source. The time of the atomic clock generating the navigation signals from the ground subtracting the time delays through the up-link signal and transponder is equivalent to the time generated from the satellite transponder for down-link signal, for those time delay results, they can be measured constantly by the ground station and be known to users from the navigation information. Definitely, $t_s^i = t_A^i - (t_D^i + t_T^i)$, t_A^i is ground atomic clock time, t_D^i is the time delay of the up-link signal, t_T^i is the time delay of the satellite transponder. Thus, for the user, a virtual time of down-link transmission may be obtained, it is called a "virtual atomic clock", without on-board atomic clock[4]. In the next section, we will show that the applied virtual atomic clock has a significant weakening effect on orbit deviation.

2.2 CAPS Velocity Measurement

Similar to GPS, the principle of CAPS velocity measurement is that the velocity may be obtained from the measured Doppler frequency shift of down-link signal (Kaplan 1996; Zhou 2002; Xu 2003; Xiong 2005). Four unknown quantities: the 3-D velocity and the clock differential rate of the receiver, may be obtained by solving four equations those are derived from the observed Doppler values of four simultaneously observed satellites. A crystal clock onboard the satellite less accurate than an atomic clock is not able to meet the velocity measurement requirement of $\pm0.1\,\mathrm{m\,s^{-1}}$, not even the carrier phase measurement. This is a common inherent defect of communication satellite systems which makes them not applicable to navigation. Thus, CAPS has to adopt two solutions for frequency stability.

2.2.1 Real-time following-up frequency stabilization and velocity measurement

In principle, if the carried Doppler frequency shift of the down-link signal is measured accurately, then the radial velocity of satellite relative to receiver can be obtained independently. Their relation can be expressed as (Kaplan 1996; Xu 2003):

$$f_{d1}(t) = \frac{v_r}{c}\left[f_1(t) - \frac{v_s}{c}f_1(t) - f_{LO}(t)\right],\tag{3}$$

where, f_{d1} is the carried Doppler frequency shift of the down-link signal, v_s the radial velocity of the satellite relative to ground station, f_{LO} the local oscillator frequency on the satellite. According to Equation (3), the radial velocity of the satellite relative to the receiver is:

$$v_r = c \cdot \frac{f_{d1}(t)}{f_1(t) - \frac{v_s}{c}f(t)_1 - f_{LO}(t)}.\tag{4}$$

The carrier frequency obtained actually by the receiver is the observed value of the down-link signal which is related to f_{d1}(t) by:

$$f_{d1}(t) = f_{s1}(t) - f_{r1}(t) = f_1(t) - \frac{v_s}{c}f_1(t) - f_{LO}(t) - f_{r1}(t).\tag{5}$$

Inserting Equation (5) into Equation (4), we obtain the velocity formula:

$$v_r = c \cdot \left[1 - \frac{f_{r1}(t)}{f_1(t) - \frac{v_s}{c}f(t)_1 - f_{LO}(t)}\right].\tag{6}$$

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[4] National Time Service Center, CAS, Virtual atomic clock technique of transponder satellite navigation, Wu H. T., Li X.H., Bian Y. J., PRC Patent, No. 200610012055.X, 2006.

Obviously, the determination of the radial velocity of the satellite relative to the receiver is dependent on three parameters, the up-link carried frequency of the ground station, F_{LO} of satellite oscillator and the radial velocity of satellite relative to ground station. Of these, instability of F_{LO} affects the velocity measurement. The carrier frequency difference of 2.225 GHz made by the frequency mixer onboard the satellite between the up-link and down-link signals avoids mutual frequency interference, as the CAPS carrier signal is transmitted transparently via the satellite. Instead of the atomic clock, a crystal oscillator of a lower stability is deployed on the satellite, and its entire life time stability is only 1×10^{-6} with standard deviation of 3000 Hz, most daily fluctuation being ± 400 Hz, while a second fluctuation is only about ± 0.2 Hz. For the down-link frequency, C_{1d}=4143.15 MHz, the standard deviation may reach 7×10^{-7}, and the daily fluctuation is 9×10^{-8}, while a second fluctuation is only 5×10^{-11}. According to those parameters, we proposed one innovative method for the velocity measurement, named "real-time following-up frequency stability"[5](Wu et al. 2009). The principle is shown in Figure 2, where, $f_{L0} = F_0 + f_0$.

Supposing that F_{10} is the up-link carrier frequency generated by a high-accuracy atomic clock in the ground station, F_{1down} is the down-link mixed carrier frequency of the satellite, F_L is the standard mixed frequency difference on the satellite, f_0 is the error caused by the mixed frequency, after removing the Doppler frequency shift of the up-link signal we will obtain a high-accuracy F_{1down} that is free of the effect of f_0, and indicates the movement of the satellite. This high-accuracy F_{1down} free of the influence of f_0 can be obtained by means of f_{1upup} resulting from correcting simultaneously f_0 to f_{1up}. A frequency stability better than ± 3 cm s^{-1} (2σ) can be obtained with this method in the on-going research. This performance can still be improved by more than 2-3 times for the corresponding 1×10^{-10} frequency stability of atomic clock.
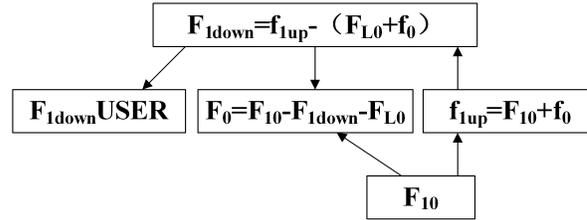

Fig. 2 Real-time following-up frequency stabilization.

2.2.2 *Velocity measurement by dual-carrier difference*

Figure 3 shows the block diagram of two down-link frequencies and velocity measurement when CAPS operates in the dual-carrier mode. In the figure all frequencies are expressed in terms of the transient frequency $f(t)$. Obviously, the determination of the radical velocity of the satellite relative to the receiver involves only the two up-link dual-frequency difference of the ground station, the radial velocity of the satellite relative to the ground station and the two down-link dual-frequency difference of the receiver, and not involve the satellite oscillator. Using the frequency stability of dual-carrier difference may realize higher frequency stabilization and apply to carrier phase measurement, see the literature for detail[6].

2.3 CAPS Time Service (T) and Terrestrial Reference Frame

2.3.1 *CAPS time*

Similar to GPS, the CAPS time service provides standard time information to users and the application system (Liu 2003). The user may obtain UTC (USNO) maintained by National Time Service Center (NTSC) with CAPS, ultimately traceable to the UTC coordination (Liu 1996; Xiong 2005). The flow chart of CAPS time reference generation is shown in Figure 4.

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[5] National Astronomical Observatories of China, CAS, National Time Service Center, CAS, High accuracy Doppler velocity measurement technique by frequency correction in satellite navigation, Ai G. X., Wu H. T., Li X. H., Bian Y. J., PRC Patent, No. 200410009928.2, 2004.

[6] National Astronomical Observatories of China, CAS, National Time Service Center, CAS, Frequency differential velocity measurement method of satellite navigation, Yan Y. H., Shi H. L., Bian Y. J. et al., PRC Patent, No. 200410058161.2, 2004.
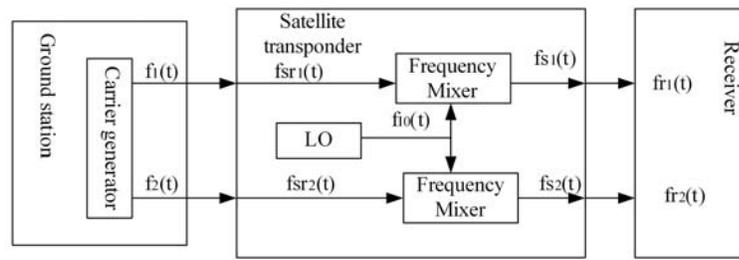
Fig. 3 CAPS down link generation and velocity measurement.
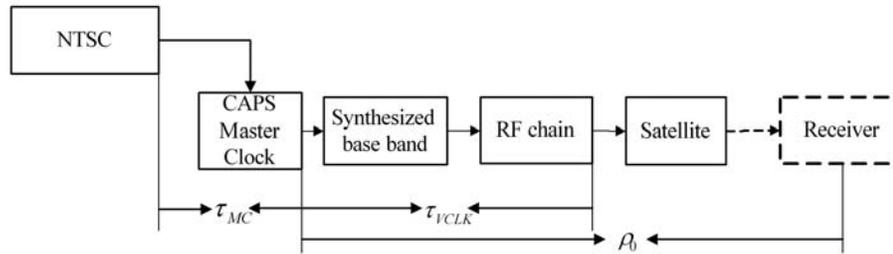

Fig. 4 Flow chart of CAPS time reference generation.

The CAPS master clock provides the standard time reference for the CAPS system, and after it is calibrated by the master clock of NTSC, the clock offset (τ_{MC}) between the master clocks of CAPS and NTSC may be obtained for broadcast. This time delay from the CAPS master clock through integrated base band, Radio Frequency (RF) chain and satellite transponder export is called "virtual clock time correction" (τ_{VCLK}), its model will also be broadcast and used to solve τ_{VCLK} for the user. If the user also needs UTC, the clock offset of UTC and UTC (NTSC) can be obtained from navigation message and CAPS network time service or NTSC published "Time and frequency Bulletin" (Journal of Time and Frequency, 2006).

2.3.2 CAPS time system

CAPS has its own special time system-called CAPS Time System (CAPST). CAPST is on atomic time scale, and uses the international atomic second, its calendar definition is on Dec 27, 2003 $00^{\mathrm{h}}\ 00^{\mathrm{m}}\ 00^{\mathrm{s}}$ (UTC), i.e. CAPST is synchronized with world UTC on Dec 27, 2003 $00^{\mathrm{h}}\ 00^{\mathrm{m}}\ 00^{\mathrm{s}}$. Because it is a continuous timing system without leap second insertion, its offset (the whole second) with UTC will have to be added into the navigation message. Because CAPST does not contain leap seconds, a constant deviation exists with the International Atomic Time (IAT) at any time: IAT–CAPST=32 s.

CAPST traces to the source UTC (NTSC). CAPST and UTC (NTSC) maintain a good synchronization, the bias between them is within 10 ns.

2.3.3 CAPS-03 Earth coordinates frame

The precisions of WGS-84 terrestrial coordinates reference frame and International Terrestrial Reference Frame (ITRF) are comparable (Liu 2003; Yuan 2003; McCarthy 2003). WGS-84 is suitable for traditional basic geodetic survey governed by Nation, while the ITRF is a dynamic and high-accuracy reference system that is constantly improved and is more suitable for research of the crust movement, and the even greater scale or global scope diastrophism and movements related to Earth geodynamics. As regards the number and location of tracking stations, many more are used to determine the ITRF than the WGS-84. In view of above characteristics of ITRF frame coordinates, and the naming rule of coordinates frame of other positioning systems, the CAPS coordinates frame in CAPS system, can not be called ITRF2000: it should be called by a new name, when improving and updating the system, while its kernel remains ITRF2000. Thus, the CAPS coordinates frame is denoted definitively as CAPS-03.
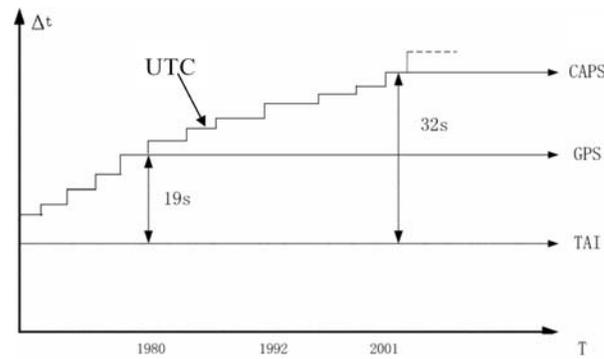
Fig. 5 Relationships of CAPST and other time systems.

2.4 Constellation and Virtual Constellation

The CAPS constellation consists of GEO, DGEO and IGEO. Barometric altimetry is used as a virtual constellation (Shi et al. 2006; Ai et al. 2009).

2.4.1 GEO constellation

There are approximately 300 GEO communication satellites operating at present around the world, and about 100 of them are observable within $40°\sim180°$ in China, C-band GEO satellites that can be used by CAPS approximately number 150, and about 65 of them are observable within China. Thus, it is convenient and flexible to directly lease the transponders of GEO communication satellites, and costs less than launching special-purpose navigation satellites. The longitude coverage of each GEO navigation satellite is normally considered to be $30°\sim60°$, so it is generally enough to cover a regional system of width of 1/3 world with $3\sim4$ GEOs. The GEO satellite used by CAPS should provide backup satellites in order to improve its availability and integrity. The interval of two satellites for CAPS should be about $25°$ in longitude.

2.4.2 DGEO constellation

The in-orbit life of a GEO communication satellite is normally $10\sim15$ years, and it will be replaced by a new one before it is gone. Some decommissioned satellites still have a little fuel remaining and could work normally in other sub-systems. Twenty four transponders of DGEO satellite, e.g. Asia Pacific 1A and I, have passed its designed life-time and are still working normally, six backup transponders were never used, they do not perform any worse than new satellites. Asia Pacific 1A and I still have about one year's fuel remaining, available for about $5\sim10$ years in the CAPS mode. The orbit is kept along meridian longitude, while allows to drift in the Northern-South direction (inclination between satellite and equator) for CAPS operation. Thus, 90% fuel can be saved in a given run time. CAPS may be reused 10 times more than normal time with the remained fuel. The orbital inclination may vary by $0.85°$ per year without controlling in its inclination, as DGEO is affected by various perturbations, its inclination will change from $0°$ to $14.67°$ and return to $0°$ in 26.6 years (Wang et al. 2004). It is a new discovery and innovation of CAPS constellation to use DGEO satellites and allow the inclination drifting under perturbation[7]. Thus, the CAPS constellation may extend to 10 times the in-orbit life, and may provide lower-accuracy 3-D positioning without using any larger IGEO communication satellites. Furthermore, the abundant transponders available on DGEO communication satellite make it possible to realize a large-capacity communication mission, as well as to integrate navigation and communication. As is well known, the DGEO communication satellite is a low-cost one.

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[7] National Astronomical Observatories of China, CAS, Retired GEO reused as small inclined GEO satellite method, Shi H. L., Ai G. X., Chen J. B., PRC Patent, No. 200610055909.2, 2006.

2.4.3 IGSO constellation

Using GEO constellation only realizes 2-D positioning. For 3-D positioning, CAPS adopts the following three methods:

(1) using IGSO communication satellite constellation;
(2) using DGEO communication satellite;
(3) using barometric altimetry as a virtual constellation.

GEO+IGSO own functions in terms of high accuracy and broad application fields: land, sea and aerospace. Since IGSO is a special system, it may be designed global area to reinforce regional area of GEO communication satellite. IGSO is a requisite constellation in CAPS implementation phase.

2.4.4 Barometer altimetry as virtual constellation

It is simple to make the elevation measurements of barometric pressure using a load cell in the receiver. The key is how the receiver can obtain real-time scalar parameters. By means of the DGEO communication system, the barometric pressure and temperature values in the earth stations are collected to the main navigation station and are classified and processed, then assembled into navigation message, and then transferred in good time to the user receiver. As a reference datum, the barometric pressure and temperature values measured in the receiver are combined to obtain the altitude of the receiver site (Sheng et al. 2003; Ai et al. 2009).

Basically, the barometric altimeter work is based on the fact that barometric pressure decreases monotonically and exponentially with increasing altitude. Instead of using satellite range signal, a barometric altimeter equipped in the navigation user terminal can be used to obtain the altitude so as to improve the geometric configuration of the constellation in CAPS: it is equivalent to a range signal from a satellite. The problem is how to gain the necessary accuracy through the altimeter measurements.

When the atmosphere is in hydrostatic equilibrium, we have, according to hydrodynamics principle:

$$P = P_0 \exp\left[-\frac{1}{R_d}\int_{h_0}^{h}\frac{g}{T}dh\right], \tag{7}$$

where, P is the barometric pressure measured by the user set, P_0 the barometric pressure at the reference point, h_0 the altitude at the reference point, h the altitude at the user set, R_d the gas constant of $287.05\,\mathrm{J\,kg^{-1}\,K^{-1}}$, T the air temperature in units of K, and g the acceleration of gravity.

In Equation (7), g may be treated as a constant although there is some slow variation along the altitude. The atmosphere keeps moving, but generally speaking, it is in the hydrostatic balance state in the vertical direction in a large area, excepting local areas with violent convection. Hence it is possible to modify Equation (7) without losing accuracy into

$$h = h_0 + \left[\frac{R_d}{g}\int_{P}^{P_0} T d\ln P\right]. \tag{8}$$

The temperature T in Equation (8) varies along with altitude in a complex way and it is hard to be represented by a mathematical function of the altitude. On the other hand, h is not sensitive to T as we can see from Equation (8). The common way to treat the problem is to assume that the atmosphere temperature is kept a constant in the same pressure level and take T_{m} (K) as the average temperature between the levels with P_0 and P. Then we have

$$h = h_0 + \frac{R_d T_{\mathrm{m}}}{g}\ln\frac{P_0}{P}.$$

After changing the logarithm from base e to 10 and expressing temperature in degrees centigrade, we have

$$h = h_0 + 18410\left(1 + \frac{T_{\mathrm{m}}}{273.15}\right)\lg\frac{P_0}{P},$$

or

$$h = h_0 + 67.4(273.15 + T_{\mathrm{m}})\lg\frac{P_0}{P}. \tag{9}$$

This is the well known Laplace Equation which derives the altitude from a measured barometric pressure. T_{m} in Equation (9) can be calculated approximately as follows. Assuming that the temperature of the atmosphere falls by 5°C for every 1 km increase of altitude, then the atmosphere temperature around the user set will be

$$T = T_0 - (h - h_0) \times 5(°\mathrm{C}),$$

and

$$T_{\mathrm{m}} = (T_0 + T)/2.$$

In order to derive h according to Equation (9) from the measured P of the user set, h_0, P_0 and T_0 at the reference point should be given in the navigation message of CAPS.

There are altogether 1860 existed weather stations over China which monitor the local P_0 and T_0 continuously. The CAPS master station collects and processes these data from the weather stations and broadcast them to navigation users in navigation messages. If a user is located near a weather station, then h_0, P_0 and T_0 of the station are directly used to derive the altitude. If a user is located far from any weather stations, interpolation should be made to derive the reference h_0, P_0 and T_0.

Tests show that the barometric altimeter works well in China and the accuracy of altitude measurement is dependent on the user set altitude as follows, in most part of China.

Altitude of user set	$\leq$ 1000m	$1000 \sim 3000$m	$3000 \sim 5000$m	$5000 \sim 10000$m
Accuracy of altimeter (1σ)	$3 \sim 5$m	$5 \sim 7$m	$6 \sim 10$m	$10 \sim 20$m

2.5 Ground Receiving Power Budget of Communication Satellite

2.5.1 Real satellite EIRP computed from ground receiving power

The EIRP of the transponders of the GEO communication satellite situated at the altitude 36 000 km in many carriers are insufficient for navigation. To overcome this drawback, a single carrier is used in the transponder with band-width 36 MHz. Not only is the power of the band used for CAPS increased, but also the transponder output back-off is decreased, so the ground receiving power is significantly increased. The ground receiving power = real satellite EIRP − transponder output back-off − down-link loss − other loss (rain attenuation, polarized loss, troposphere flicker and atmospheric absorption). The output back-off of transponder for a single carrier is 3 dB, atmospheric influence, such as rain attenuation, etc., is taken as 1 dB; down-link loss = 92.45 + 20 lg (distance from satellite to ground) + 20 lg (carrier frequency), where, the carrier frequency is in GHz. In comparison with the EIRP value provided by satellite company, the calculated satellite EIRP value is not obviously different in Lintong (NTSC), hence, the EIRP value published by satellite company is basically correct.

2.5.2 CAPS signal to noise ratio in preliminary trial

A preliminary trial of CAPS was completed from the end of May to the beginning of July, 2005. The receiver signal to noise ratios (SNR) in the test sites are given in Table 1, calculated by the same method as the GPS. The result is satisfactory. For a normal GEO communication satellite, if EIRP is over 35 Bw, the ground receiving power approximates –150 ∼ –165 dBw and meets fully the receiver requirements in satellite navigation.

Table 1 Receiver SNR in Test Area

Satellite	A.P.-IA	SINO-I	CBS-I	A.P.-I
Test area	18.00000	19.00000	17.00000	20.00000

2.5.3 Test for effect of mutual interference on communication and CAPS reception

Because many C-band communication satellites are located in East longitudes near the equator, transmitting signals at 4143.15 ± 10 MHz and 3826.02 ± 10 MHz will result in homo-frequency interference in CAPS receiving terminals. Homo-frequency interference was tested in Xian and CBS ground station respectively, on 3 days during July and August of 2003. There were about 60 (including 12 strong ones) interference sources within the CAPS bands. The average intensity of interference is -195.8 dBw, the mode is -176 dBw. The average total power is $\log(60) - 195.8 = -178$ dBw. The measured results indicate that narrow band interference took place within CAPS bands in other satellites operating in the data transmission mode. In the worst case of interference, CAPS still has 37.7 dB redundancy, hence, CAPS is not afraid of the interference by other satellites and solar radiation. The test demonstrates that CAPS does not interfere with the GEO satellites, either way.

2.6 Band, Frequency, Code and Modulation

2.6.1 Band and frequency selection

With GEO commercial communication satellite for navigation and positioning, firstly, CAPS chose the C band as the carrier band, since the resources in the L band are very limited and susceptible to the ionosphere. The Ku and Ka bands are susceptible to large rain attenuation, hard to be technically resolved. The resources in the C band are abundant and the techniques are mature and have only about 0.5 dB rain attenuation. Therefore, CAPS selects the C bands of $C_1 = 4143.15$ MHz, $C_2 = 3979.47$ MHz and $C_3 = 3826.02$ MHz, respectively, as the carrier band. While the GPS uses $L_1 = 1575.42$ MHz, $L_2 = 1227.6$ MHz and $L_3 = 1176.45$ MHz, respectively, as the carrier band. The influence of the ionosphere scales inversely as frequency squared, the influence of ionosphere on C_1 is only 1/7 of L_1, and the influence on C_3 is only 1/11 of L_3 (Lu et al. 2009).

2.6.2 Code and modulation selection

Dual-carrier with $C_1 = 4143.15$ MHz and $C_2 = 3826.02$ MHz have been selected as the down-link carrier frequencies. The I/Q branch in each carrier with P code and the C/A are designed reasonably. The C/A code uses GOLD code with rate of 1.023 M, and P code uses special security code with rate of 10.23 M. At present, CAPS system adopts dual-carrier and orthogonal BPSK mode (Kaplan 1996; Yuan 2003; Lu et al. 2009). Branch I and Q of carrier may modulate C/A code and P code, respectively, however, both of I and Q of carrier may modulate P code. The dual carrier power for I/Q branch can be different, thus, CAPS adopts UQPSK mode. A test demonstrated that this modulation is feasible.

2.7 Combination of Navigation and Communication

The CAPS combination of navigation and communication implies the integrated function in terms of positioning, velocity measurement, time dissemination and communication [8], it is named PVTC, C standing for "combination". The navigation and communication system consists mainly of DGEO communication satellites, master ground communication stations, navigation and communication equipments (user communication/navigation terminal), and a data dissemination and network management system (Chen 2003). The primary mission of CAPS navigation and communications system is to provide short messages, images and voice data. In total, 3 DGEOs, 60 transponders with 36 MHz band are used to provide services of short messages, images and voice data for about 300 000 users.

2.8 Combination of Positioning and High Accuracy Orbit Determination

Based on the classical method of Two Way Satellite Time Comparison (TWSTC) to realize high accuracy time transfer (Li et al. 2002; Li et al. 2003; Li et al. 2006), a multi-station TWSTC method with dual-carrier and high accuracy orbit determination has been proposed, and dynamics model has been used to realize orbit determination and prediction, which is called the method of orbit determination by satellite transponders (Li et al. 2002; Li et al. 2003; Li et al. 2009b). It will be introduced briefly in the following section.

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[8] National Astronomical Observatories, CAS, Integrated navigation and communication system based on time position and state information. Shang J. N., Shi H. L., Lu X. CH., Zhou X., PRC Patent, No. 200610012056.4, 2006.

TWSTC may realize simultaneous transmission and reception of multi-station signals. Each station transmits modulated carrier signal to satellites with different pseudo-codes, and all the station carrier signals (each station uses the same frequency) will be combined and retransmitted to the ground station via the satellite transponder. After the ground station has demodulated the carrier signals, the time difference between the local time and the station time reference is used for time synchronization between a substation and the master station. Each station receives its own carrier signal for the pseudo range measurement (Fig. 6). The internal precision of the pseudo range measurement is 7~9 mm. In the pseudo range, the biases of time delay of various effects should be eliminated. Since it is hard to extract satellite transponder time delay from satellite pseudo range measurement, the satellite dynamics method regards the transponder time delay as an unknown and eliminates it with the satellite orbit determination.
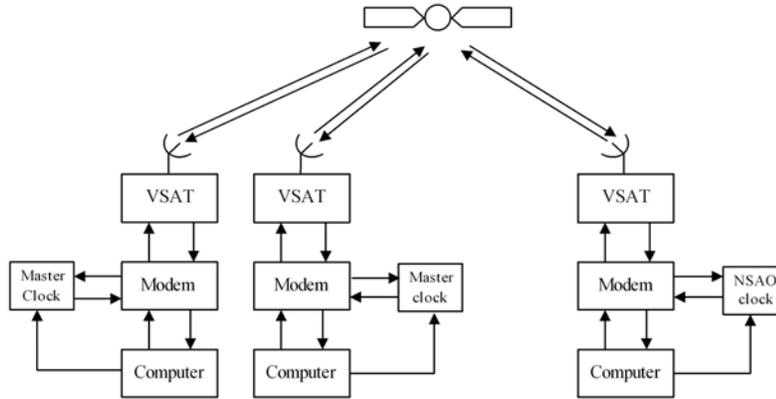

Fig. 6 The Multi-station of TWSTC method.

This system provides automated ground orbit determination, instrument control and data transmission via satellite, and uses the internet and special telephone as backups.

The 3-D Position Dilution of Precision (PDOP) is generally estimated to be between 20 and 30 for the current orbit measurement stations. When there are over five orbit measurement stations that are located relatively centrally, the measurement accuracy is better than 2 m, and the accuracy better than 1 m is easily obtained if there are more orbit measurement stations involved and located not centrally.

2.9 Combination of Navigation Message and Wide Area and Local Area Differential System

2.9.1 Combination of Wide Area and Local Area Differential System

The Wide Area Differential method is used to correct orbit deviation of navigation satellite and on-board atomic clock bias; and the Local Area Differential method is used to correct the ionosphere and troposphere biases, etc., and both are important means of improving the positioning accuracy (Liu et al. 1999; Yuan et al. 2003). In view of the GPS in the 3"G" systems, a special satellite or communication system is deployed for the collection of wide area and local area differential signals and broadcast to users such as in marine communication and mobile communication, etc.. Thus, the system operator will need more investment and upload work, and the users also need to add extra receiving channels and increase technical complication. However, CAPS uses DGEO as a navigation satellite and generates navigation messages on the ground, and sends easily observed results collected automatically from local ground stations to the master station via the remaining transponder of the satellite. After processing, the generated navigation message of wide area and local area differential data are sent to the user. Therefore, navigation and positioning and wide area and local area differential can be combined into one system.

2.9.2 Elimination of ephemeris biases by the method of indirect correction of the virtual clock

Deviations in the ephemeris from the real position will introduce a positioning error to the navigation user. This error is called the direct bias for the time being. On the other hand, in CAPS, the satellite position

deviation in the navigation message will introduce a virtual clock bias because the ephemeris is used to derive the satellite's position when commuting the signal down link transmission delay. The virtual clock bias will introduce pseudo range measurement error and so users' positioning error. This kind of users' positioning error that is also introduced by satellite position deviation in ephemeris through the virtual clock will be called the indirect error. Fortunately, the effects of the direct and the indirect errors cancel each other to some extent in CAPS. It may be explained as follows: when a satellite position deviation in ephemeris makes the satellite distance to the master station farther, the satellite transmitting time of the virtual clock is increased; when a satellite position deviation in ephemeris makes the satellite distance to the master station shorter, the satellite transmitting time of the virtual clock is delayed. Thus the combined effect of a direct and an indirect errors in the users' positioning are smaller than the effect introduced by the individual bias, based on the multilateral positioning principle of satellite navigation system. Hence, the resulted user positioning accuracy in CAPS will be better than the estimated accuracy based on the ephemeris bias from the viewpoint of existing satellite navigation systems without the virtual clock.

Because the direct bias is determined by the projection of the ephemeris deviation vector on the line from the satellite to the user, and the indirect bias by the projection of the ephemeris deviation vector on the line from the satellite to master station which is not related to the user location, the resulting User Equivalent Ranging Error (UERE) from the combined effect is dependent on the distance between the user and the master station as follows,

$$\text{UERE} = R\frac{\text{distance between user and master station}}{\text{distance between satellite and master station}},$$

where R is the ephemeris deviation in the direction from the satellite to the master station.

The distance between the user and the master station is usually much shorter than the distance between the satellite and the master station. So UERE is much less than R. For example, if the distance from the satellite and the master station is 36 000 km and R=10 m, then the UERE for different distances between the user and the master station is as follows:

The distance between user and master station (km)	100	500	1000	2000	5000
UERE(m)	0.03	0.14	0.28	0.56	1.39

These results show that the indirect correction of virtual clock offset significantly acts against the ephemeris bias, for detail, see Li et al. (2009a).

2.10 Combination of Alterability in the Satellite's Carrier Frequency and Code

CAPS uses the satellite transponder to broadcast navigation messages generated on the ground to users and so realizes navigation and positioning. The method of orbit determination in CAPS can realize high-accuracy orbit determination of with a power 1/300 lower than normal and the spread spectrum technique. These two functions may be realized within the satellite communication bands (including L\C\Ku and Ka). It is completely possible to realize the navigation and positioning in weak signal through alteration signal frequency and code. In compliance with the provision of International Radio Union Committee (IRUC), the band of satellite navigation was assigned to L band in order to be free of any influence between the satellite communication and navigation. A naturally asked question is whether the bands of satellite communication are capable of being applied to navigation, the answer is simple and positive. CAPS navigation and positioning is a complete communication application that conforms to the communication rule. More communication applications, such as TV broadcast, telephone and telegraph etc., can be provided via communication satellites where it requires the user to comply with the communication rule, but no contents restriction. CAPS only uses satellite communication without increasing or exceeding the functional permission of satellite communication, thus, it does not violate any provisions of IRUC. During our CAPS trial operation, the applications to use satellite communication in China are permitted exclusively by the Chinese Radio Committee. It is a natural result that a lot of communication can be used for CAPS, which means switching ability for satellite, frequency and code, when a interference takes place.

2.11 CAPS Combination of Navigation Message and Barometric Altimetry

CAPS uses the data collection system for barometric pressure and temperature to send real time data from local observatories to the master station. After classifying them, navigation message including barometric pressure and temperature data is sent instantaneously to the receiver. The geodetic altitude of the receiver may be measured exactly by the barometric parts in the receiver which uses the relation of barometric pressure and altitude.

2.12 CAPS High-Accuracy Characteristic of Real Time Positioning

1) GPS positioning error may be defined by following equation (Liu 2003):

$$Mp = \text{PDOP} \times M\rho.$$

PDOP is the abbreviation for 3-D Position Dilution of Precision. $M\rho$ is the measurement error of the distance between the satellite and the station. HDOP, VDOP, λDOP and φDOP are defined as the Dilution of Precision in the horizontal, vertical, longitudinal and latitudinal directions, respectively. The objective of constellation configuration design is to obtain the least average value of DOP. $M\rho$ is normally taken into User Effective Range Error (UERE) in order to compare various error items. $M\rho$ includes (a) ephemeris and clock bias, (b) broadcasting biases, e.g. ionosphere and troposphere time delay, multi-path error, relativity effect and Earth rotation, etc., (3) receiver error, e.g. pseudo code noise error, internal time delay and antenna phase center error.

2) CAPS, is fundamentally different from GPS in that it uses a seamless satellite communication and navigation system which can collect continually various biases and correct it through successive real-time up-link signal and navigation messages. Compared to GPS, CAPS is improved dramatically: its continuing real-time positioning accuracy is approaching the post-processing level of GPS. The reasons are as following:

(1) Due to the offset action of indirect correcting method of the virtual atomic clock to ephemeris bias, the effect of ephemeris bias on CAPS positioning result involves the distance to the master station, for example, distances of 1000 km, 2000 km and 4000 km correspond only to 0.028, 0.056 and 0.112, respectively, in the ephemeris bias. Since the ephemeris bias is decreased by 1–2 orders of magnitude, and the system has a high accuracy in the orbit determination (easily less than 1 m), the greatest error – the ephemeris bias in GPS positioning errors, is offset substantially in CAPS.

(2) Virtual atomic clock bias. Since clocks are installed on the ground, the virtual atomic clock of satellite is generated from the same source – hydrogen atomic clocks, whose bias is less than 0.2 ns, the corresponding UERE is less than 6 cm, which is several orders of magnitude less than in GPS.

(3) Ionosphere influence. Since CAPS uses the C band, the influence of the ionosphere on the signal frequency is 7 times less than that of the L band used by GPS. In addition, using the dual-carrier, the ionosphere influence is degraded to cm class.

(4) CAPS navigation message includes the error correction of the pseudo range transmission that responds to the wide area/local area differential system and enables the basic elimination of the residual bias of the troposphere and ionosphere, while GPS does not include the wide area/local area differential system.

(5) Besides the CAPS suppression of four systematic errors by more than one order of magnitude, the other main source is random error which includes random synchronous fluctuation of range code source and measurement error of the receiver to range code, etc. The Kalman filter is widely applied to deal with random errors. Most GPS receiver uses the Kalman filter technique to reduce greatly random error. The experience of CAPS illustrates that the Kalman filter technique may suppress random error by 70%–50%. Thus, its application is one of important components of CAPS.

(6) Multi-path error, internal time delay error and antenna phase center error, etc., still exist in CAPS, which can be reduced greatly with various techniques. In these respects, CAPS is not essentially different from GPS.

According to the measurement result to CAPS P-code and C/A code receiver, we find the CAPS synthesized positioning error (1σ) as follows: for the average P-Code error, $M\rho = PDOP \times 0.35$ m; for C/A code error, $M\rho = PDOP \times 1.1$ m.

These numbers demonstrate that in CAPS the positioning error is reduced obviously more than that in GPS under same DOP condition, due to the several innovations of CAPS.

3 THE TRIAL OF CAPS DEMONSTRATION SYSTEM

Based on the research in the key issues and the development of related techniques, a demonstration system of CAPS is designed, established and tested. The design and trial of CAPS demonstration system are introduced as follows.

3.1 System Configuration

3.1.1 Constellation and virtual constellation

The constellation consists of two GEO satellites located at E87.5° and E110.5°, two DGEOs located at E134° and E142°, as well as the barometer virtual constellation. Its PDOP is shown in Figure 7.
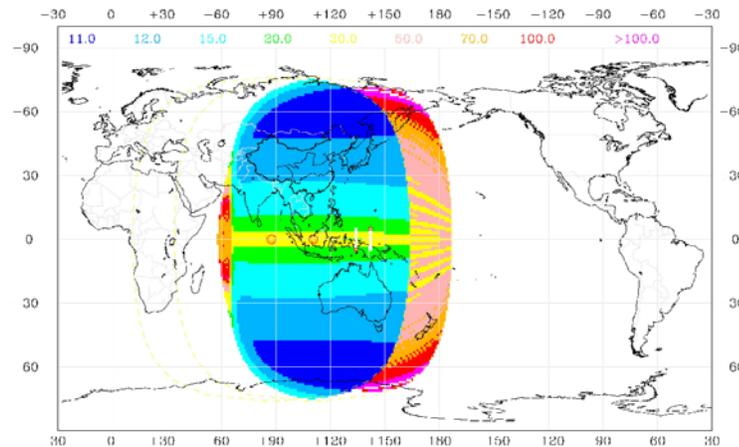
Fig. 7 PDOP with 2GEO+2DGEO Satellites and barometric altimetry.

3.1.2 Other aspects

1) The two C-Band carrier frequencies are 4143.15 MHz and 3826.02 MHz. The self-assembled P code rate is 10.23 MHz, the C/A code rate is 1.023 MHz with GOLD code and UQPSK modulation.
2) The up-link navigation information transmission system with six 7.5 m antennas in Xian.
3) CAPS orbit measurement stations located in Changchun, Urumqi, Xi'an, Shanghai and Kunming.
4) Seven wide area differential and observation stations.
5) Signal frequency, dual-carrier P and C/A code receivers for handholding, vehicle and ship model were developed.
6) Remained transponders on DGEO capable of being used for communication.

3.2 System Performances

A dynamic and static performance test of the CAPS demonstration system was carried out in eastern, southern, western and northern China. The vehicle and shipboard user sets were used for the dynamic performance test. The test results are summarized as follows.

1) Static positioning accuracy on the ground
   Horizontal   Ordinary service   15~25 m (1σ),
                   Precision service   5~10 m (1σ).
      Vertical   1~3 m.

2) Dynamic positioning accuracy on the surface
    Horizontal   Ordinary service   15~25 m (1σ);
                        Precision service   8~10 m (1σ).
3) Velocity accuracy
    Ordinary service   0.13~0.3 m (1σ);
    Precision service   0.15~0.17 m (1σ).
4) Timing accuracy
    Ordinary service   160 ns (1σ);
    Precision service   13 ns (1σ).
5) Two way timing transfer accuracy: average accuracy 0.068 ns(1σ).
6) Random error of satellite distance measurement 10.7 mm (1σ).
7) Satellite orbit determination accuracy better than 2 m (1σ).

Note: the above measured random error is the 1σ value. In the positioning error above, the major error source resulted from the lack of large inclination IGSO constellation in the latitude. If an IGSO is added, the latitude error would decrease by one order of magnitude. The other method to improve accuracy is to add one GEO or DGEO along the East and West direction, respectively, then the PDOP will decrease by about 20 to 6, and the accuracy will increase by about 2–3 times.

In the course of two years and at a cost of about 20 MUS$ only, a trial system was established and the relative performance test completed. The CAPS demonstration system will become rapidly a preliminary operation system for applications of handholding, vehicle and ship model.

4 THE DEVELOPMENT OF CAPS OPERATIONAL SERVICE

After the CAPS functionality validation system done, the CAPS operational service system has been successfully completed.

4.1 System Design Performance

(1) Service area:
    first class service area: 115°E~135°E, 15°N~34°N;
    second class service area: 75°E~135°E, 15°N~55°N;
    third class service area: 60°E~150°E, 30°S~55°N.
(2) Positioning accuracy (second class, 95% credibility, same below):
    Standard precision range code: horizon $\leq$10 m;
                                     vertical $\leq$10 m.
    High precision range code: horizon $\leq$2 m;
                                     vertical $\leq$2 m.
(3) Timing accuracy: 40 ns.
(4) Velocity measurement accuracy: 0.1 m s^{-1}.
(5) Updated rate for navigation message: 30 s.
(6) Updated rate of differential message: 6 s.
(7) System error code rate: $\leq$1$\times$10^{-5}(receiver sensibility: –135 dBm).
(8) System availability: 99.99% (first class service area); 99.85% (second class service area); 95% (third class service area).
(9) System integrity: Failure Alarm limiting: 3 time spec. in horizontal direction; 2.5 time spec. in altitude direction; Alarm time requirement: 6 s; Miss Alarm probability of limiting time less than 5$\times$10^{-7} per 150 s; Integrity better than 99.9%.
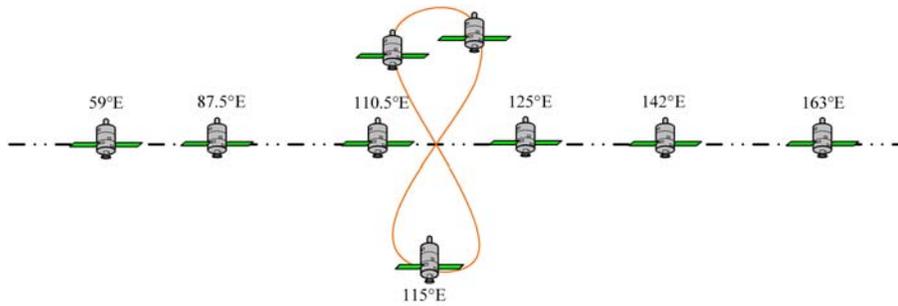
4.2 Constellations

CAPS constellations in the operational service system consist of 3 GEO, 3 DGEO 3 IGSO and the virtual constellation of barometer data. The 3 GEO satellites are located in the same geo-stationary orbit at 87.5 °E, 110.5°E and 125°E.

In Figure 8, the DOP is shown and analyzed.

4.2.1 6 GEO satellites and barometer

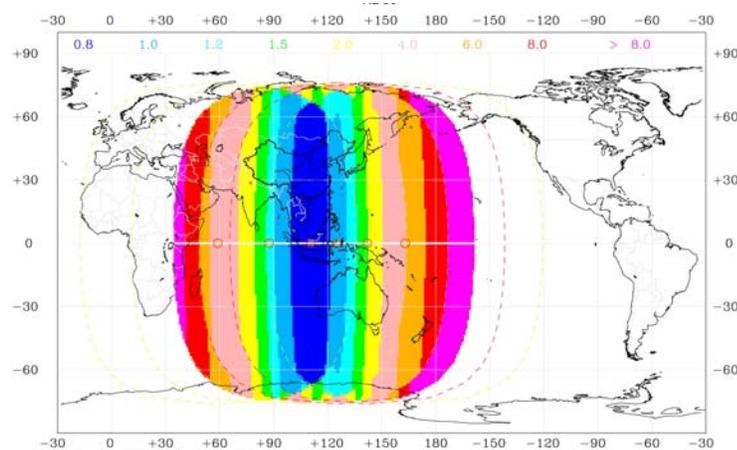The calculated PDOP and λDOP (longitude) are shown in Figures 9 and 10.

From those figures pertaining to the six GEO satellites and barometric altimetry, the PDOP in the major service area is approximate 4∼6, and λDOP is less than 1. Therefore, the error comes mainly from latitude:
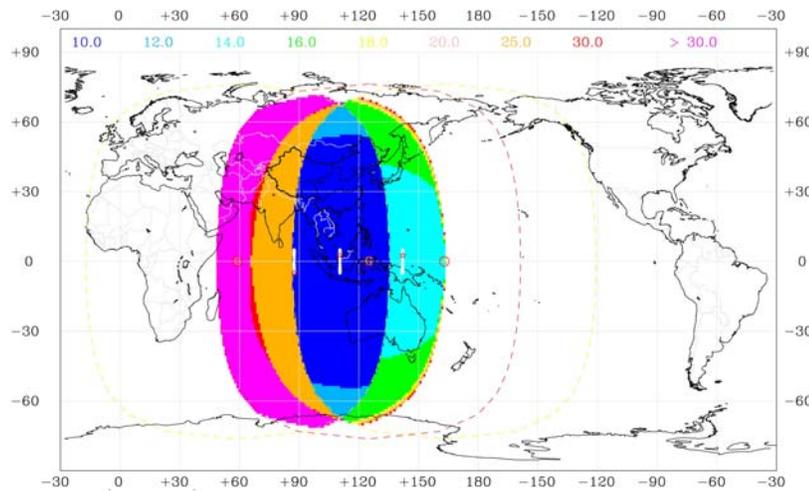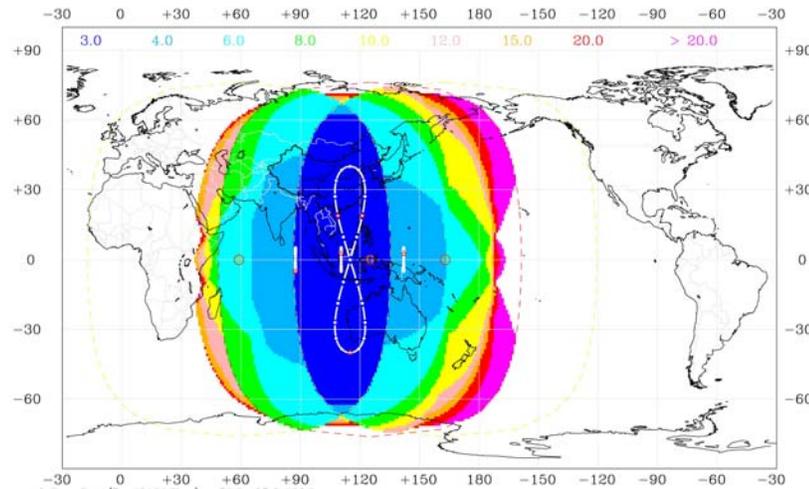

Fig. 8 CAPS constellation.
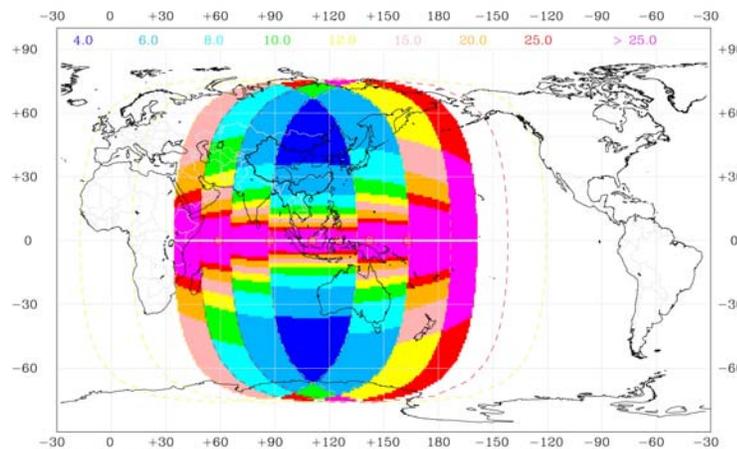
Fig. 9 PDOP in 6 GEO satellites and barometric altimetry.

Fig. 10 λDOP in 6 GEO satellites and barometric altimetry.

Fig. 11 PDOP in 3 GEO and 3 DGEO satellites.

Fig. 12 PDOP in the 3GEO+3DGEO satellitesplus 3 IGSO constellation.

the performance is better in higher than lower latitude area. Thus, the system with 6 GEO satellites and barometric altimetry performs adequately and can be applied.

4.2.2 3 GEO and 3 DGEO

The DGEO satellites are located in orbits at 87.5°E, 110.5°E and 142°E, respectively, with orbital inclinations 5°and separated by 120°in phase. Their calculated values of the PDOP are shown in Figure 11. This shows that the PDOP in the major service area is about 12. According to the preliminary test results, the P code accuracy approximates to the DOP value. Compared to pre-IGSO launches, this system is low-cost, easily completed and fast to work.

4.2.3 The 6 GEO and 3 IGSO constellation

The IGSO satellite pass the equator at 115°E, and its inclination is 40°. Taking the intersection at 115°E, the phase difference of the three satellites is 120°E (Fig. 8). The computed PDOP is shown in Figure 12.

Table 2 DOP average values for the 6 GEO plus 3 IGSO constellation in three service areas.

		GDOP	PDOP	HDOP	VDOP
$I = 40°$	R1	3.3	2.7	1.7	2.0
	R2	3.6	2.9	2.0	2.1
	R3	4.3	3.4	2.2	2.6
$I = 63.4°$	R1	3.1	2.6	1.5	2.1
	R2	3.3	2.8	1.7	2.2
	R3	3.8	3.2	1.8	2.5

From the statistics in Table 2, the inclination of IGSO varies from $40°$ to $63.4°$, which is not obviously different from the CAPS performance in the service area. In the case of $I = 63.4°$ inclination, and considering that the up-link navigation stations are to be set in China, these stations can only be set at about 21 °N. Therefore, the navigation signal will break off when the IGSO satellite is in southern latitudes, for example, when at south of 45°N. The DOP will decrease greatly in lower latitude areas of the north and south hemispheres, and the performance will be worse than $I = 40°$. In addition, for the three figure-of-eight satellites, the computed results are similar for $I = 60°, 55°, 50°, 45°$. Thus, the proposal of a 40° or 45° inclination was adopted, in consideration that the up-link navigation stations are to be set only in China.

4.3 Ground System

The ground system will be described briefly here (see Wu et al. 2009 for details). The distribution of the ground system is shown in Figure 13.

Fig. 13 CAPS Ground System.

4.3.1 Navigation station

The CAPS ground segment is a most important part of the CAPS system. The key element in the ground system is a master control station which manages master station operation, constellation control and the ground branches. The master control station consists of the following facilities: RF synthesis base band, data processing, measurement, time reference, observation unit, barometric altimetry and differential unit. There are two master control stations in CAPS: master one is in Lintong, and its emergency backup in Xishuangbanna.

4.3.2 Ground stations for orbit determination

There are eight ground stations for orbit determination: the main ground station located in Lintong and seven sub-ground stations in Urumqi, Kashgar, Lhasa, Shanghai, Changchun, Sanya and Xishuangbanna.
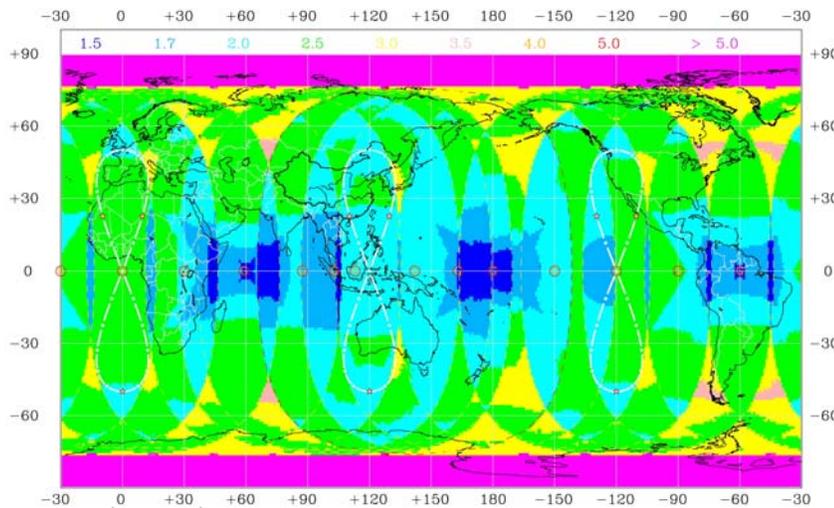
4.3.3 Communication stations

The master communication station is located in Beijing, and its deputy station in Xishuangbanna.

4.3.4 Basic additional reference stations for different measurements

A total of 20–25 basic reference stations will be built in China for correcting and monitoring navigation signals to service a wide area and the differential CAPS system.

5 GCPS FOR GLOBAL SYSTEM

To replenish the CAPS infrastructure, we shall be leasing eight commercial GEO communication satellites with 16 transponders distributed in geostationary orbits at 30 °E, 182°E, 0°, 30°W, 60°W, 90°W, 120°W and 150°W, respectively. The constellation consisting of six IGSO in two groups around 0 °W and 120 °W can realize the Global Chinese Positioning System (GCPS). The computed PDOP is shown in Figure 14, showing it is less than 2.5 in most areas.

Fig. 14 PDOP for Global system: GCPS.

6 CONCLUSIONS

As a new development of satellite navigation and positioning system, CAPS uses a mature satellite communication system rather than using a special navigation satellite system. It is based on eight innovations: (1) multi-communication satellite for satellite navigation constellations; (2) real-time following and dual-carrier difference method for frequency stabilization and high accuracy measurement of velocity; (3) orbit determination method by reverse CAPS transponders, combination of CAPS positioning and high accuracy orbit measurement; (4) combination of CAPS positioning and communication; (5) using DGEO for 3-D positioning; (6) Wide Area Differential System to correct orbit deviation by virtual atomic clock; (7) alterability in satellite, carrier and code; (8) combination of CAPS navigation message and barometric altimetry. The CAPS system based on the eight innovations, labelled a PVT5C system, has obvious advantages in applications. The main advantages include: (1) excellent PVT5C performance over the 3"G" systems; (2) a fast time of construction, about 3 years for the area system and 5 years for the global system; (3) flexible expansibility and adaptive capacity to new technical developments, e.g. following up of improvement in atomic clock accuracy, three carrier frequencies, multi-spread spectrum, changing code and anti-jam, etc.;

(4) strong capacity of mobility, anti-jam and anti-destruction; (5) low costs of construction and maintenance, amounting to approximately 15% of the 3"G" systems. CAPS also has some disadvantages. For example, the extra signal up-link transmission depends on the ground system, which will increase the possibility of being interfered with and being destroyed. An ultimate consideration of these problems should be analyzed in the perspective of satellite communication. In principle, any anti-jam and anti-destruction methods that are used and developed by satellite communication can be used directly to CAPS, and enable CAPS to have anti-jam capability and feasibility.

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