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INVITED REVIEWS

Communication-based positioning systems: past, present and prospects

Guan-Yi Ma[1], Qing-Tao Wan[1] and Tong Gan[1,2]

[1] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China; *guanyima@nao.cas.cn*
[2] Graduate University of Chinese Academy of Sciences, Beijing 100049, China

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Abstract This paper reviews positioning systems in the context of communication systems. First, the basic positioning technique is described for location based service (LBS) in mobile communication systems. Then the high integrity global positioning system (iGPS) is introduced in terms of aspects of what it is and how the low Earth orbit (LEO) Iridium telecommunication satellites enhance the global positioning system (GPS). Emphasis is on the Chinese Area Positioning System (CAPS) which is mainly based on commercial geostationary (GEO) communication satellites, including decommissioned GEO and inclined geosynchronous communication satellites. Characterized by its low cost, high flexibility, wide-area coverage and ample frequency resources, a distinctive feature of CAPS is that its navigation messages are generated on the ground, then uploaded to and forwarded by the communication satellites. Fundamental principles and key technologies applied in the construction of CAPS are presented in detail from the CAPS validation phase to its experimental system setup. A prospective view of CAPS has concluded it to be a seamless, high accuracy, large capacity navigation and communication system which can be achieved by expanding it world wide and enhancing it with LEO satellites and mobile base stations. Hence, this system is a potential candidate for the next generation of radio navigation after GPS.

Key words: satellite navigation — communication — mobile positioning — CAPS — iGPS — LBS

1 INTRODUCTION

Broadly speaking, the term positioning, if related to radio, means radiodetermination. As defined by FS-1037C[1], radiodetermination is the determination of the position, velocity, time (PVT) or other characteristics of an object, or the acquisition of information relating to these parameters, by means of the propagation properties of radio waves. There are two main fields of radiodetermination. One

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[1] *http://www.its.bldrdoc.gov/fs-1037/fs-1037c.htm*

is radiolocation, which is the process of finding the location of an object using radio waves, typically applied in a radar or mobile system. The other one is radionavigation, which provides continuous tracking of position, such as in the Global Positioning System (GPS).

Since it was made available to civilians in 1995, GPS has become a widely deployed and useful tool for commerce, scientific research, tracking, and surveillance (Kaplan & Hegarty 2006; Msira & Enge 2010). The success of GPS and the fact that access to GPS is not guaranteed in hostile situations has stimulated the development of other Global Navigation Satellite Systems (GNSS) and Regional Navigation Satellite Systems (RNSS) (Hegarty & Chatre 2008). The GNSS also includes the Global Navigation Satellite System (GLONASS) of Russia, which is fully operational (Daly 1993); the Galileo Positioning System of the European Union (GALILEO) (Sharpe 2001) and the Compass Navigation System of China (COMPASS), both of which are under development (Tan 2008). As for the RNSS, there is the Beidou Navigation System (Beidou) of China (Huang & Tsai 2008), the Indian Regional Navigational Satellite System (IRNSS) (Neetha et al. 2011) and the Quasi-Zenith Satellite System (QZSS) of Japan (Inaba et al. 2009). Operating at L or S frequency bands, these systems utilize the concept of one-way time of arrival (TOA) ranging. Launching a series of specific navigation satellites is necessary to construct the associated constellation.

Aiming to develop a regional navigation system with independency, high flexibility and low cost, another RNSS was proposed in China in 2003[2]. It is named the Chinese Area Positioning System (CAPS) (Ai et al. 2008, 2009b). It is fundamentally different from the other GNSS or RNSS in that it is based on commercial high Earth orbit (HEO) or geostationary (GEO) communication satellites and inclined geosynchronous orbit (IGSO) communication satellites, and the navigation messages are generated on the ground and uploaded to the communication satellites with the satellites acting only as transponders (Ai et al. 2008, 2009b; Wu et al. 2009; Li & Dempster 2010). Using four GEO communication satellites, a validation system for CAPS was developed in 2005 (Han et al. 2009). This type of constellation cannot provide three-dimensional (3D) positioning because the satellites are all located in orbit over the equator. Consequently, a barometer is incorporated into CAPS receivers to provide an estimate of height (Ai et al. 2009a). Since 2006, the CAPS experimental system has been set up with two GEO and four decommissioned geostationary obit (DGEO) communication satellites. To ensure the required precision, several systematic innovations were proposed: triple frequency signals and a physical augmentation factor for precision[3] (Ai et al. 2011).

CAPS is not the only positioning system based on a communication system. The high integrity global positioning system (iGPS)[4] provides ranging measurements from the GPS and low Earth orbit (LEO) Iridium communication satellites. It is a Boeing initiative under contract from the U.S. Navy. The basic goal of the system is to enhance GPS timing and positioning performance, especially under jamming (Joerger et al. 2010). In addition, large satellite geometry variations generated by fast-moving Iridium spacecraft enable rapid estimation of floating cycle ambiguities. Augmentation of GPS with Iridium satellites also guarantees signal redundancy, which enables Receiver Autonomous Integrity Monitoring (RAIM) (Joerger et al. 2010). While many details of iGPS are not public, assumptions are made herein indicating that iGPS opens the possibility for rapid, robust, and accurate floating carrier-phase positioning over wide areas (without the need for local reference stations). The system's promise for real-time high-accuracy positioning performance makes it a potential navigation solution for demanding precision applications, such as autonomous terrestrial and aerial transportation.

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

[3] National Astronomical observatories, CAS, A method of improving positioning precision in satellite navigation systems, Ai, G. X., Ma, L. H., Shi, H. L., Ji, H. F., PRC Patent, No.201210090864.8, 2012

[4] *http://www.insidegnss.com/node/1594*

Both CAPS and iGPS work with the aid of space-based communication systems. Positioning using ground-based mobile networks can be traced back to 1996 when the Federal Communication Commission (FCC) issued rules requiring all cellular providers to generate location estimates for Enhanced-911 (E-911) services[5]. Soon location-based services (LBSs) were proposed in 2001 (Virrantaus et al. 2001). Finding the location of a mobile phone is one of the important features of the current third generation (3G) mobile communication system. Many valuable LBSs can be enabled by this new feature. The most widely employed location technologies are radio location systems that attempt to locate a mobile user by measuring radio signals between the mobile user and a set of base stations. Radio location systems can be based on signal strength, TOA, time difference of arrival (TDOA), or angle of arrival (AOA), and can be network or terminal-based (Zhao 2002). The latest issue of standards regarding the positioning methods specified for 3G systems include cell-ID, assisted GPS (A-GPS), and TDOA-based methods, such as Observed Time Difference of Arrival (O-TDOA), Enhanced Observed Time Difference (E-OTD), and Advanced Forward Link Trilateration (A-FLT) (Zhao 2002 and references therein; Schiller & Voisard 2004; Bellavista et al. 2008).

It can be observed that as the only positioning system to have reached full functionality, GPS has opened a new era of radio navigation. It also stimulates the development of other positioning systems, either to compete with or to enhance GPS. Under such circumstances, CAPS has been implemented based on communication satellites. With high flexibility and low cost, it meets the ongoing demands for both navigation and communication in cases such as disaster recovery and vehicle monitoring.

It is the purpose of this paper to give a comprehensive review of the positioning systems in the context of communication systems. Emphasis is on CAPS: to give a retrospect of the history and development, to understand its current status, to analyze its advantages and disadvantages, and to predict its potential. The work done so far tends to provide a reference of strategic planning for future development of CAPS.

The remainder of the review is organized as follows: Section 2 is about the positioning technologies used in mobile communications. In Section 3, iGPS is fully presented in the frame of LEO Iridium communication satellites. Section 4 deals with CAPS under the architecture GEO communication satellites, focusing on CAPS' fundamental principles, key technologies, development, advantages and disadvantages. Section 5 proposes an extension of CAPS to a global positioning system based on communication systems. Also, suggestions for future development are presented. Finally, conclusions are drawn in Section 6.

2 POSITIONING BASED ON MOBILE COMMUNICATION

GPS is widely used for various purposes. It dominates all other forms of positioning because of its high accuracy, world wide availability, reliability and low cost (Rappaport et al. 1996). However, GPS may not provide the expected positioning accuracy in urban areas because of the reflection, deflection and blocking of satellite signals by buildings. It is also not intended for an indoor environment. In these cases, using the existing cellular network may be an alternative method to provide location estimation (Dai et al. 2010).

Mobile positioning was initiated by the FCC of USA. It issued an E-911 mandate in 1996 requiring cellular providers to generate location estimates for 911 emergency calls. Later LBS was proposed to meet the personalized requirements of instant location identification (Schiller & Voisard 2004). It is a virtual information service, which is accessible with a mobile device through the mobile network and utilizes the information about the geographical position of the mobile device. Mobile network operators were required to provide the location estimation within 125 m in 67% of the cases

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[5] *http://transition.fcc.gov/cgb/dro/e911tty.html*

before the year 2001 (see footnote 4). Similar steps were considered in the European Union and soon world wide. Currently the LBS is a compulsory standard in the 3G mobile communication system. These regulations and requirements indicate the trends of mobile positioning and provide a stimulus for various applications and business opportunities (Wylie & Holtzman 1996; He et al. 2004; Li et al. 2005; Bellavista et al. 2008; Wang et al. 2008).

2.1 Basic Location Technologies

Three basic radio positioning technologies are introduced: TOA, TDOA and AOA (Zhao 2002). The implementation of these technologies requires radio transmitters, receivers, or transceivers (Cong & Zhuang 2002; Catovic & Sahinoglu 2004; Al-Jazzar et al. 2009).

2.1.1 TOA

TOA is the travel time of a radio signal from a transmitter to a receiver. The TOA technique is based on the precise measurement of the signal's arrival time from the mobile device to several base stations (Zhao 2002). It requires the mobile device and base stations to be accurately synchronized with a precise time standard. The distance between the mobile device and each base station is determined by the product of the TOA and the speed of light. With distance used as a radius, a circular representation of the area around the station can be constructed for which the location of the mobile device is highly probable. The position of the mobile device is obtained by TOA trilateration, which makes use of three base stations to calculate the position of the mobile device (Li & Pahlavan 2004).

Figure 1 illustrates the concept of TOA trilateration. The signal's propagation times from mobile device X to base stations A, B, and C are precisely measured as t_{A}, t_{B}, and t_{C}, respectively. The distances from the mobile device to the three stations, ρ_{A}, ρ_{B} and ρ_{C}, can be calculated by multiplying the speed of light. The intersection of the three circles is then the location of X (Chan et al. 2006; Qi et al. 2006).

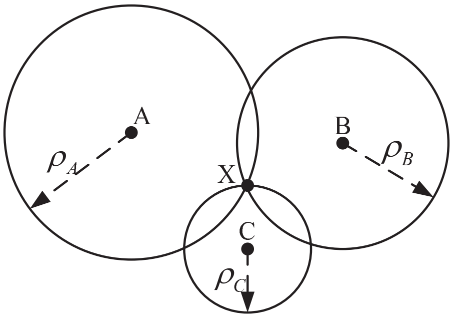

Fig. 1 A diagram of TOA positioning.

2.1.2 TDOA

TDOA is the time difference of arrival of a signal from the transmitter at three or more receiver sites. As shown in Figure 2, it uses time difference measurements rather than absolute time measurements (Bard & Ham 1999; Bocquet et al. 2005; Juang et al. 2007). It is often referred to as the hyperbolic system because the time difference is converted to a constant distance difference to two base stations

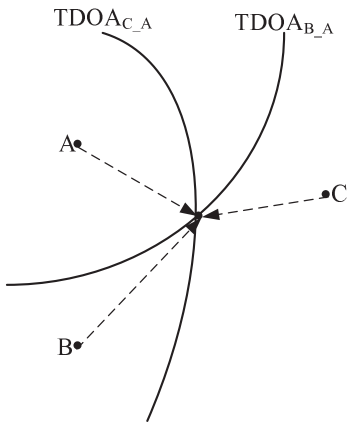

Fig. 2 The sketch of TDOA.

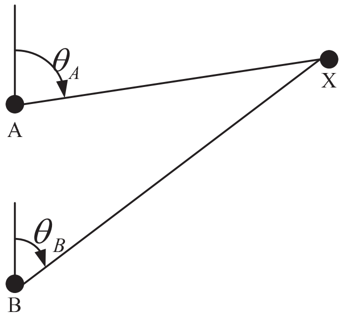

Fig. 3 AOA positioning method.

(as foci) to define a hyperbolic curve. This intersection of two hyperbolas is the unique position of the mobile device. Therefore, it requires two pairs of base stations (or at least three stations) for positioning. It also requires either precisely synchronized clocks for all transmitters and receivers or a means to measure these time differences (Cong & Zhuang 2005; Ni et al. 2008).

2.1.3 AOA

AOA measures the direction of the incident radio wave to a radio receiver equipped with an antenna array. AOA determines the direction by measuring the time difference of arrival at individual elements of the array. From these delays and the distances between antenna elements, the AOA can be calculated. If using a directional antenna, AOA is determined by adjusting the antenna to the point with the highest signal strength. As shown in Figure 3, A and B are base stations, and X is the mobile device whose position needs to be estimated (Pages et al. 2002). The directional antennas deployed at the base stations are adjusted to the point with the highest signal strength. The positioning of the directional antennas can be directly used to determine the angles of incidence, θ_A and θ_B. This technique requires a minimum of two stations to determine a position. If available, more than two can be used in practice (Caffery Jr & Stuber 1998; Gezici 2008).

2.2 Positioning Techniques for a Mobile Communication System

It is important to understand how positioning technologies are studied and used in a mobile communication system. Described here are the latest location techniques being discussed or adopted by mobile providers.

2.2.1 Cell-ID

The Cell-ID technique is a purely network-based positioning solution, as shown in Figure 4. It uses the latitude and longitude coordinates of the base station to locate a mobile device (Zhao 2002). As such, Cell-ID has the highest response time (Roos et al. 2002; Lin et al. 2004; Lin & Juang 2005; Chen & Chen 2010; Fang et al. 2012). Positioning accuracy of Cell-ID depends on the size of the cells.

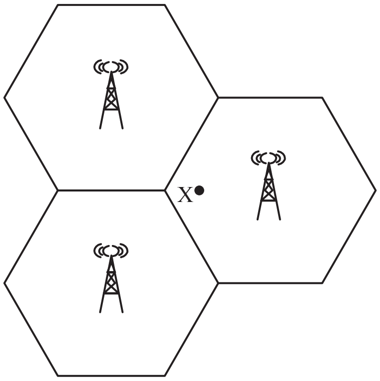

Fig. 4 Location by Cell-ID.

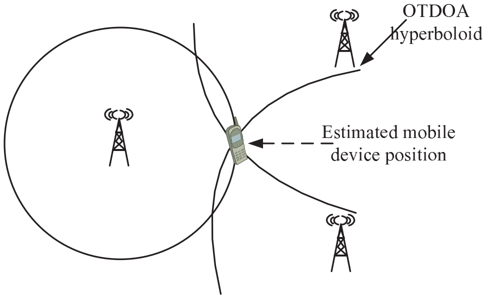

Fig. 5 The principle of O-TDOA.

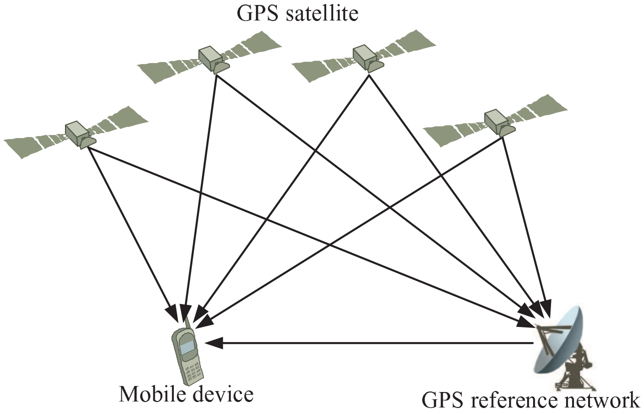

Fig. 6 A-GPS positioning system.

2.2.2 O-TDOA

O-TDOA is a TDOA-based positioning technique. It determines the position of the mobile device based on trilateration as shown in Figure 5. Each O-TDOA measurement describes a line of constant difference (a hyperbola) along which the mobile device may be located. The mobile device position is determined by the intersection of hyperbolas for at least three base stations (Porcino 2001; Johnson et al. 2002; Ahonen & Eskelinen 2003).

2.2.3 A-GPS

The basic idea of A-GPS is to establish a GPS reference network whose receivers have clear views of the sky and can operate continuously. The A-GPS network is shown in Figure 6. This reference network is also connected with cellular networks, continuously monitors the real-time constellation status, and provides data such as approximate handset position (or base station location), satellite visibility, ephemeris and clock correction, Doppler, and even the pseudorandom noise code phase for each satellite at a particular epoch. Then, the assistant data derived from the GPS reference network are transmitted to the mobile phone's GPS receiver to aid fast startup and increase sensor sensitivity. The A-GPS process allows the GPS sensors to initialize and locate satellites much faster. It also increases the accuracy of the positioning, and uses less power than the GPS receiver (Djuknic & Richton 2001; Feng & Law 2002; Akopian & Syrjarinne 2009).

2.2.4 E-OTD

The E-OTD technique is similar to TDOA, but it is a handset-based positioning solution rather than a network-based solution (Fischer & Kangas 2001). E-OTD takes the data received from the surrounding base stations to measure the time difference. Then, the time difference is used to calculate the position of a mobile device. The location of the base stations must be known and data sent from different base stations must be synchronized (Charitanetra & Noppanakeepong 2003).

Base stations are typically synchronized using fixed GPS receivers. E-OTD requires additional memory and processing power in the handset. It can be used both when the terminal is idle and when the device is handling a call (Wang et al. 2000; Fischer & Kangas 2001; Bai et al. 2003; Buchanan et al. 2004).

2.2.5 A-FLT

The principle of A-FLT is not much different from TDOA. The basic idea is to measure the time difference (phase delay) between pilot signal pairs. Each pair consists of the serving cell pilot and a neighboring pilot. The difference is converted to range information. Finally, the range data are used to form certain hyperbolic curves at which an intersection is defined for the handset's location (Nissani & Shperling 2000).

2.3 A Comparison of Mobile Positioning Techniques

A comparison of the above mentioned mobile positioning techniques is presented in Table 1. All of them have been implemented in commercial applications. A-GPS has the best accuracy. Cell-ID has the largest error, but the cost for update is the lowest. These techniques tend to co-exist for different requirements in different environments (Zhao 2002).

Table 1 Comparison of Mobile Positioning Techniques

Positioning method	System accuracy (m)	Response speed (s)	Network update cost
A-GPS	<50	10–60	Medium
A-FLT	50–200	<10	Medium
E-OTD(OTDOA)	50–200	<10	Medium
Cell-ID	100–3000	<10	Minimal

2.4 Standardization for Mobile Phone Positioning

Standardization is the process of developing technical standards and putting them into action. Standardization for mobile positioning was formulated in both the 3rd Generation Partnership Project (3GPP)[6] and the 3rd Generation Partnership Project 2 (3GPP2)[7] by collaboration among

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[6] *http://www.3gpp.org/*

[7] *http://www.3gpp2.org/*

Table 2 Iridium System Parameters

Iridium system parameters	Value
Service links intersatellite	23.18–23.38 GHz, Ka-band
Telephone and message	1616–1626.5 MHz, L-band
Ground segment links	19.4–19.6 GHz, Ka-band (downlinks); 29.1–29.3 GHz, Ka-band (uplinks)
Data rates	2.4 kbps
Multiple-access	FDMA/TDMA
Carrier bandwidth	31.5 kHz
Modulation	DQPSK
Encode mode	2/1 convolutional encoding

groups of telecommunication associations, including China, USA, Europe, Japan and Korea. The 3GPP has been concentrating on wideband code-division multiple access (W-CDMA) and Global System for Mobile Communication (GSM) systems while 3GPP2 has been focusing on CDMA2000 and CDMA(1X) systems.

In a W-CDMA system, three positioning techniques have been specified: the cell-ID-based, OTDOA, and A-GPS method. When the mobile phone's position is calculated by the network, it is called a user equipment-assisted (UE-assisted) solution. When the position is calculated by the mobile device, it is called a UE-based solution. Note that except for the UE-assisted OTDOA method, the other methods are optional for the user's equipment. In the GSM system, three location methods are specified: cell-ID, E-OTD, and A-GPS.

The methods of 3GPP2, A-FLT and A-GPS have been standardized by Telecommunication Industry Associations. Unlike GSM and W-CDMA, CDMA (1X) and CDMA2000 are time-synchronized systems. Therefore, time difference measurements from them are easier than for GSM and W-CDMA.

Standardization for mobile positioning indicates that the related technology is highly developed and mature. It provides a stimulus for various applications and business opportunities.

3 GPS ENHANCEMENTS BY THE IRIDIUM COMMUNICATION SYSTEM

The Iridium system is a worldwide communication system. It consists of 66 active satellites distributed among six orbital planes. The orbits have an altitude of 780 km and an inclination of 86.4 degrees. The period of the polar orbit is about 100 minutes. The system is designed to provide not only voice service but also short burst data (SBD) service, which is the same as short message service (SMS) in ground mobile communication (Evans 1998).

The specifications of the Iridium system are shown in Table 2. It works in L-band for voice and data communications, which is the same as that of GPS. Owing to its low orbit, the signal from the Iridium satellite is much stronger than that of GPS when being received on Earth. These features make it possible to use the Iridium satellite system to enhance GPS.

3.1 Benefits of Iridium to GPS

Combining the GPS network with the Iridium LEO communication network, GPS signals can be acquired more quickly through amplification and rebroadcasting by LEO satellites, which can improve accuracy and signal acquisition, especially in urban environments. Space-based LBS becomes possible with the Iridium communication function.

3.1.1 Improvement of GPS positioning accuracy

The over-the-pole design of the Iridium orbits ensures very good high-elevation satellite visibility in the Arctic, and Iridium satellites have already provided voice and data services to satellite phones and integrated transceivers around the globe. GPS constellation distribution in the Arctic is not as good as in other areas; the vertical dilution of precision (VDOP) values in the Arctic are about 2.1 and 1.8 for 24 and 31 GPS satellites respectively, which are worse than the average VDOP values elsewhere on the Earth (1.7 and 1.5 for 24 and 31 GPS satellites, respectively) (Gao et al. 2011). So, the Iridium satellites become a strong candidate for improving the GPS constellation by relaying GPS signals.

Due to LEO and short orbital periods, the Iridium satellites move more quickly than GPS satellites. For a static user on Earth, an Iridium satellite is only visible for about 10 min (Danchik 1998). This poses a challenge in using Iridium satellites to make fast switching among them (Rabinowitz et al. 1998).

3.1.2 Carrier phase positioning

Carrier phase positioning is a method to make ranging measurements by using a carrier phase. It is much more precise than that by using a code. To convert the phase to range, the cycle ambiguities have to be determined, which remain constant as long as they are continuously tracked by the receiver. A costless yet efficient solution for the estimation is to exploit bias observability provided by redundant satellite motion. Unfortunately, the large amount of time for GPS satellites to achieve significant displacement in line of sight (LOS) precludes its use in real-time applications that require immediate position fixes. In contrast, fast-moving LEO Iridium satellites are capable of making rapid estimation of cycle ambiguities. In the late 1990s, Rabinowitz et al. (1998) designed a receiver capable of carrier-phase measurements from the GPS and LEO communication constellation. Using rapid geometry variations of LEO satellites, precise cycle ambiguity resolution and positioning with respect to a nearby reference station was achieved within 5 min.

3.1.3 Communication

GPS provides PVT functions. In cases of vehicle monitoring or rescuing a life, the PVT information and other data or messages should be sent out rather than just keeping them. With the help of Iridium, a GPS receiver can fulfill the function of communication with full coverage of the globe. An integrated terminal of GPS navigation and Iridium communication has the ability to send its location information to other Iridium terminals using SBD[8]. These terminals have already been turned into products for both navigation and communication in the market, such as the SkyNode Series by Latitude Technologies Corporation[9].

3.2 iGPS

iGPS is a practice of GPS navigation and Iridium communication integration. It aims to augment GPS capability by exploiting the Iridium LEO communication satellite system (see footnote 3). The basic goal of the system is to enhance GPS timing and positioning performance. It is developing techniques that enable faster acquisition (time to first fix) of GPS satellite signals in adverse operating environments, including those with radio frequency (RF) interference or urban settings (Joerger et al. 2010).

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[8] *http://www.insidegnss.com/node/745*

[9] *http://latitudetech.com/*

The principle of iGPS works with satellite signals from both the Iridium LEO satellites and GPS satellites. Through relaying the GPS signals, the iGPS involves high-precision time transfer of GPS time and rebroadcast over the higher powered Iridium communication channels. Availability of the precise time allows the GPS receiver to reduce the search volume of the correlators and accelerate signal acquisition. The stronger Iridium signals also make the GPS signal tracking more robust by increasing the anti-jamming capability of user equipment. The iGPS also has the potential to achieve centimeter positioning. It will be a vast improvement over the current standalone GPS system, which has a precision of meters.

4 CAPS

CAPS has been established since 2002. Experiencing a validation phase, it is currently being constructed as an experimental system. CAPS is composed of a space segment and a ground segment as shown in Figure 7. The space segment includes four commercial GEO communication satellites which are located at longitudes of $87.5°$E, $110.5°$E, $134°$E, and $142°$E respectively, and the latter two are DGEO communication satellites with slight inclination angles ($\leq 5°$) (Ai et al. 2009a; Cui et al. 2009; Lu et al. 2009; Shi et al. 2009; Shi & Pei 2009). There are preparations to deploy another two DGEOs at $\sim 59°$E and $\sim 163°$E, respectively. These DGEO satellites have ample frequency resources in the C-band, and the available frequency band for each satellite is about 500 MHz (see footnote 4) (Ai et al. 2011). CAPS is different from all the other satellite navigation systems in that it uses commercial communication satellites, and the navigation messages are generated on the ground and uploaded to the communication satellites, with the satellites acting only as transponders. Moreover, C-band is used as the navigation carrier in CAPS (Irsigler et al. 2004).

The ground segment of the CAPS system consists of five ground stations: one master station located at Lintong ($109.2°$E, $34.4°$N), and four orbit determination stations located at Urumqi ($87.6°$E, $44.1°$N), Shanghai ($121.2°$E, $31.1°$N), Changchun ($125.4°$E, $43.7°$N), and Kunming ($102.8°$E,

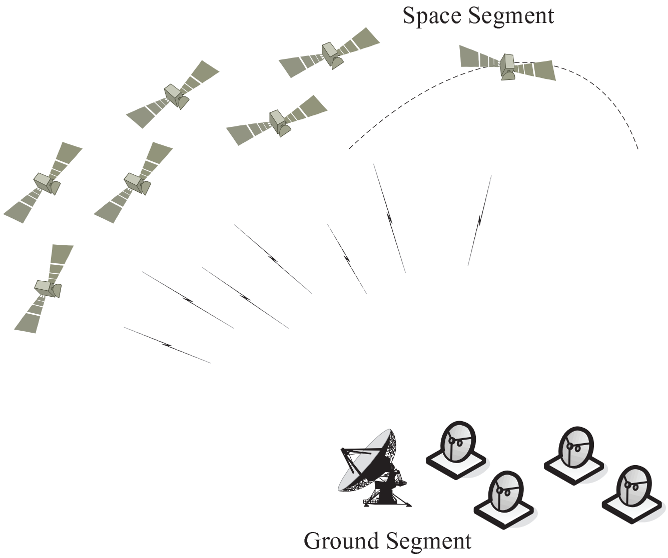

Fig. 7 The composition of CAPS.

$25.0°$N) respectively. In addition, there is a differential reference station in Beijing. All stations are linked together by a special network or with the internet for data transmission.

Six reflector antennas with a diameter of 7.3 m have been installed in the master station for transmitting and receiving signals. The master station generates the system time, ephemeris and navigation messages, determines and predicts satellite orbits, measures and calculates satellite transmission time, adjusts satellite signal carrier frequency, and collects and processes barometric data from weather stations all over China. Every orbit determination station transmits and receives orbit determination signals. The differential reference station generates position and pseudorange differential data, as well as corrects and monitors navigation signals.

4.1 The Key Technology and Innovations

CAPS is fundamentally different from GPS or other GNSS in that it employs commercial GEO communication satellites and operates in C-band. Navigation messages and related signals should be generated on the ground and uploaded to the communication satellites. The frequency standard for the communication satellite is much poorer than that for the navigation satellite. Key technologies and innovations are necessary for such an architecture to carry out functions for navigation (Ai et al. 2008, 2009b).

4.1.1 *Virtual onboard clock*

In CAPS, the system time is generated and maintained by atomic standards in the master station and traced to coordinated universal time (UTC). Then the navigation signal is generated according to the CAPS system time in the master station. A schematic of the transmitting loop in CAPS is shown in Figure 8. Here, UTC is represented by t_N, and CAPS system time is t_C. The difference between CAPS system time and UTC, $\tau_{MC} = t_C - t_N$, is monitored in real time and involved in the navigation message. The time at which the master station receives the signals is t_r. The user will hence be able to derive UTC from the CAPS system time (Ai et al. 2009b).

In order to make the communication satellite work like a navigation satellite, one of the tasks is to derive the time t_{VCLK}, which is the time at which the navigation signal is transmitted by the

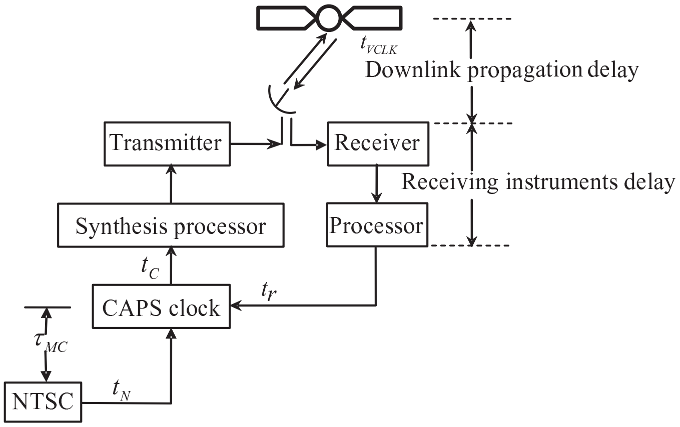

Fig. 8 The virtual clock loop in CAPS.

satellite transponder. An approach called a virtual onboard clock is defined in CAPS for determining the time t_{VCLK} [10].

Based on the CAPS system time, the delay time from the transmission loop $t_r - t_C$, downlink propagation and receiving instruments can be continuously calculated at the master station. By means of processing the real-time data, a virtual onboard clock model is established and broadcasted in a navigation message for users to predict the satellite's transmission time t_{VCLK}. In this sense, the highly accurate time standard of CAPS is transferred from the master station to the satellites. The communication satellites are turned into virtual navigation satellites with a virtual atomic clock onboard (Li et al. 2009a).

4.1.2 Carrier frequency adjustment

For a typical satellite navigation system, such as GPS, the atomic frequency standards are equipped onboard to provide time reference and generate navigation signals with a required frequency stability. The CAPS navigation signal is generated at the master station. The carrier is controlled by an atomic clock with high frequency stability. The navigation signal is transmitted to the communication satellite in an uplink and transferred to the Earth after frequency conversion. Due to local oscillator drift onboard the existing communication satellite, some uncertainty in carrier frequency is introduced in the communication satellite relaying the signal. It was shown that the carrier frequency uncertainty could be up to 3000 Hz with a small fluctuation for some existing communication satellites (Liu et al. 2008; Cai et al. 2009; Jing & Danni 2011).

Two techniques are developed to eliminate the frequency uncertainty. One is for users who receive a single frequency signal[11] (Wu et al. 2009). The other is for dual frequency receivers[12]. In the single frequency method, the original signal carrier f, which is generated by the atomic clocks in the master station, is constantly converted to $f + \Delta f$. The frequency drift $\triangle f$ is obtained by measuring the received signal's frequency. In the dual frequency method, two navigation signals with different carriers of f_1 and f_2 are generated at the master station and transmitted to the satellite. The two carriers picked up by the receiver are subtracted from each other, then the frequency shift can be derived and the system can maintain a precise carrier frequency. Details can be found in the related papers (Wu et al. 2009).

4.1.3 Orbit measurement

The orbit prediction of the communication satellite in CAPS is based on the continuous and real time determination of satellite position by means of distance measurements from the satellite to several ground stations which are distributed over a wide area and located at known positions (Huang et al. 2009). The distance measurement from the satellite to the ground station is performed in a way extending from two-way satellite time and frequency transfer (TWSTFT)[13] (Li et al. 2009b; Yang et al. 2009; Cai et al. 2009).

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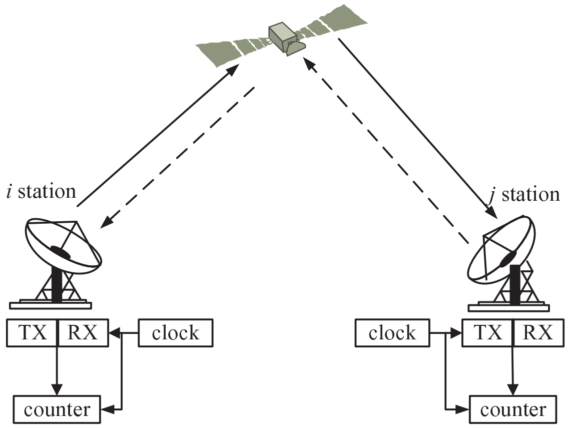

Fig. 9 The principle of orbit determination.

In CAPS orbit determination, all of the ground stations continuously transmit time signals to the other stations through the communication satellite transponders. Meantime, all the stations receive the time signals transferred by the communication satellites, including the time signal from the other stations and the station itself. The time signals are a kind of signal with a spectrum spread by a pseudo-random noise (PRN) code and modulated by tags in the time scale of the transmitting station clock.

The overview of the observational relationship for orbit determination by transfer is shown in Figure 9.

The time relationship for the signal transmitted from station i and received by station j is,

$$R_i^t + O_i^u + I_i^t + \tau_s + R_j^r + O_j^d + I_j^r - \Delta T_i + \Delta T_j = R_{ji} \tag{1}$$

where R_{ji} is the transmission time from station *i* to *j*; R_i^t is the signal propagation time from station *i* to the satellite; O_i^u is the time delay by the ionosphere and troposphere for the uplink propagation; I_i^t is the transmission time delay at station *i*; τ_s is the time delay for the satellite transponder; R_j^r is propagation time from the satellite to station *j*; O_j^d is the delay introduced by the ionosphere and troposphere for the downlink propagation; I_j^r is the receiving instrument's delay at station *j*; ΔT_i and ΔT_j are the differences in clock time scales for stations *i* and *j* with respect to the time reference of the CAPS system time.

When *N* ground stations are used to determine a satellite's orbit using the TWSTC method and each station transmits its time signal to the satellite with a unique PRN code, τ_i, the distance from the satellite to station *i* can be solved as

$$\tau_i = \frac{1}{N+2} R_{ii} + \frac{1}{2(N+2)} \sum_{j=1}^{N} (R_{ji} + R_{ij}) - \frac{1}{(2N+2)(N+2)} \sum_{j=1}^{N} \left(R_{jj} + \sum_{j=1}^{N} R_{ij} \right). \tag{2}$$

Based on the continuous and real-time determination of the satellite's position, the orbit prediction will be performed by dynamics and ephemeris generated by the master station.

A test shows that the error in determination of distance from the satellite to a ground station is less than 10 cm (1σ). The error in determination of the position of the satellite is 2.0 m (1σ) and the error in orbit prediction (2 h) is 2.5 m (2σ) (Li et al. 2009b).

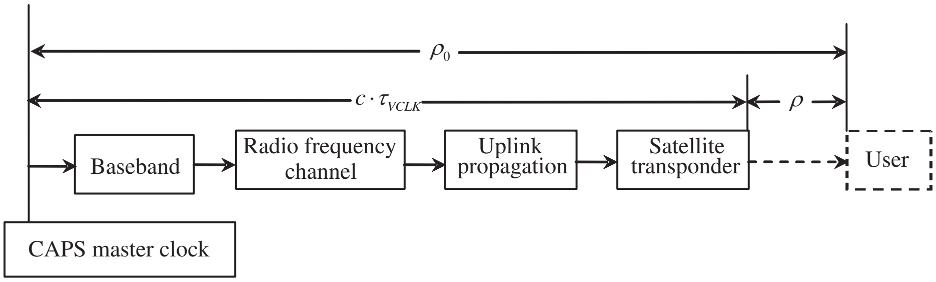

Fig. 10 The principle of acquisition of ephemeris time.

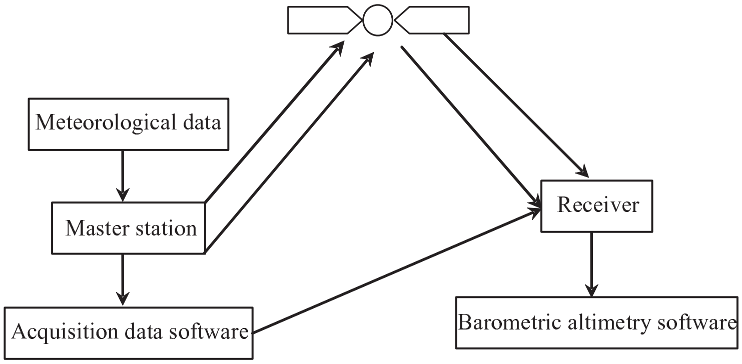

Fig. 11 The barometric altimetry system.

4.1.4 Acquisition of ephemeris time

As shown in Figure 10, the basic pseudorange observation equation of CAPS could be expressed as

$$\rho = \rho_0 - c \cdot \tau_{\mathrm{VCLK}} = c \cdot (\tau_t(ST) - \tau_r(\mathrm{Local})) - \mathrm{c} \cdot \tau_{\mathrm{VCLK}} \tag{3}$$

where ρ denotes the pseudorange from the satellite to the user; ρ_0 is the pseudorange from the master clock at the master station to the user, and it is a measurement value actually obtained by the CAPS receiver. τ_{VCLK} is the time modification of the virtual onboard clock and it is broadcasted in the navigation message. This technique uses a virtual onboard clock to obtain and broadcast τ_{VCLK} to users. Details can be found in Li et al. (2009a).

4.1.5 Barometric altimetry

Using barometric altimetry as a virtual constellation is applied to CAPS for three-dimensional (3D) positioning. Barometric altimetry depends on the relationship of air pressure variations with altitude in the Earth's atmosphere. Once the air pressure at a location is measured, the site's altitude can be calculated. The barometric altimetry system of CAPS is shown in Figure 11. The master station receives atmospheric pressures P and temperatures T from all weather stations around China and surrounding areas. Then the weather data are transmitted to a satellite, and then broadcasted to the receiver. The receiver calculates height with barometric altimetry software.

The Laplace pressure-height formula is,

$$h = h_0 + 67.4\,(273.15 + T_m)\,\lg \frac{P_0}{P}, \tag{4}$$

where $T_m = (T_0 + T_R)/2$, T_0 is the temperature, and T_R is the value measured by a receiver. h and h_0 are the receiver's and reference heights respectively. P and P_0 are atmospheric pressure values at heights h and h_0 respectively. Once the air pressure P is measured, and the reference quantities h_0, P_0 and T_0 are available, then the receiver's height h can be found. This method is able to enhance and improve the availability of 3D positioning. The difficulty is that the relationship between barometric pressure and altitude is variable in different areas and under various weather conditions. Hence, in order to obtain higher accuracy, the acquisition of real-time air pressure corresponding to an altimetric region's reference height is needed. An innovative method is proposed to solve this problem, which is to collect the real-time air pressure and temperatures of the 1860 weather observatories with known altitude around China and, via satellite communication, to carry out a time extrapolation. To reduce data quantity, we first partition the data and encode them, then broadcast the information via a navigation message to CAPS receivers. Upon the interpolations being completed in the receivers, the reference air pressure and temperature at the place near the receiver are derived (Ai et al. 2009a).

4.1.6 The integration of communication and navigation

Because the CAPS spacecraft become communication satellites, they can be used not only for navigation but also for navigation-related communications or redeployed primarily for general communications at any time.

The space segment of CAPS is composed of four DGEO communication satellites, so its ample frequency resources can be used not only for navigation but also for navigation-related communications. In the validation phase of the CAPS project, a kind of terminal has been designed that can receive the navigation and message signals with the same antenna, and then demodulate the signals with the same baseband device[14]. The CAPS system could fulfill message communication with a data rate of 50–100 bps and a bit error rate of 10^{-6} (Cui et al. 2009).

4.1.7 Triple-frequency signals

The CAPS uses communication frequency in the C-band for navigation services, and all the navigation and ranging signals are generated by the ground stations instead of onboard satellites. Two carriers, C1 and C2, at respective frequencies of 3826.02 MHz and 4143.15 MHz have been adopted by CAPS.

The core algorithm of the carrier phase based GPS kinematic positioning techniques is carrier phase integer ambiguity resolution. After integer ambiguities have been successfully resolved, the position estimation with the unambiguous phase measurements can achieve centimeter accuracy. The next generation of GNSS systems will all operate with three or more frequencies. For instance, GPS has introduced L5 signals at 1176.45 MHz, in addition to the currently operational L1 at 1575.42 MHz and L2 at 1227.6 MHz. The combination of the selected observables from signals at three frequencies often have minimum or low ionospheric effects. As a result, the effects of the ionospheric biases in the geometry-based phase observation models can be significantly mitigated or even eliminated for long baselines (Feng 2008). However, the number of available combinations is few and amplified measurement noise severely degrades performance of kinematic positioning (Cocard et al. 2008).

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[14] National High Technology Research and Development Program of China (Grant No. 2007AA12Z343)

Optimal code and phase combinations from three frequencies are studied for CAPS to remove the ionospheric delays and ambiguities in combined selected phase signals can be determined over a few epochs with a high probability of success. Each candidate phase-code combination is constructed to form one "positive" linear combination of carrier phase measurements and one "negative" linear combination of code measurements, both of which have ionospheric terms with approximately the same magnitude and opposite sign, so that the difference between the chosen code and phase combinations can eliminate the effect of the ionosphere. Any two of these unambiguous phase signals can be used to estimate the ionospheric corrections and form an ionospheric-free phase measurement for position estimation. The precision of the ionospheric corrections and unambiguous phase ranges can be refined to a standard deviation of 1 cm through standard smoothing over a few tens of seconds. The shortest time required for the refinement of an ionospheric correction to a certain level of accuracy is achieved when the third frequency is close to the middle of the two outer frequencies. This has become a selection principle for the three carrier frequencies of the satellite navigation system. A wider separation between frequencies may lead to higher precision in ionospheric correction, thus achieving high-precision ranging for kinematic positioning with the triple frequency CAPS signal structure (Ai et al. 2011).

4.1.8 Physical augmentation factor of precision

The method of positioning for CAPS is similar to that of GPS, which is based on trilateration. Considering the offset of the receiver clock with respect to the satellite, signals from four satellites are needed to solve the 3-D position and time. The positioning performance is primarily affected by the satellite geometry and the ranging error. The effect of satellite geometry is generally described by geometric dilution or position dilution of precision (PDOP). Then the position error is the ranging error amplified by a factor of PDOP. For the CAPS experimental system, the PDOP ranges from 5 to 14. It is the main factor restricting the positioning precision of CAPS.

When more than four satellites are available, there is a minimum PDOP for a certain combination of four satellites. The PDOP will be slightly improved if all the satellites are employed for positioning. Theoretically, if each satellite is replaced by a cluster of n satellites, the PDOP is then decreased by a value of $\frac{1}{\sqrt{n}}$. Inspired by this, related studies found that the same result can be obtained if each satellite transmits navigation signals over n frequencies. Accordingly, $\frac{1}{\sqrt{n}}$ is defined as a physical augmentation factor (PAF) of precision, and multi-frequency navigation is proposed to largely improve the PDOP (see footnote 3). In this sense, the position error is the product of PAF, PDOP and the ranging error. This method can be implemented in CAPS since it possesses ample frequency resources. It is also applicable to any other navigation systems if the required frequency band is available.

4.1.9 Voice communication

The CAPS satellites are communication satellites, so the system has can enable data and voice communication. The multiple access method for voice communication in CAPS is FDM/CDMA. The ALOHA technique is used for inbound channel requests. The system channels are divided into a service channel (voice channel) and a signaling channel (control channel). QPSK is used for signal modulation, the I sub-channel transmits signaling data, and the Q sub-channel transmits voice data. The information transmission rate is 700 bps (Cui & Shi 2011).

The CAPS network configuration for voice communication is generally designed as a star topology, with the same basic configuration for each remote site. In addition, the communication center's station is the hub station, which is in charge of management and control of the entire network. In this

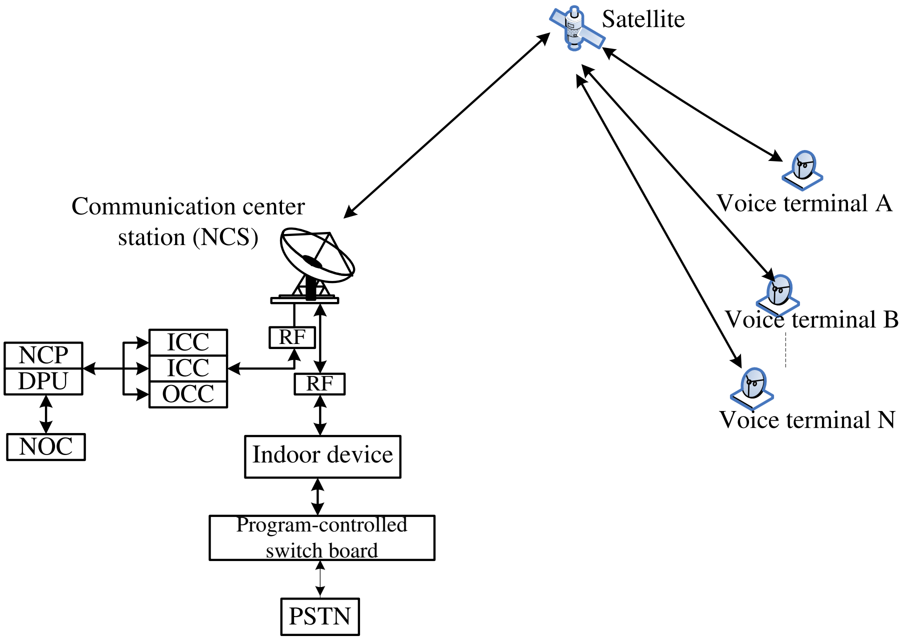

Fig. 12 Diagram of the satellite telephone system.

voice system for CAPS, because the terminal antenna aperture is rather small, its transmission and receiving abilities are limited. As a result, one remote terminal cannot directly communicate with another one, and it must be completed by forwarding the communication to the Earth station with a large-diameter antenna. That is to say, it must be completed by “two jumps” via the satellite.

The communication center’s station with a large diameter antenna works not only as a hub station, but also as a program-controlled switching center. The whole network is intensively managed by the network control system (NCS). NCS is in charge of network management and control, as well as channel allocation and other functions. In the service area, regional management can be implemented, different centralized satellite communication stations are set up for every satellite, and each of them implement the regional network management and control functions.

This voice communication system can not only realize voice communication between the terminal and the master station, as well as between different terminals, but it can also communicate through the central station gateway into the Public Switched Telephone Network (PSTN) (Nunn 2005).

A schematic diagram of the system and the configuration of the communication hub are shown in Figure 12. NCP is the network control processor, which maintains the system’s configuration database, manages events, and collects the status of the components . The DPU sub-system is responsible for satellite voice communication’s circuit assignment to the voice terminals and the voice units in the central communication station. The NOC subsystem includes a high-resolution color monitor. A form-based human-machine interface is displayed on the monitor. OCC is the outbound control channel, and ICC is the inbound control channel.

4.2 Performance and Functionality of the System

The dynamic and static performance tests of the CAPS demonstration system were carried out in eastern, southern, western, northern and middle parts of China. The vehicle and shipboard user sets were used for a dynamic performance test. The test results are summarized as follows (Ji & Sun 2009; Ai et al. 2008, 2009b):

(1) Static positioning accuracy: Horizontal: ordinary service 15–25 m (1σ), precision service 5–10 m (1σ); Vertical:1–3 m;
(2) Dynamic positioning accuracy: Horizontal: ordinary service 15–25 m (1σ), precision service 8–10 m (1σ);
(3) Velocity accuracy: ordinary service 0.13–0.3 m s^{-1} (1σ), precision service 0.15–0.17 m s^{-1} (1σ);
(4) Timing accuracy: ordinary service 160 ns (1σ), precision service 13 ns (1σ);
(5) TWSTC accuracy average: 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);
(8) Message communication: data rate 50 bps, bit error rate 10^{-6}.

4.3 The Advantages and Disadvantages of CAPS

Through analyzing the trade-offs of the past and present performance of CAPS, we clarify both advantages and disadvantages of the system. The evaluation is of great significance to guide future development. Concerning the use of C-band frequencies for satellite navigation, Irsigler et al. (2004) provided a detailed analysis. Here, the assessment is mainly on the effects brought by the configuration of the CAPS constellation.

4.3.1 The advantages of CAPS

CAPS is much cheaper than other navigation satellite systems owing to the construction of its constellation. The system uses GEO communication satellites, especially DGEOs and generates the navigation messages on the ground, so the associated expenses can be saved by developing and launching specific satellites. It would only cost an estimated US$300 million to build a CAPS-like system that covered one-third of the Earth’s surface. This is just about one percent of the cost for a fully developed GNSS. The use of DGEOs by CAPS in effect extends the lifetime of some communication satellites and leads to recycling in space. Moreover, the system can be built up very quickly. All the important equipment in a traditional navigation satellite can be deployed on the ground. Only several more IGSO satellites are potentially needed in the constellation and those are basically communication satellites, which do not need a special design. Building the validation system only took three years (Ai et al. 2008; Li & Dempster 2010).

The system can integrate navigation and communication. Because CAPS spacecraft are communication satellites, they can be used not only for navigation but also for navigation-related communications or redeployed primarily for general communications at any time. It has a similar signal structure to GPS (in a different band), making the development of an all-in-one receiver (for GPS, Galileo, Compass, QZSS, and so forth) easier, while making the equipment more robust against interference at any given radio frequency.

Developed for China, CAPS not only increases the number of navigation satellites visible in the Asia-Oceania area but also benefits a much larger region, especially South East Asia and part of Australia. Japan’s QZSS has already attracted much attention from some Asia-Oceania countries, including Australia. Because the CAPS constellation has more satellites and is a civilian system, it also has potential for international collaboration (Li & Dempster 2010).

4.3.2 The disadvantages of CAPS

The CAPS space segment consists of commercial communication satellites, which only relay received signals back to Earth. The navigation signal relies solely on the ground station. If anything happens to the ground station or the uplink, the system loses its navigation function. Compared with other navigation satellite systems, therefore, CAPS is more vulnerable in terms of its ground station. Besides, since C-band is used for the data link and navigation signal, the interoperability with other systems is more complicated than those systems operating at L-band.

Although this system employs DGEOs and lets them drift freely, the inclinations of the DGEOs are basically small. The PDOP of CAPS is not as good as that of GNSS systems. The PVT accuracy is also not as good as for GNSS systems. A barometer may be needed in CAPS receivers to provide altitude. Local pressure and temperature data around China must be collected in the navigation message and broadcast by the satellites. This requirement is likely to become a problem if other countries want to use this system, since other countries far from China would have to build their own ground station to generate the broadcast messages (Li & Dempster 2010).

There has been the RNSS of Beidou, which is working well and being expanded to COMPASS, which is under construction and slated to become a powerful GNSS consisting of five GEO satellites, three IGSO satellites, and 27 MEO satellites (Zhang et al. 2011; Han et al. 2011). Since COMPASS takes priority over CAPS, it is likely to affect the budget and schedule of CAPS.

The above mentioned points highlight disadvantages of the CAPS experimental system. After the launch of IGSO satellites, the PDOP and hence the accuracy is expected to improve by several times. With continuing innovations such as multi-frequency positioning implemented in CAPS, it is possible that the system will overcome these disadvantages and catch up with other systems.

5 THE FUTURE OF CAPS

As a system with distinct advantages and disadvantages to be overcome, it is worth developing further to meet more needs of society and offer benefits. A prospective vision of CAPS can be described with the following aspects.

5.1 Global Extension

There are approximately 300 GEO communication satellites operating at present around the world (Ai et al. 2008). It is convenient and flexible to directly lease the transponders of GEO communication satellites, and the costs are much less than launching special-purpose navigation satellites.

The process of replenishing the CAPS infrastructure requires leasing 14 commercial GEO communication satellites with 28 transponders distributed in geostationary orbits at $0°$E, $30°$E, $59°$E, $87.5°$E, $103°$E, $113°$E, $142°$E, $163°$E, $180°$E, $30°$W, $60°$W, $90°$W, $120°$W and $150°$W, respectively. The constellation, consisting of nine IGSOs, whose angle of inclination is $50°$, in three groups around $0°$E, $120°$E and $120°$W, can build a global Chinese positioning system (G. X. Ai 2012, personal communication).

The computed PDOP is shown in Figure 13, where the different color areas mean the different values of PDOP. In the area of China, the PDOP is about 1.7–2.5. It can be seen that PDOP is feasible even in polar areas. It is a seamless global navigation and communication system.

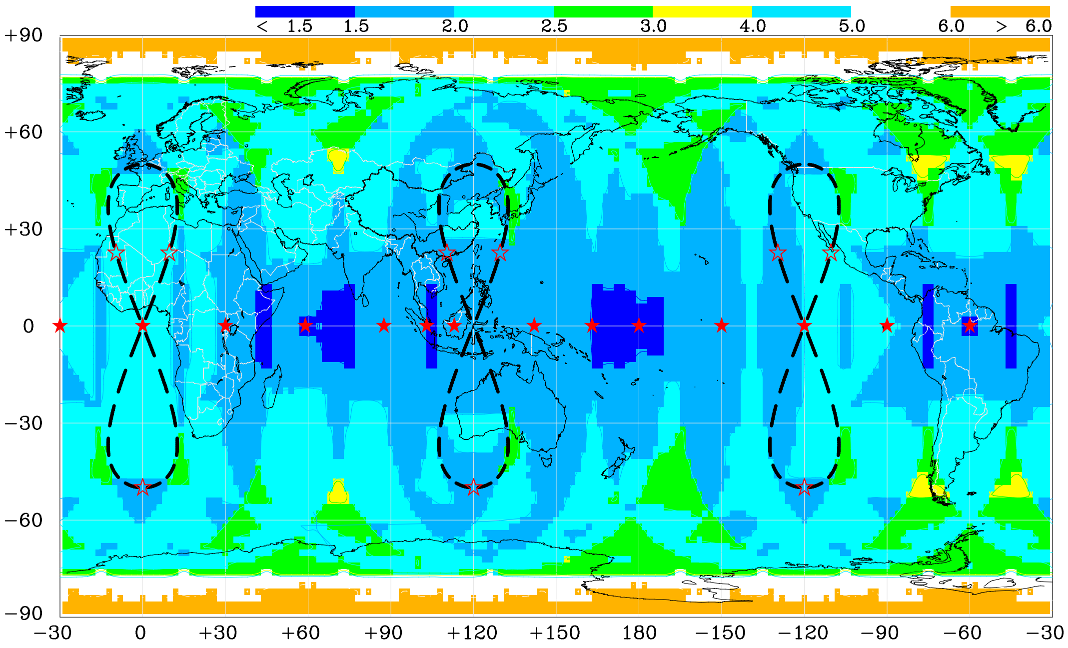

Fig. 13 PDOP for a global CAPS.

5.2 Combination of Navigation and Communication

A combination of navigation and communication implies an integrated functionality in terms of positioning, velocity measurement, time dissemination and communication. It is named PVTC, where C stands for "communication." Since there are four DGEO communication satellites in CAPS, apart from a few frequencies used for navigation, most of the transponders are unexploited. This enables the system to use the residual frequency resources to implement communication. The primary mission of CAPS, in the aspect of communication, is to provide transmission services of short messages, images and voice data for about 300 000 users (Ai et al. 2008).

The process of short message communication has already been implemented with a data rate of 50–100 bps, and it was successfully demonstrated in the Xinjiang transport monitoring project, in which positioning precision was achieved within 15 m (see footnote 14). Recently, a low rate voice communication study started for portable terminals to make full use of the residual transponders, with the lowest data rate being 600 bps. In the future, the CAPS project plans to contribute to various enhancements such as data transfer, vehicle monitoring and life rescue.

5.3 Highly Accurate Positioning

Carrier phase based GPS kinematic positioning techniques have been extensively studied since the mid-1980s. The core algorithm has carrier phase integer ambiguity resolution. After integer ambiguities are successfully resolved, the position estimation with the unambiguous phase measurements can achieve centimeter accuracy. The reliability of ambiguous solutions has been an inherited problem because the effects of ionospheric and trospheric bias and multipath errors cannot be easily separated from integer parameters. GPS has introduced the L5 signal at 1176.45 MHz, in addition to the currently operational L1 at 1575.42 MHz and L2 at 1227.6 MHz. They have attempted to use three GPS carrier signals for improved carrier phase ambiguity resolution (Li et al. 2010).

Based on CAPS, triple-frequency signals in C-band were also studied for high accuracy positioning. It has been proved that CAPS can achieve centimeter accuracy with three properly selected frequencies, which are 4143.15 MHz, 3826.02 MHz, and 3979.47 MHz (Ai et al. 2011). There are prospects for broad application of this technique, including (1) high-accuracy kinematic positioning over a large area no matter if at sea or in remote regions, (2) high-accuracy kinematic autonomous navigation for middle and low orbit satellites, (3) en route navigation with high accuracy providing approach and landing service for every aviation user, and (4) high-precision geodesy. This project currently plans to implement a triple-frequency technique in the CAPS experimental system to achieve centimeter positioning accuracy.

5.4 Anti-jamming

Jamming is the transmission of radio noises that disrupt navigation and communication by decreasing the signal to noise ratio. Unintentional jamming occurs when an operator transmits on a busy frequency, or equipment accidentally emits a signal. Deliberate use of radio noise or signals in an attempt to disrupt a system's normal operation is intentional jamming.

Anti-jamming ability is one of the important performance measures for any navigation or communication system. A direct-sequence spread spectrum, which is already implemented in CAPS, is a favorable modulation technique to protect the signal transmissions below the level of noise. With ample frequency resources in CAPS DGEO communication satellites, frequency switching can be implemented. It is useful method for countering interferences by switching carrier frequencies when needed[15].

5.5 Using LEO Satellites to Enhance CAPS

The positioning precision is proportional to the product of PDOP and pseudorange error. The PDOP of CAPS will be better if LEO satellites are placed into the CAPS constellation. Moreover, the carrier phase can replace the code measurement to improve the pseudorange error. The tracking error for a signal's carrier phase is lower than the code's by two to three orders of magnitude, but it requires that an unknown ambiguity in the constant cycle be determined. An efficient solution for this problem is to exploit the observable bias provided by the motion of satellites. By contrast, angular variations from LEO satellites quickly become substantial. Therefore, the positioning accuracy is enhanced using additional carrier phase measurements from moving LEO satellites.

5.6 Positioning in the Conditions of an Urban Environment

CAPS has accurate position information under good environmental conditions. However, CAPS only works well if all the four satellites (or three satellites with added barometric altimetry) can be accessed simultaneously, which is not always feasible in urban situations. It can be shown that multi-path effects are one of the dominant sources in the error budget for CAPS (Ji & Sun 2009). There are numerous base stations in Chinese mobile communication networks. In this case, we can make full use of the mobile networks. This strategy can supply orbital data or satellite ephemeris to the CAPS receiver, enabling the receiver to track the satellites more rapidly in urban situations. CAPS can also provide precise time signals to a mobile network.

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6 CONCLUSIONS

Benefiting from large numbers of available facilities, communication-based positioning systems are a promising supplement and enhancement for the dominant GPS. Since CAPS consists of commercial GEO and DGEO communication satellites, it is characterized by low cost, high flexibility, wide-area coverage and ample frequency resources. Coming up with an ingenious utilization of a direct-sequence spread spectrum, CAPS has achieved an integration of satellite navigation and communication. It provides the multiple functionality of PVTC within one system. The sufficient frequency resources enable CAPS to improve positioning precision with multiple frequencies of wideband signals. They also make it possible to overcome interferences by switching carriers.

The global implementation of CAPS will occur if it is expanded world wide. With further enhancements with LEO satellites and mobile base stations, CAPS will possibly turn into a seamless, highly accurate, large capacity navigation and communication system, and hence become a potential candidate for the next generation of radio navigation after GPS.

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