

# Research and Development on Satellite Positioning and Navigation in China\*

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**SUMMARY** With the development of Global Navigation Satellite System (GNSS), the amount of related research is growing rapidly in China. A lot of accomplishments have been achieved in all branches of the satellite navigation field, especially motivated by the BeiDou Program. In this paper, the current status, technologies and developments in satellite positioning and navigation in China are introduced. Firstly, an overview and update of the BeiDou Program is presented, known as the three-step development strategy for different services. Then signal design for the BeiDou system is discussed, including the generation of pseudo-random noise (PRN) codes for currently available signal B1, and the investigation of a new signal modulation scheme for interoperability at open frequency B1C. The B1C signal should comply to Multiplexed Binary Offset Carrier (MBOC) constraints, and a modulation called Quadrature Multiplexed BOC (QMBOC) is presented, which is equivalent to time-multiplexed BOC (TMBOC) for GPS and composite BOC (CBOC) for Galileo, while overcomes the drawback of CBOC. Besides, the inter and intra system compatibility is discussed, based on the effective  $C/N_0$  proposed by International Telecommunication Union (ITU). After that, receiver technologies in challenging environments are introduced, such as weak signal acquisition and assisted GNSS (A-GNSS). Moreover, a method of ambiguity mitigation for adaptive digital beam forming (ADBF) in large spacing antenna arrays is proposed, by which interference suppression is available. Furthermore, cutting edge technologies are brought in, including seamless navigation for indoor and outdoor, and collaborative navigation. After all, GNSS applications in China for industry and daily life are shown, as well as the market prospectation.

**key words:** GNSS, BeiDou, MBOC, navigation receiver, signal design

## 1. Introduction

USA owns the earliest operating and currently the most successful Global Positioning System (GPS), and Russia has completed the Global Navigation Satellite System (GLONASS) constellation, while European Union (EU) is carrying out the Galileo program. In recent years, China has been developing the BeiDou Project, which was planned in the 1990s. The current evolution is BeiDou-2, known as Compass [1]. The employments of GPS in the Gulf War and E911 policy of the federal government greatly drive the research and development of Global Navigation Satellite System (GNSS) in both military and civil areas all over the world.

The research activities in China mainly focus on the construction and applications of the BeiDou system. The

BeiDou program consists of three steps [2]: BeiDou-1 was the first step and completed in 2003, officially called BeiDou Navigation Experimental System; in the second step, a regional navigation system for Asia-Pacific region is expected by 2012, and it is a part of BeiDou-2; in the third step, BeiDou-2 is planned to be finished by 2020 and to provide global navigation service. There have been more than 150 thousand registered users of BeiDou-1 in fishery and disaster relief applications so far, while BeiDou-2 is still under construction, in which the work related to modernization signal design plays an important role.

In 1999, USA announced the GPS modernization program, and indicated that two signals would be added for civil service: L2C and L5. In order to achieve interoperability with Galileo in L1 band, another modernization signal of GPS L1C was presented, which was modulated by Multiplexed Binary Offset Carrier (MBOC) at 1575.42 MHz, as well as E1OS signal of Galileo [3]. Analogously, Compass proposed B1C signal modulated by MBOC in L1 band. In addition, Compass occupies the same frequency band with Galileo E5 in B2 band and the signals overlap in each other. Thus, the GPS/Galileo/Compass radio frequency compatibility (RFC) should be taken into account.

Aiming at challenging environments, various receiver and augmentation technologies have been investigated and assessed in China. Multipath, weak signal and barrage interference are typical causes which make conventional receiver's performance degradation or even out of work [4]. High performance receivers are needed to solve these problems. Besides, assisted GNSS (A-GNSS) and seamless navigation are new challenging technologies developed in China, which will make daily life more convenient and there will be a huge pie for civilian service market in the future.

This paper presents the current research and development situations mentioned above in China. The remainder of this paper is organized as follows: in Sect. 2, the BeiDou program is introduced in detail, from the original plan to the future; in Sect. 3, the PRN codes generation for B1 signal of Compass is presented, and for open service signal B1C, Quadrature Multiplexed BOC (QMBOC) modulation is described; in Sect. 4, receiver technologies studied in China are introduced, including some novel and advanced methodologies appeared in recent years; in Sect. 5, practical applications in fishery and disaster relief are presented, as well as the industry and market in future will be indicated; Sect. 6 offers some concluding remarks.

Manuscript received March 19, 2012.

Manuscript revised July 13, 2012.

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\*This paper was supported by The National High Technology Research and Development Program of China (863 Program) (2012AA120802)

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DOI: 10.1587/transcom.E95.B.3385

## 2. BeiDou Program Development

According to China National Space Administration (CNSA), BeiDou program is carried out by three steps.

### 2.1 BeiDou-1 (2000–2003): BeiDou Navigation Experimental System

Satellites information of BeiDou-1 is shown in Table 1. The launch of BD-1C in 2003 meant the completion of BeiDou-1 navigation system. The first two launched satellites were used for positioning and communication, and the third one was the backup, while the fourth launched in 2007 was for experiments in space, as well as a backup for the early three ones. BeiDou-1 is different from GPS or GLONASS, since it is a regional active navigation system with GEO satellites. It contains three parts: Space Segment, Control Segment (Monitor Station), and User Terminal. When positioning is needed, the user transmits request signal to the satellites in L band, and the satellites relay it to Ground Control Station in C band, and then servers on ground calculate the position solution for the user, according to the known positions of satellites and ground station, as well as the relief map; after that, the position is sent to satellites and then broadcasted to remote terminals [5]. It is shown in Fig. 1.

Therefore, the receivers need no resolution and the satellites need no atomic clock. The architecture of receivers and satellites is simplified. The satellites of BeiDou-1 work as communication relays between remote terminals and ground stations. In addition, the ability of communi-

cation makes it more adequate than GPS for positioning and data communication situations, such as transportation, search and rescue, scheduling, etc. The communication ability is a most significant advantage, and the user is able to send short message up to 120 Chinese characters each time.

While the accuracy of positioning and time service is limited by the constellation, the position error is 100 m, or 20 m if calibration stations are available; then the timing error is 100 ns for unidirectional synchronization or 20 ns for double directions [6]. As a result of active positioning, the capacity of total positioning request is limited at 540000 times per hour, and the satellite relay adds the time delay for real time movement. What's worse, radio quiescence cannot be achieved, and that the remote terminal needs transmit signal to satellites makes the receiver cost rise and portability lose, which is adverse to customers.

### 2.2 BeiDou-2 (2007–2012): Regional Navigation System Covering Asia-Pacific Area

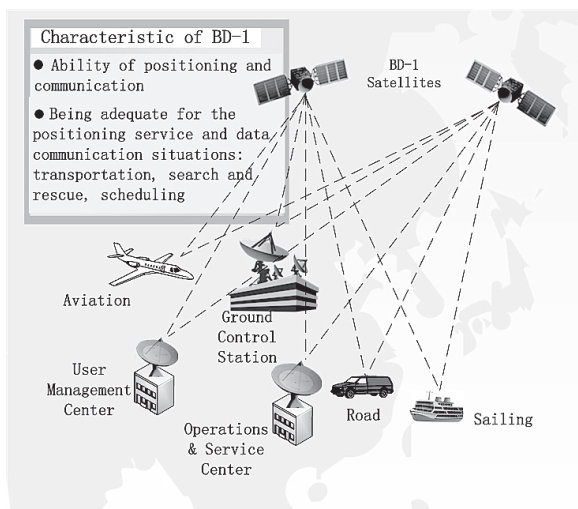
Based on the experimental system BeiDou-1, BeiDou-2 program was designed as a global navigation system, and the communication band and navigation band are separated, thus the communication ability can be improved obviously.

BeiDou-2, namely the Compass program, was planed in two stages: the regional navigation system covering Asia-Pacific area by 2012 and the global navigation system by 2020. The first step will be completed after 14 satellites launched, containing 5 GEO, 5 IGSO and 4 MEO satellites. There have been 13 satellites successfully launched for BeiDou-2 network so far, and 2 MEO satellites and 1 GEO satellite will be launched respectively in August and October, 2012 [7]. The satellites launch information is shown in Table 2 and the trajectories of satellites in orbit by January 2011 are shown in Fig. 2. The launch of M3 and M4 is the first time China that has launched two navigation satellites with one rocket for BeiDou-2 program.

In this stage, there are three signal frequencies: B1, B2 and B3, all of which are modulated by Quadrature Phase Shift Keying (QPSK) [2]. The positioning and timing service accuracy is improved to 10 m and 50 ns, and the velocity accuracy is 0.2 m/s. B1 and B2 frequencies contain I and Q channels and I channels provide open service. China

**Table 1** Launches of BeiDou-1 satellites.

Satellite	Lunch Data	Orbit
BD-1A	10/31/2000	GEO 59° E
BD-1B	12/21/2000	GEO 80° E
BD-1C	05/25/2003	GEO 110.5° E
BD-1D	02/03/2007	Supersync orbit



**Fig. 1** BeiDou-1 system.

**Table 2** Launch of in-orbit BeiDou-2 satellites.

Satellite	Lunch Date	Orbit
Compass-M1	04/14/2007	MEO 21500km
Compass-G2	04/15/2009	In-Orbit Maintenance
Compass-G1	01/17/2010	GEO 144.5° E
Compass-G3	06/02/2010	GEO 84° E
Compass-IGS01	08/01/2010	118° E incl 55°
Compass-G4	11/01/2010	GEO 160° E
Compass-IGS02	12/18/2010	118° E incl 55°
Compass-IGS03	04/10/2011	118° E incl 55°
Compass-IGS04	07/27/2011	95° E incl 55°
Compass-IGS05	12/02/2011	IGSO
Compass-G5	02/25/2012	GEO 58.75° E
Compass-M3	04/30/2012	MEO 21500km
Compass-M4	04/30/2012	MEO 21332km

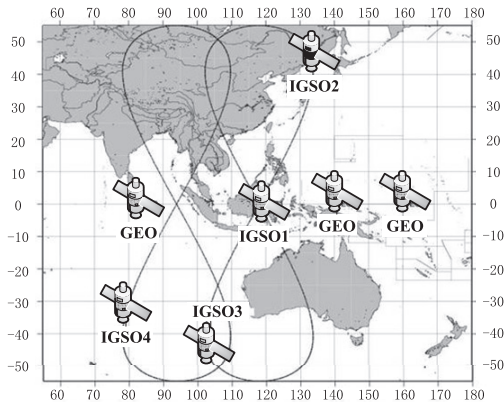


Fig. 2 Trajectories of BeiDou-2 satellites in orbit by January 2011.

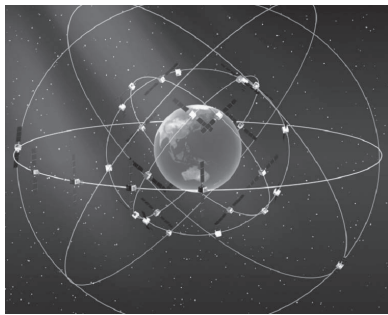


Fig. 3 Compass global navigation system.

begun trial operations of BeiDou-2 on December 27, 2011 [8].

### 2.3 BeiDou-2 (2012–2020): Global Navigation System

After 2012, the remainder satellites will be launched continually to complete BeiDou-2 system by 2020, which will be a global navigation system containing 5 GEO, 3 IGSO and 27 MEO satellites in three types of orbits, shown in Fig. 3. Since GPS only contains MEO satellites, BeiDou-2 could provide better performances in satellite availability and GDOP (Geometric Dilution of Precision) than GPS, especially in Asia-Pacific area. While the far-near effect induced by different orbits needs to be corrected. Besides, the launch of GEO or IGSO satellite is more difficult and costly. The positioning and timing accuracy will be 10 m and 20 ns for open service, and there will be differential signal to provide 1 m accuracy positioning service [2].

The frequencies in B1 and B2 band will be adjusted during this phase. B1C signal will be added at frequency 1575.42 MHz, the same as GPS L1 and Galileo E1OS frequency, in order to implement interoperability with different constellations. As a result, the interoperability signal will be modulated by MBOC(1,6,1/11), the same as GPS L1C signal and Galileo E1OS signal in frequency domain. B2 signals will be all open service, modulated by AltBOC(15,10) at 1191.795 MHz, the same as Galileo E5 signals, which is the life and safety service channel [1].

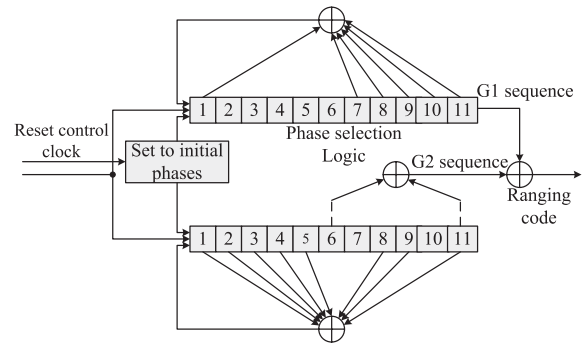


Fig. 4 Ranging code generator of carrier B1.

## 3. BeiDou Signal Design and Assessment

In December 2011, China Satellite Navigation Office published the test version of BeiDou Navigation Satellite System Signal In Space Interface Control Document (ICD) [9], in which the specifications of B1 signal at 1561.098 MHz was presented. The design of B1C signal is still under research, the realization in time domain has not been determined until now, and in this section it will be discussed later, as well as the RFC of BeiDou system.

### 3.1 PRN Code Generation for B1 Signal

B1 signal carrier frequency is 1561.098 MHz, QPSK modulated, ranging code rate and length of channel I is 2.046 Mcps and 2046 chips. The ranging code in channel I is a balanced Gold code sequence truncating the last one chip. The Gold code is generated by means of Modulo-2 addition of  $G1$  and  $G2$  sequences, which are respectively derived from two 11-bit linear shift registers. The generator polynomials for  $G1$  and  $G2$  are as follows [9]:

$$G1(X) = 1 + X + X^7 + X^8 + X^9 + X^{10} + X^{11} \quad (1)$$

$$G2(X) = 1 + X + X^2 + X^3 + X^4 + X^5 + X^8 + X^9 + X^{11} \quad (2)$$

The initial phases of  $G1$  and  $G2$  are  $G1$ : 01010101010,  $G2$ : 01010101010. The ranging code generator of carrier B1 is shown in Fig. 4.

The different phase shift of  $G2$  sequence is accomplished by respective tapping in the shift register which generates  $G2$  sequence. By means of Modulo-2 addition of  $G1$  and  $G2$  with different phase shift, a ranging code in channel I is generated for each satellite.

### 3.2 QMBOC Modulation for B1C Signal

With the modernization of GNSS, there are more signals in L1 band. RFC and interoperability become key issues for GNSS. On June 26 2004, USA and EU reached an agreement on sharing L1 band for interoperability. In 2006, Guenter W. Hein and John W. Betz recommended the optimized spreading modulation MBOC for Galileo E1OS and GPS L1C signals, instead of the previously proposed BOC

modulation [3]. Finally, MBOC(6,1,1/11) was the determination for GPS and Galileo to achieve a common power spectrum, while realized in different ways in time domain.

MBOC(6,1,1/11) defines the signal constraint in frequency domain, it can be expressed as:

$$G_{MBOC(6,1,1/11)}(f) = \frac{10}{11}G_{BOC(1,1)}(f) + \frac{1}{11}G_{BOC(6,1)}(f) \quad (3)$$

In BOC( $m, n$ ) expression,  $m$  denotes the subcarrier rate at  $m \times 1.023$  MHz and  $n$  denotes the PRN code rate at  $n \times 1.023$  MHz. GPS L1C is defined in time domain as

$$G_{MBOC(6,1,1/11)}(f) = \frac{1}{4}G_{Date}(f) + \frac{3}{4}G_{Pilot}(f) \quad (4)$$

$$G_{Pilot}(f) = \frac{29}{33}G_{BOC(1,1)}(f) + \frac{4}{33}G_{BOC(6,1)}(f) \quad (5)$$

$$G_{Data}(f) = G_{BOC(1,1)}(f) \quad (6)$$

While Galileo E1OS signal is defined in time domain as

$$G_{MBOC(6,1,1/11)}(f) = \frac{1}{2}G_{Data}(f) + \frac{1}{2}G_{Pilot}(f) \quad (7)$$

The subcarrier for both data and pilot channel is

$$s_{CBOC}(t) = \sqrt{\frac{10}{11}}s_{BOC(1,1)}(t) \pm \sqrt{\frac{1}{11}}s_{BOC(6,1)}(t) \quad (8)$$

BOC(1,1) owns more high-frequency components than BPSK(1) spreading modulation of C/A code. As a result, BOC(1,1) has better performances in code tracking and anti-multipath. By adding a small fraction of BOC(6,1) to BOC(1,1), MBOC(6,1,1/11) provides more components in higher frequency, as shown in Fig. 5, and it achieves better performances than BOC(1,1) [3], [10].

BeiDou-2 is developing a different modulation in time domain for MBOC(1,6,1/11), and QMBOC is one most representative modulation methodology.

QMBOC was proposed by Z. Yao et al. in 2010 [11], it was different from time multiplexing of GPS, either from spatial multiplexing of Galileo QMBOC( $m, n, \gamma$ ) can be expressed as

$$s_{QMBOC}(t) = \sqrt{1-\gamma}s_{BOC(n,n)}(t) \pm j\sqrt{\gamma}s_{BOC(m,n)}(t) \quad (9)$$

It is similar to CBOC but different in multiplexing. Component BOC( $n, n$ ) is modulated in phase quadrature with BOC( $m, n$ ), in order to eliminate the cross-term between them in the autocorrelation, which appears in CBOC

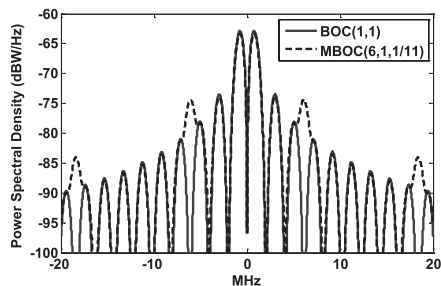


Fig. 5 Power spectral density of BOC(1,1) and MBOC(6,1,1/11).

and results that the spectrum of each individual CBOC signal does not meet the MBOC definition. Therefore, the two components of QMBOC signal are not constrained by the same power ratio, more flexible than CBOC. As a result, no matter with which sign of the second component, the auto-correlation function of QMBOC is

$$R_{QMBOC}(\tau) = E \left\{ s_{QMBOC}(t) s_{QMBOC}^*(t-\tau) \right\} \\ = (1-\gamma)R_{BOC(n,n)}(\tau) + \gamma R_{BOC(m,n)}(\tau) \quad (10)$$

Where ‘\*’ denotes the conjugate. Thus the power spectral density of each individual component can satisfy the MBOC constraint.

### 3.3 QMBOC Correlation Receiver

The received signal can be expressed as

$$s_{IF}(t) = A Re \left\{ s_{QMBOC}(t) c(t) d(t) e^{j\omega_{IF}t} \right\} \\ = A c(t) d(t) \left[ \sqrt{1-\gamma} s_{BOC(n,n)}(t) \cos(\omega_{IF}t) \right. \\ \left. - \sqrt{\gamma} s_{BOC(m,n)}(t) \sin(\omega_{IF}t) \right] \quad (11)$$

Where  $A$  is the signal amplitude,  $c(t)d(t)$  is the PRN code with modulated data and  $\omega_{IF}$  is carrier angular frequency. The noise term is omitted for simplicity. After received,  $s_{IF}(t)$  is firstly multiplied by an in-phase (I) replica and a quadrature-phase (Q) replica of the carrier respectively, and then the signals are correlated with replicas of PRN code with a BOC( $m, n$ ) spreading symbol and with a BOC( $n, n$ ) spreading symbol, respectively, over a period  $T$  referred to as the coherent integral time. Ignoring the frequency error, the outputs of the correlators can be expressed as

$$\begin{cases} I_1 = A \sqrt{1-\gamma} R_{BOC(n,n)}(\Delta\tau) d \cos \phi - A \sqrt{\gamma} R_c(\Delta\tau) d \sin \phi \\ I_2 = A \sqrt{1-\gamma} R_c(\Delta\tau) d \cos \phi - A \sqrt{\gamma} R_{BOC(m,n)}(\Delta\tau) d \sin \phi \\ Q_1 = A \sqrt{1-\gamma} R_{BOC(n,n)}(\Delta\tau) d \sin \phi + A \sqrt{\gamma} R_c(\Delta\tau) d \cos \phi \\ Q_2 = A \sqrt{1-\gamma} R_c(\Delta\tau) d \sin \phi - A \sqrt{\gamma} R_{BOC(m,n)}(\Delta\tau) d \sin \phi \end{cases} \quad (12)$$

Where  $\phi$  and  $\Delta\tau$  represent the estimation errors of the carrier phase and code phase respectively, and  $R_c$  denotes the correlation of PRN codes. The outputs of the correlators are then merged by the following rules:

$$\begin{cases} I' = \sqrt{1-\gamma} I_1 + \sqrt{\gamma} Q_2 = A R_{QMBOC}(\Delta\tau) d \cos \phi \\ Q' = \sqrt{\gamma} I_2 - \sqrt{1-\gamma} Q_1 = A R_{QMBOC}(\Delta\tau) d \sin \phi \end{cases} \quad (13)$$

It is obvious that  $I'$  and  $Q'$  have the same characteristic as traditional correlator outputs. As a result, traditional acquisition and tracking architectures can be employed subsequently. Since the correlation functions have identical form, the correlation receivers of the QMBOC signal have the same performance as that of the TMBOC signal, while those of CBOC<sup>+</sup> and CBOC<sup>-</sup> have different properties, owing to the effect of vestigial cross-term. The correlation receiver of QMBOC signals is shown in Fig. 6. For simplicity, correlators corresponding to only one PRN code phase are shown,

and the structures after correlation value combination are omitted. Although the number of correlators in QMBOC receivers is twice as that in TMBOC and CBOC correlation receivers, the complexity introduced by the time multiplexing switch or the multilevel multiplication-accumulator is never a concern in QMBOC receivers. When matched receiving, QMBOC has the same performance with TMBOC.

### 3.4 Assessment of RFC

RFC has become a matter of concern in GNSS filed since multiple systems such as GPS, Galileo and Compass are going to serve in the same band [1], [12]. Some methodologies for GNSS RFC analysis have been developed in order to investigate intra- and inter-system interference. Spectral separation coefficient (SSC) and effective  $C/N_0$  proposed by ITU (ITU-RM) [13] are most popular. SSC indicates the correlation between spectrum overlapping signals, and it is affected by signal modulations, center frequencies,  $T_x$  and  $R_x$  bandwidths [14]. While effective  $C/N_0$  takes other signals as noise and evaluates the effect to the expect signals.

In this paper, effective  $C/N_0$  is employed, and together with the degradations induced by intra- and inter-system interference are summarized in Table 3, including B1C signal and B2 civil signals of Compass. We can conclude that, in the E1-L1-B1 band, the inter-system interference from GPS

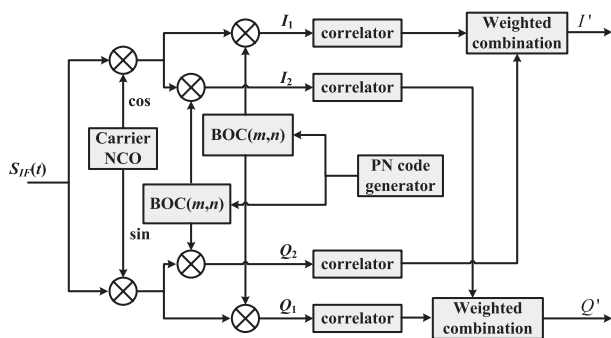


Fig. 6 QMBOC receiver structure.

Table 3 The effective  $C/N_0$  and degradation of BeiDou-2.

Interference condition	E1-L1-B1		E5-L5-B2	
	$(C/N_0)_{eff}$	Degradation of $(C/N_0)_{eff}$	$(C/N_0)_{eff}$	Degradation of $(C/N_0)_{eff}$
Thermal noise	45.40 dBHz	-	42.89 dBHz	-
Intra-system interference	44.62 dBHz	0.78 dB	42.18 dBHz	0.71 dB
Inter-system interference from Galileo	44.19 dBHz	0.43 dB	41.49 dBHz	0.69 dB
Inter-system interference from GPS	43.31 dBHz	1.31 dB	41.75 dBHz	0.43 dB
Inter-system interference from GPS and Galileo	42.98 dBHz	1.63 dB	41.12 dBHz	1.07 dB

is higher than that from Galileo. In the E5-L5-B2 band, the inter-system interference from Galileo is higher than that from GPS. The total inter-system interference in E1-L1-B1 band is higher than that in E5-L5-B2 band. While Compass induces more degradation to GPS and Galileo in L1 band than that they do to Compass, owing to the GEO satellites principally, yet the degradations are all within an acceptable range.

## 4. Receiver Technologies

When China is developing the autonomous BeiDou system, GNSS receiver technologies are studied simultaneously. Because GPS was designed early and some disadvantages were not considered enough, which made it imperfect, various of receiver and augmentation technologies are investigated to keep GPS working in challenging conditions [4]. The general interests in China will be introduced as follows.

### 4.1 Weak Signal Acquisition

The study on this subject is mainly based on coherent integration, incoherent integration, difference algorithm, full-bits method, half-bits method, and so on. An improved difference coherent integration algorithm can increase the coherent integration time and reduce the square loss by estimating the combination of the product of adjacent navigation data bits, which induces a long time coherent integration can be used in difference algorithm. With the increase of data length accumulation, superiority of the new method is more significant, comparing with the full-bits and half-bits methods, and detection probability could achieve 96% with  $C/N_0=20$  dB-Hz and data length=160 ms [15], which can be drawn from Fig. 7.

### 4.2 Assisted GNSS

For urban users suffering shading and multipath interference, assisted GNSS is proposed. The architecture is shown in Fig. 8. A-GNSS receiver gets assistance information by cellular network from reference stations and location server. According to the difference of assistance approach, it can be defined as MS-assisted or MS-based [16], where MS denotes mobile station, namely the GNSS receiver, and in for-

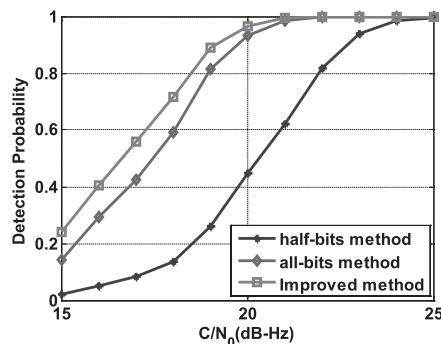


Fig. 7 Detection probability with data length of 160 ms.

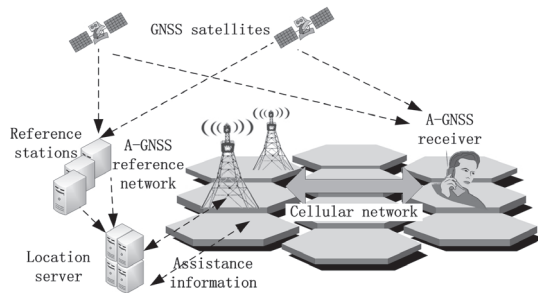


Fig. 8 Assisted GNSS architecture.

mer case the position is calculated by server while in the latter case it is calculated by the receiver itself.

### 4.3 Interference Suppressing

To combat against malicious interferences, antenna array with ADBF (adaptive digital beam forming) or STAP (space-time adaptive processing) has been indicated to be an effective technology. Various algorithms have been proposed in the past to demonstrate the effectiveness of such method, while the antenna array is requested to be uniform and half wavelength spacing, and the algorithms are not available in irregular or large spacing array, which is inconvenient. Novel array processing techniques could be potentially employed to combine the signals incident on the multiple antenna elements, and process them coherently to achieve interference reduction.

When elements spacing is greater than  $0.5\lambda$ , the problem to find DOA of a signal is to resolve the inherent ambiguities in the estimation process. Once the DOA is known, location of the emitter can be performed, and modified null-steering beamforming techniques can be used to reduce the amplitude of signals in the interference directions [17].

There is a method based on double frequency to resolve the ambiguity [18]. Assume the phase differences measured between two nodes are  $\Delta\zeta_1$  for L1 frequency and  $\Delta\zeta_2$  for L2 frequency respectively,  $\Delta\zeta_1$  and  $\Delta\zeta_2$  belong to range of  $(-\pi, \pi)$ . Then the real phase differences can be written as  $\Delta\zeta_1 + 2n_1\pi$  and  $\Delta\zeta_2 + 2n_2\pi$ , in which  $n_1$  and  $n_2$  denote the unknown ambiguous period. The distance differences expressed by L1 and L2 frequency are the same, therefore

$$\Delta S = \frac{\Delta\zeta_1 + 2n_1\pi}{2\pi} \cdot \lambda_1 = \frac{\Delta\zeta_2 + 2n_2\pi}{2\pi} \cdot \lambda_2 \quad (14)$$

Where  $\lambda_1$  and  $\lambda_2$  are wavelengths of L1 and L2 frequency respectively,  $n_1$  and  $n_2$  are integer and have the same symbol. Because  $\Delta S$  is smaller than the distance between nodes, that  $n_1$  and  $n_2$  have ambiguous values is an event of small probability. After ambiguity resolved the interference is suppressed and position is calculated.

In Fig. 9 and Fig. 10 the simulation results are shown, assuming that there are 7 antennas distributed with a spacing from 30 m to 50 m randomly on a plane. For conventional ADBF, the large spacing introduces grating lobe, and the

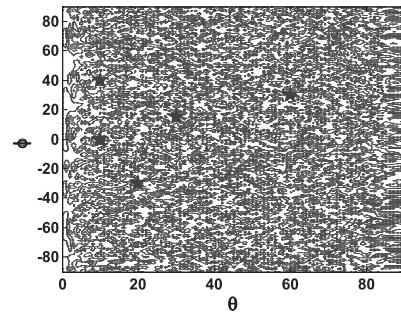


Fig. 9 Contour pattern without ambiguity resolved.

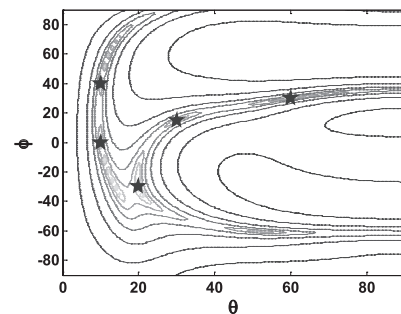


Fig. 10 Contour pattern after ambiguity resolved.

beam pattern is orderless. The star points are interference directions, while the peaks and nulls cannot be distinguished. After the ambiguity resolved, it can be seen that the nulls and interference directions are clear, and the nulls mostly lie near to the directions of interference and the interference can be suppressed effectively.

### 4.4 Seamless Indoor and Outdoor Positioning

For indoor positioning the power of satellite signal is too weak to be acquired by the receiver, thus an alternative system is needed to provide navigation service for indoor users. Concerning about the cost of constructing a new system, the existing communication network is considered as the solution, such as WLAN and UWB, which are broadly installed at school and shopping mall. Based on these network, cell ID, TOA (time of arrival), TDOA (time difference of arrival), DOA, fingerprint and fuzzy logic algorithms are widely investigated for indoor navigation.

Positioning for indoor and outdoor employs different system respectively, thus switches are needed for users when going through between indoor and outdoor, which would make receivers more complex and discontinuity. Therefore, seamless indoor and outdoor positioning methods are investigated and most are focused on handover methodologies. A novel methodology based on finger print algorithm is proposed, as shown in Fig. 11. The indoor transmitters employ the same carrier and PRN code series with those of outdoor GNSS, so the indoor receiver could be the same as that of outdoor and little changes needed in software [19]. Combining with finger print algorithm, the indoor positioning

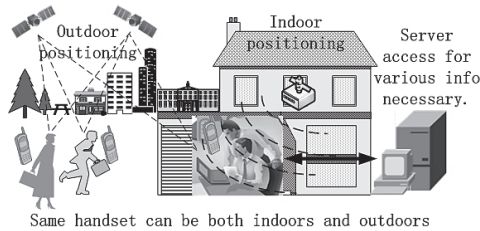


Fig. 11 Seamless indoor and outdoor navigation.

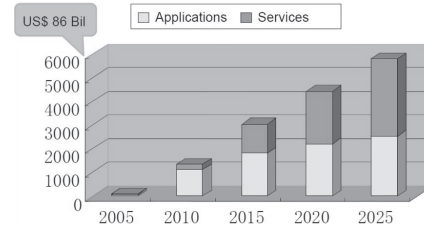


Fig. 12 Projected GNSS sales of China for 2005–2025.

accuracy could be better than 2 m. The handover between indoor and outdoor achieves real seamlessness since there is no difference in navigation signal acquisition and tracking.

#### 4.5 Collaborative Navigation

Thanks to GPS fast development, the number of users rises rapidly. As a result, the GPS users are dense in urban area, which can implement collaborative navigation to improve single receiver performance in challenging environments. Literature [20] presents the collaborative satellite navigation concept and approach for robust GPS positioning in a dynamic sensor network using a distributed aperture and RF ranging signals among the network nodes.

### 5. Applications and Market

#### 5.1 BeiDou Applications in Industry and Daily Life

- Fishery command and monitoring system. In 2011, the fishery command center and fishery boats applications project was finished in Hainan Province by BD-Star Navigation Co., Ltd and proved admission. It is the largest civilian promotion project so far for BeiDou system, and is supported by Ministry of Agriculture. This dispatch system provides services in South China Sea first, and then will be extended to deep-sea fishery boats in East China Sea, Yellow Sea and Bohai Sea, and has more than ten thousand onboard users. It consists of one Operation&Service Center, two Master Monitor Stations and tens of Center Stations, providing services for thousands of fishing boats.
- Disaster prevention and relief. After earthquake happened in Wenchuan of Sichuan Province and Yushu of Qinghai Province, BeiDou terminals sent the disaster and rescue information to command center timely, as the only available communication system at that time. More than one thousand terminals were equipped with rescuers in Wenchuan, and they provided more than 1.64 million times positioning and 740 thousand times short message service [21]. In addition, the Three Gorges hydrology monitoring system based on BeiDou was employed around Barrier Lake to collect and transmit information about flood situation to command center with 125 automatic terminals, and the prevention work kept the disaster victims downstream safe when flood discharging.

#### 5.2 Market Development

As a result of the development and applications of BeiDou system as well as other GNSS, the navigation market grows rapidly in China [22]. Figure 12 shows the sales projection of GNSS in China, from 2005 to 2025. It can be drawn that applications grows slowly after 2010, while services will develop faster and exceed applications.

### 6. Conclusions

In this paper, the situation of research and development on GNSS in China is introduced, together with applications and technologies status. As the national strategy, BeiDou is being constructed smoothly, and BeiDou-1 has been widely applied in different fields for production and daily life service, such as fishing boats monitoring system, the largest civilian promotion project of BeiDou.

With the development of GNSS, the market in China has been growing rapidly for years, and mobile users and service sales will grow faster than ever in the future. Though in China the share of BeiDou in GNSS market is less than 1%, due to the bottleneck of chip manufacture, it will explode after breakthroughs in chip fabrication and the introduction of BeiDou-2. China is definitely pushing the GNSS industry forward.

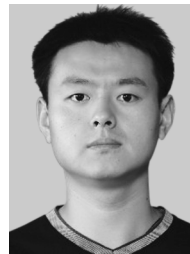
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