10. Chinese Navigation Satellite Systems

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This chapter introduces the BeiDou (COMPASS) Navigation Satellite System from its early stage as a demonstration system to its evolution to a global system. First, the development strategy and basic principle of BeiDou Demonstration System are reviewed. Its basic performance is given in details. Second, the basic information of BeiDou (regional) system including constellation, frequency, coordinate reference system, and time datum is described. Its initial performance is evaluated by using single-point positioning, code and carrier phase differential positioning. Some application examples are introduced. Third, the BeiDou (Global) Navigation Satellite System (BDS) is described. Position dilution of precision is analyzed and BeiDou's contribution is summarized. At last, Chinese Area Positioning System is briefly introduced.

The Big Dipper, the Plough or the Saptarishi (in Chinese 北斗, BěiDǒu) are well recognized in many cultures as the most important set of stars giving directions to people in the Northern Hemisphere. Besides telling the north direction, the Big Dipper also indicates the seasons. An ancient Chinese book already states that it is spring when the dipper handle directs east, summer when it directs down, autumn when it directs west, and winter when it directs up.

The Big Dipper can only be used for orientation in clear nights. As the first manmade navigation device, which was not affected by weather and could always identify the cardinal directions during day and night, the ancient compass was invented in China [10.1]. It is composed of a box frame and magnetic needle, or a spoon made from lodestone (Fig. 10.1). This magnetic device is used as a means of orientation, which always points in the northern (or southern) direction.

In Chinese mythology, the army of Huangdi (the *Yellow Emperor*, who was regarded as the initiator of Chinese civilization) lost their direction in a heavy fog around 2697 BC. In a dream, a Fairy clued to Huangdi that the compass could show the south direction. Then the compass was invented. The compass vehicle used in the war helped Huangdi to win the war against Chi You (who was a tribal leader of ancient China). The above story is just one of the many beautiful legends left to Chinese. More than that, the compass was widely

Fig. 10.1 A Chinese ancient compass (called *Sinan*) made up of a spoon from loadstone and a bronze plate with direction markings. Reproduced with permission of Panorama Media, Inc.

used in ancient China from the Qin Dynasty to Early Ming dynasty. It helped the traders and sailors find the direction during their voyages and expeditions around Southeast Asia and Pacific and Indian Ocean [10.3].

As Chinese scientists and engineers started to implement their own navigation satellite system, *BeiDou* was given as its name which was naturally chosen and recognized by the Chinese people. At the same time, its English name *COMPASS* has been also used for a dozen of years, which is largely used in the system's official frequency filing to the International Telecommunication Union (ITU).

China decided to build an independent navigation satellite system in the 1980s. Three steps for constructing the system were planned (Fig. 10.2). The first step is the BeiDou Navigation Satellite Demonstration System which is called BeiDou-1 or simply BDS-1 [10.2]. In 1994, China started the buildup of the BeiDou Navigation Satellite Demonstration System. In 2000, two BeiDou navigation experiment satellites were launched. In 2003, the third BeiDou satellite was launched, further enhancing the system's performance. Thus, BDS-1 was formally established, which made China the third nation in possession of an independent navigation satellite system following the United States and Russia.

The second step is the regional BeiDou Navigation Satellite System. Implementation of BDS-2 was started in 2004, and the first satellite, a medium Earth orbit (MEO) satellite was launched in 2007. An op-

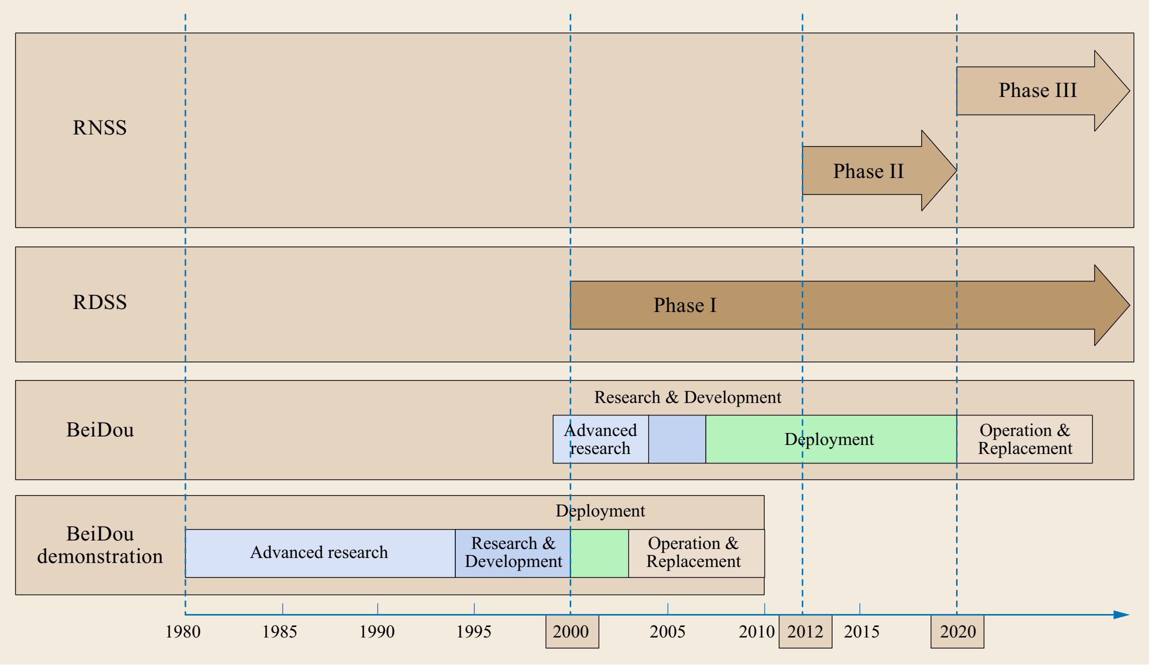

Fig. 10.2 The three phases in the development of the BeiDou Navigation Satellite System. Following the implementation of a regional radio determination satellite service (RDSS) in the frame of BDS-1, a regional radio navigation satellite service (RNSS) was established by BDS-2 in 2012. This will ultimately be extended to a global service by the third generation BeiDou Navigation Satellite System, BDS-3. After [10.2], reproduced with permission of Beijing Satellite Navigation Center

erational navigation service available for China and large parts of Asia-Pacific region was declared by the end of 2012 [10.4]. It is accomplished through a constellation of 14 satellites, including five satellites in geostationary Earth orbit (GEO), five satellites in inclined geosynchronous orbit (IGSO), and four MEO satellites.

As a third step, the BeiDou Navigation Satellite System with global coverage (BDS-3) is built-up, which will be completed around 2020.

10.1 BeiDou Navigation Satellite Demonstration System (BDS-1)

The BeiDou Navigation Satellite Demonstration System (BDS-1; [10.5]) offers a combined localization and communication service through a pair of geostationary satellites. Its main functions comprise:

- Positioning (navigation): quick determination and provision of the user's location.
- Short message communication: provision of two-way message exchange between the users and the master control station (MCS), as well as among the users themselves.
- Timing: broadcast of timing information and provision of time delay corrections for timing users.

All of these functions are achieved through the same channel. The concept is known as *radio determination satellite service* (RDSS, [10.6]) and has first been proposed for the Geostar system. Geostar was developed in the United States throughout the 1980s as a civil localization and communication system [10.7], but soon abandoned in view of the emerging availability of GPS.

Key differences between the BDS-1 RDSS and the RNSS of other constellations such as GPS, GLONASS, and BDS-2/3 are highlighted in Table 10.1.

10.1.1 System Architecture and Basic Characteristics

Similar to other satellite navigation systems, the BDS-1 system architecture comprises a space segment, a ground control segment, and the user terminals.

The initial BDS-1 constellation was made up of two geostationary satellites launched in late 2000 and positioned at 80°E and 140°E. According to their position, they are called BeiDou-West and BeiDou-East, simplified as BeiDou 1A and BeiDou 1B (Fig. 10.3). For backup purposes, a third satellite (BeiDou 1C) was added in 2003 at 110.5°E [10.5]. Meanwhile, all of

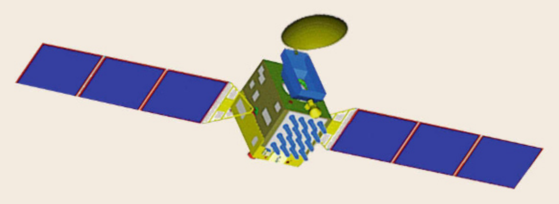

Fig. 10.3 GEO satellite of the BeiDou Navigation Satellite Demonstration System (BDS-1). Reproduced with permission of Beijing Satellite Navigation Center ►

Table 10.1 Comparison of the BDS-1 RDSS with the RNSS of other satellite navigation systems

	BDS-1 RDSS	RNSS
Basic principles	Determination of the user's location by the master control station	Determination of the user's location and velocity by the user
Constellation	GEO	GEOs, MEOs, IGSOs
Service type	Positioning, timing, location report, short message communication	Positioning, timing, velocity determination
User transmits response signal	Yes	No
Observation	Sum pseudorange from the user to the master control station via the satellite	Pseudorange from satellite to user and Doppler measurement
Payload complexity	Low	High
Coverage	Regional	Regional or global coverage
Service frequency	Single service for low- and medium-dynamic users	Continuous service for low, medium and high dynamic users
Application	Positioning, location report, communication, rescue	Navigation

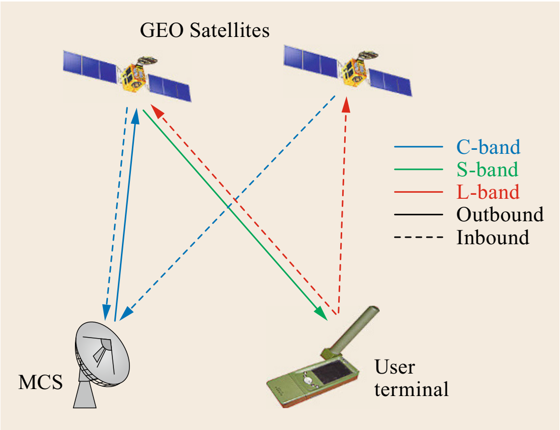

Fig. 10.4 RDSS links of BeiDou-1. Individual frequencies are distinguished by different *colors*. *Solid lines* refer to output signals (master control station to user), while *dashed lines* refer to inbound (return) signals

Fig. 10.5 BeiDou master control station at Beijing. Reproduced with permission of Beijing Satellite Navigation Center

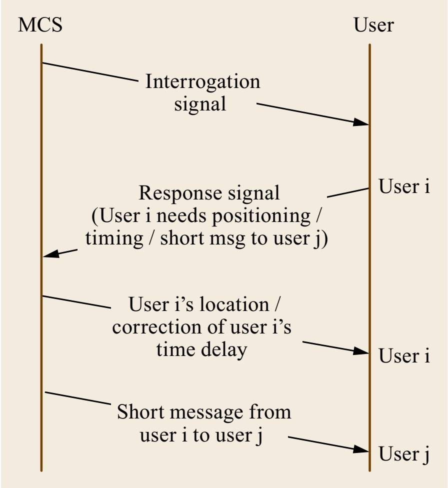

Fig. 10.6 Information flow of the BDS-1 radio determination satellite service

Part B | 10.1

these spacecraft have reached their end of life and have been substituted by satellites of the second-generation BeiDou system. These hold the same positions in the geostationary belt and continue to provide a BDS-1-type RDSS in addition to their primary RNSS.

Each satellite has two outbound transponders and two inbound transponders. The outbound transponders transfer signals which are emitted from the MCS to the satellites and further to the users. Vice versa, the inbound transponders transfer the signals which are emitted from the user to the satellites and further to the MCS (Fig. 10.4). The feeder link, which includes the uplink from the MCS to the GEO satellite of outbound signals and the downlink of the inbound signal from the GEOs to the MCS, uses the C-band frequency allocation for Fixed Satellite Service. The service link, which includes the uplink of inbound signals from the user to the GEOs and the downlink of the outbound signal from the GEOs to the user, uses the L-band (1610–1626.5 MHz; uplink) and S-band (2483.5–2500 MHz; downlink) frequency allocation for RDSS.

The BDS-1 ground control segment consists of the MCS (Fig. 10.5), at Beijing and more than 20 Calibration Stations. The MCS is responsible for transmitting the outbound signals and for receiving the inbound signals, for performing satellite orbit determination and ionosphere correction, for determining the user location, and for sending the short message to the subscribed users. The calibration stations provide the basic measurements for orbit determination, wide area differential positioning, and user elevation computation from barometric altimeter data.

The information flow of BDS-1 is illustrated in Fig. 10.6. For a positioning request, the MCS determines the user location from the measured signal turn-around time and the user's height. The latter is queried from the digital height database stored in the MCS or provided by the user. The resulting position information is then sent back to the user through the outbound signal. For a short message request, the MCS transmits the message to the addressee through the outbound signal. For timing requests, finally, the MCS calculates the precise correction of the user's time delay and sends it to the user through the outbound signal. The user then adjusts the local clock based on the time delay correction, thus, synchronizing it with the clock of the MCS.

The RDSS user terminals (Fig. 10.7) are capable of sending the requests and receiving location information and short messages. They can work in two modes. One mode is to receive one outbound signal and to transmit inbound signals via two satellites. Another mode is to receive the outbound signals from the two satellites

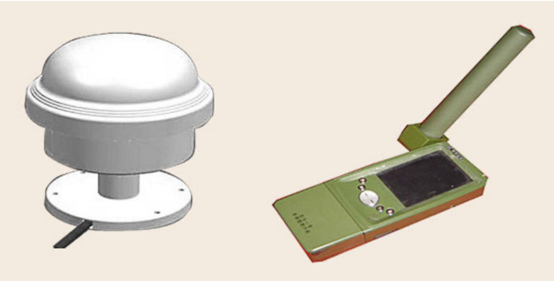

Fig. 10.7 BeiDou RDSS user terminals. Reproduced with permission of Beijing Satellite Navigation Center

when the user is located in the common coverage area of the two satellites and to transmit the inbound signal via only one satellite. According to the time difference of the two outbound signals received and the service request transmitted by one satellite, the MCS measures the pseudorange from the user to the two satellites and calculates the user position.

Following [10.5], the BDS-1 system is able to handle a total of 540 000 positioning requests per hour. To control the overall system utilization, users are divided into several service classes with update rates of 1–9 s, 10–60 s, and 60–120 s. While the BDS-1 RDSS is free of charges, potential users must register and obtain a card to uniquely identify their terminal for the localization and communication service.

The BDS-1 service area illustrated in Fig. 10.8 is governed by the location of its geostationary satellites as well as the calibration stations. Overall, it comprises China and its surrounding areas, from longitude 70°E to 140°E and from latitude 5°N to 55°N.

The BDS-1 service performance specification is summarized in Table 10.2. A positioning accuracy of about 20 m can be achieved if the terminal locates in the region with calibration stations; otherwise, the positioning accuracy is about 100 m. These specifications are in good accord with practical performance results reported in [10.5]. Here, horizontal positioning errors of about 8 m (2D, 1 σ) have been obtained both in static tests and a low dynamic test onboard a maritime vessel with BDS-1 receivers in comparison with known positions from a GPS reference receiver.

10.1.2 Navigation Principle

The localization of a user terminal in BDS-1 is based on turn-around signal travel time measurements initiated by the MCS. As mentioned before, the MCS first emits an interrogation signal to the two satellites, which is subsequently broadcast to the users in the service area via the outbound transponders of the two satellites. The user receives the interrogation signal and sends its response signal with the user's service request back to the satellite (Figs. 10.6 and 10.4).

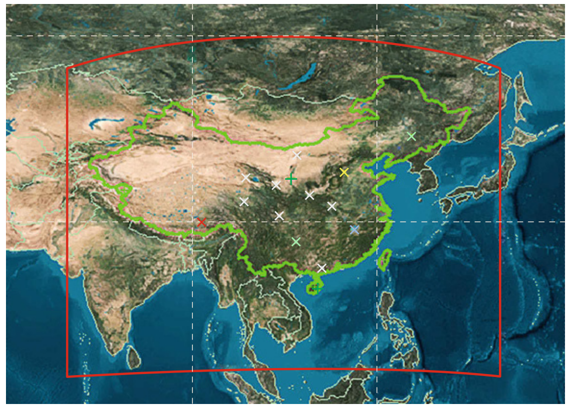

Fig. 10.8 Service coverage of BDS-1. Reproduced with permission of Beijing Satellite Navigation Center

Table 10.2 Performance specification for the BDS-1 radio determination satellite service (after [10.5])

Parameter	Value
Horizontal positioning accuracy	20 m (1σ)
One-way time accuracy	100 ns
Two-way time accuracy	20 ns
Short message communication	120 Chinese chars./msg.

A first observation L_1 is obtained by measuring the difference between the transmit time t_t and the receive time $t_{r(s,s)}$ of a signal passing through the same satellite s on both the inbound and outbound links. Likewise, a second observation L_2 is obtained from the travel time $t_{r(s,s')} - t_t$ of a signal passing through satellite s on the outbound link but through the second satellite s′ on the inbound link.

Denoting the MCS position by $\boldsymbol{r}_m$, the position of the two satellites by $\boldsymbol{r}_s$ and $\boldsymbol{r}_{s'}$, respectively, and the (unknown) user position by $\boldsymbol{r}_u = (x_u, y_u, z_u)$, the two observations can be modeled as

$$\begin{aligned} L_1 &= c \cdot (t_{r(s,s)} - t_t) \\ &= 2||\boldsymbol{r}_s - \boldsymbol{r}_u|| + 2||\boldsymbol{r}_s - \boldsymbol{r}_m|| \end{aligned} \quad (10.1)$$

and

$$\begin{aligned} L_2 &= c \cdot (t_{r(s,s')} - t_t) \\ &= ||\boldsymbol{r}_s - \boldsymbol{r}_u|| + ||\boldsymbol{r}_{s'} - \boldsymbol{r}_u|| \\ &\quad + ||\boldsymbol{r}_s - \boldsymbol{r}_m|| + ||\boldsymbol{r}_{s'} - \boldsymbol{r}_m|| \,, \end{aligned} \quad (10.2)$$

respectively. These relations are likewise applicable for the operation mode in which the user receives signals from the two satellites and transmits them back via only one satellite.

It may be noted that the BDS-1 measurement model does not include explicit clock offset terms as found in the traditional global navigation satellite system (GNSS) pseudorange model. This is due to the fact that the transmit and receive times are measured by a common clock in the MCS. The control segment (CS) clock offset from the BDS system time is common to the transmit and receive time stamps and cancels when forming the range measurement. As such, the minimum number of independent observations required for a position fix is one less than in other navigation satellite systems using one-way pseudorange observations. However, BDS-1 observations are still affected by equipment delays (transmitter, transponder, and receiver biases) which require proper consideration.

Since the positions of the satellites and the MCS are considered as known quantities, L_1 and L_2 are in fact equivalent to distance measurements of the user relative to the two satellites s and s′. These are not sufficient, though, to uniquely determine the three-dimensional user position. Information on the user's height h_u above the reference ellipsoid is, therefore, employed as an independent, third observation. h_u can either be provided from a barometric altimeter in the user terminal or provided from a digital elevation model maintained in the MCS for terrestrial users [10.5]. Given the ellipsoid height, a measurement

$$\begin{aligned} L_3 &= h_\mathrm{u} + N \\ &= \sqrt{x_\mathrm{u}^2 + y_\mathrm{u}^2 + (z_\mathrm{u} + Ne^2 \sin\varphi)^2} \end{aligned} \tag{10.3}$$

is formed, which describes the distance of the receiver from the Earth rotation axis along the normal line of the reference ellipsoid. Here,

$$N = \frac{a}{\sqrt{1 - e^2 \sin^2\varphi}} \tag{10.4}$$

is the radius of curvature in the prime vertical at geodetic latitude φ, while a and e denote the semi-major axis and eccentricity of the reference ellipsoid (Sect. 2.2.1).

Equations (10.1)–(10.3) cannot be solved directly for the unknown user position, but can be linearized in the vicinity of an approximate a priori value $\boldsymbol{r}_{\mathrm{u},0}$. This yields a three-dimensional set of linear equations from which corrections $\Delta\boldsymbol{r}_\mathrm{u} = \boldsymbol{r}_\mathrm{u} - \boldsymbol{r}_{\mathrm{u},0}$ are obtained. This process is repeated in an iterative manner until the solution is obtained with the desired accuracy.

For simplicity, atmospheric propagation effects and equipment specific delays have been neglected in the above discussion, but are taken into account in the actual MCS processing. Among others, these corrections are based on a distributed set of calibration stations enabling wide area differential positioning.

10.1.3 Orbit Determination

Similar to other satellite navigation systems, positioning with BDS-1 depends on proper knowledge of the satellite positions. In BDS-1, the orbit determination relies on measurements of the calibration stations, which follow the same principle as described in Sect. 10.1.2 for the user positioning. Calibration stations for orbit determination respond to the same frame interrogation signal from the MCS at a certain sample interval. Therefore, the MCS can measure a group of distances related to the individual calibration stations for orbit determination of each satellite.

The basic observation model for satellite orbit determinations matches (10.1) and (10.2) when replacing the user position $\boldsymbol{r}_\mathrm{u}$ by the (known) position of a calibration station. However, there are some differences between satellite orbit determination and user positioning. While the number of measurements in the positioning equations of BDS-1 matches with that of the unknown position parameters, the number of measurements in the orbit determination is usually greater than that of the orbit parameters (typically six per satellite). Also, the orbits of both BDS-1 satellites should be determined simultaneously, since the measurement equations for each calibration station depend on the position of two satellites (s and s′) at a time.

10.1.4 Timing

Apart from positioning, the BDS-1 RDSS also supports the synchronization of user terminals with the BeiDou system time (BDT) maintained at the MCS. BDT is a continuous time scale without leap seconds [10.8] that is realized by composite clocks with robust data fusion. BDT is aligned to the realization of Coordinated Universal Time UTC(NTSC) maintained by the Chinese National Time Service Center (NTSC). UTC(NTSC) itself is traced to the Coordinated Universal Time (UTC) by satellite common view (CV) links and the offset of BDT with respect to UTC is controlled within 30 ns.

BDS-1 provides two types of timing services: one-way and two-way timings with 100 ns and 20 ns timing accuracies, respectively. Both of these are based on a comparison of transmit and receive times measured relative to the local clock after accounting for the known geometric propagation time and possible correction atmospheric and equipment delays.

Each second, the MCS transmits a total of 32 frames of 31.25 ms duration aligned with the integer second of BDT. Denoting by Δ_1 the time difference between the reception of the n-th frame and the receiver's preceding 1-pulse-per-second (1-pps) epoch (Fig. 10.9), the local

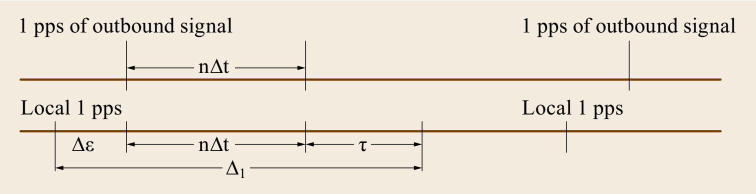

Fig. 10.9 The principle of BDS-1 one-way timing (after [10.9])

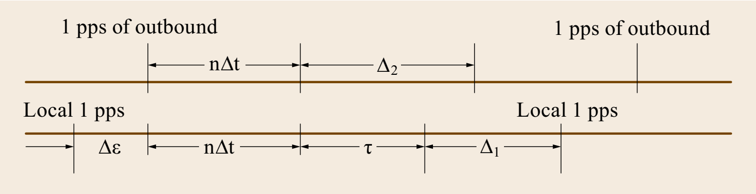

Fig. 10.10 The principle of BDS-1 two-way timing (after [10.9])

clock offset $\Delta\varepsilon$ is obtained as

$$\Delta\varepsilon = \Delta_1 - (n\Delta t + \tau) \,. \tag{10.5}$$

Here, τ is the signal travel time, which is modeled from the known MCS-satellite and satellite-user distances as well as atmospheric path delays and equipment delay corrections [10.9].

For two-way timing (Fig. 10.10), the user terminal responds to the inbound interrogation signal and the MCS measures the round trip time Δ_2. From this, the one-way travel time $\tau \approx \Delta_2/2$ is computed in the MCS taking into account various atmospheric and equipment delay corrections. The resulting value of τ is subsequently sent back to the user. Making use of a local measurement Δ_1 of the time between reception of the interrogation signal and the subsequent 1-pps epoch, the local clock offset is, finally, obtained as

$$\Delta\varepsilon = (1\,\mathrm{s} - \Delta_1) - (n\Delta t + \tau) \,. \tag{10.6}$$

In view of an improved error compensation, the two-way time synchronization achieves an accuracy of 20 ns [10.9], which represents a fivefold improvement over the one-way timing performance.

10.2 BeiDou (Regional) Navigation Satellite System (BDS-2)

In September 2004, the construction of BDS-2 was initiated and a first MEO satellite (then known as COMPASS-M1) was successfully launched in April 2007. It served to protect the frequency filings at the ITU and provided a test bed for the validation of indigenous atomic clocks, precise orbit determination, and time synchronization, as well as other key technologies. Starting with the launch of the first GEO satellite in April 2009, a constellation of 14 operational satellites was deployed in only 3.5 years (Table 10.3).

In December 2012, the BDS-2 entered into official operation and declared the start of its regional service covering latitudes 55°S to 55°N and longitudes 70°E to 150°E [10.10]. The initial service announcement was accompanied by the release of the first open service interface control document (ICD) for single frequency users in the B1 band. An updated version covering also the use of dual-frequency (B1/B2) signals was issued after one year in December 2013 [10.11].

10.2.1 Constellation

The second-generation BeiDou Navigation Satellite System uses a unique constellation design, which combines elements of global systems (such as GPS, GLONASS, and Galileo) with those of purely regional systems (such as the Quasi-Zenith Satellite System (QZSS) and the Indian Regional Navigation Satellite System (IRNSS/NavIC)). The BDS-2 space segment comprises five satellites in geostationary orbit, five spacecraft in IGSO, and four satellites in medium altitude Earth orbit (Table 10.3).

The GEO satellites are positioned at 58.75°E, 80°E, 110.5°E, 140°E, and 160°E, respectively. At least three of them are continuosly visible above 10° elevation from any point in the service area, thus, enabling a real-time exchange of information between the control center and the BDS-2 users.

The IGSO satellites operate in circular orbits with an altitude of about 36 000 km and an inclination of 55°.

Table 10.3 Satellites of the regional BeiDou Navigation Satellite System (BDS-2) at the start of operational service. For each satellite, the assigned pseudorandom noise (PRN) code, the international satellite identification number, and the launch date are provided. Satellites in geostationary, inclined geosynchronous and medium altitude Earth orbits are identified by letters "G," "I," and "M," respectively

Satellite	PRN	Int. Sat. Id	Launch	Notes
G1	C01	2010-001A	2010/01/16	140.0°E
G2	–	2009-018A	2009/04/14	Nonoperational
G3	C03	2010-024A	2010/06/02	110.5°E
G4	C04	2010-057A	2010/10/31	160.0°E
G5	C05	2012-008A	2012/02/24	58.75°E
G6	C02	2012-059A	2012/10/25	80.0°E
I1	C06	2010-036A	2010/07/31	~118°E
I2	C07	2010-068A	2010/12/17	~118°E
I3	C08	2011-013A	2011/04/09	~118°E
I4	C09	2011-038A	2011/07/26	~95°E
I5	C10	2011-073A	2011/12/01	~95°E
M1	C30	2007-011A	2007/04/13	Decommissioned
M3	C11	2012-018A	2012/04/29	B3
M4	C12	2012-018B	2012/04/29	B4
M5	C13	2012-050A	2012/09/18	A7
M6	C14	2012-050B	2012/09/18	A8

Like the GEO satellites, they exhibit an orbital period of one sidereal day (i. e., the duration of the Earth rotation relative to the fixed stars, 23 h 56 m), but exhibit a notable inclination with respect to the Earth equator. This results in continuously repeating ground-tracks with a distinct figure-of-eight shape covering a latitude band of ±55° (Fig. 10.11). The ground-tracks cross the equator from east to west and the northern part is traversed in a clockwise sense, while the southern loop is traversed in a counter-clockwise direction. Three of the BDS-2 IGSO satellites (I1, I2, and I3) describe a ground track with an equator crossing point at 118°E, while I4 and I5 describe a figure-of-eight centered at 95°E. A new satellite (BEIDOU I1-S/2015-019A) for validation of new BDS-3 signal has been launched in March 2015, filling in the third slot in this ground track.

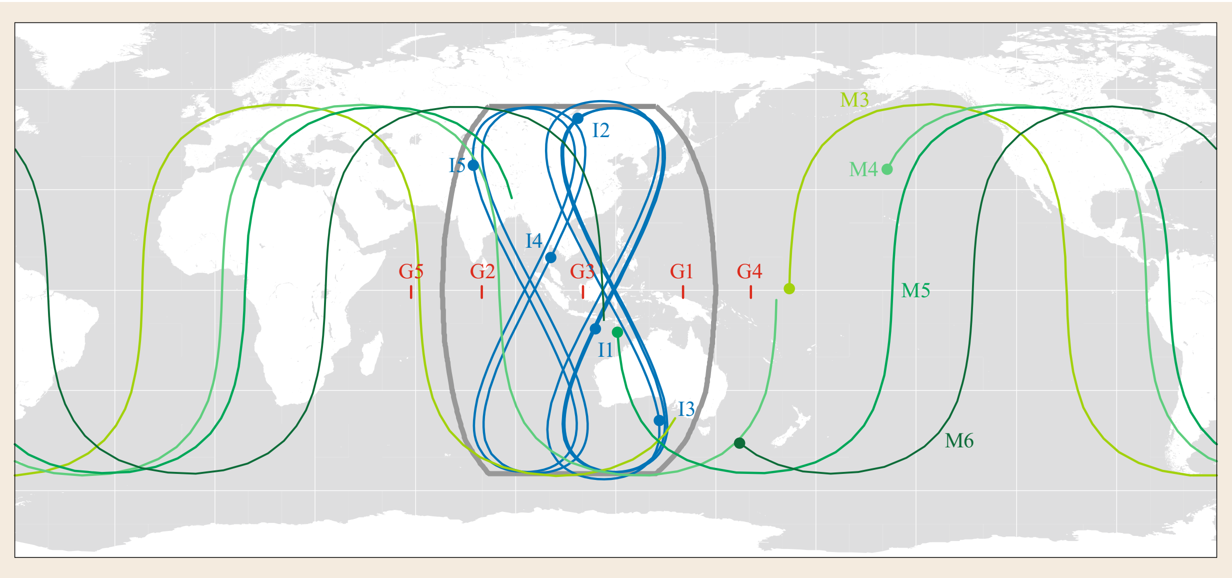

Fig. 10.11 Groundtrack of GEO (*red*), IGSO (*blue*) and MEO (*green*) satellites of the BeiDou Navigation Satellites System (BDS-2) on 1 July 2014. *Dots* indicate the initial positions at the midnight epoch. The framed region extending roughly from 70°E to 150°E and 55°S to 55°N marks the BDS-2 regional service area as specified in [10.10]

The IGSO satellites in common ground-tracks exhibit a nominal separation of 120° in their arguments of latitude as well as their right ascension of the ascending node (Chap. 3). In this way, they cross the equator at the same geographic longitude with a separation of 8 h.

Even though a combination of GEO and IGSO satellites is commonly considered sufficient and adequate for a purely regional navigation system, the BDS-2 makes complementary use of a small number of MEO satellites. These orbit the Earth at an altitude of 21 530 km (i. e., in between the global positioning system (GPS) and Galileo constellation) and an inclination of 55°. The orbital radius has been chosen such that the satellites complete a total of 13 revolutions within 7 sidereal days, which corresponds to an orbital period of 12h 53m.

The four BDS-2 MEO satellites have been launched in pairs and injected into two different orbital planes, which are separated by 120° in their ascending nodes. In anticipation of a future global extension, the BDS-2 MEO satellite orbits are designed as part of a 24/3/1 Walker constellation [10.12] with 24 satellites evenly distributed in three orbital planes. BeiDou M5 and M6 presently occupy slots 7 and 8 in plane A, while M3 and 4 are placed in slots 3 and 4 of plane B [10.11]. Even though the BDS-2 MEO constellation is still quite limited in size, it increases the average number of visible satellites in the service area and offers additional geometric diversity for improved positioning.

To maintain their nominal position, regular east–west maneuvers with a representative magnitude of about 10 cm/s are conducted by the GEO satellites about once per month [10.13]. North–south corrections, in contrast, are conducted only rarely allowing the buildup of a few degrees of inclination over a period of several years [10.14]. On the IGSO satellites, maneuvers are likewise performed at intervals of about half a year to control the equator crossing longitude [10.15].

10.2.2 Signals and Services

The BDS-2 satellites transmit a total of six signals in three distinct frequency bands: B1 at a center frequency of 1561.098 MHz, B2 at a center frequency of 1207.14 MHz, and B3 at a center frequency of 1268.52 MHz. The B1 and B3 frequencies are offset by about 14 MHz and 10 MHz, respectively, from the E1/L1 and E6 bands of Galileo/GPS, while the B2 center frequency matches that of the Galileo E5b (sub-)band. Each carrier frequency is modulated with two signals in phase quadrature using ranging codes of 2.046 MHz or 10.23 MHz chipping rate (Table 10.4). The resulting signal spectra are illustrated in Fig. 10.12.

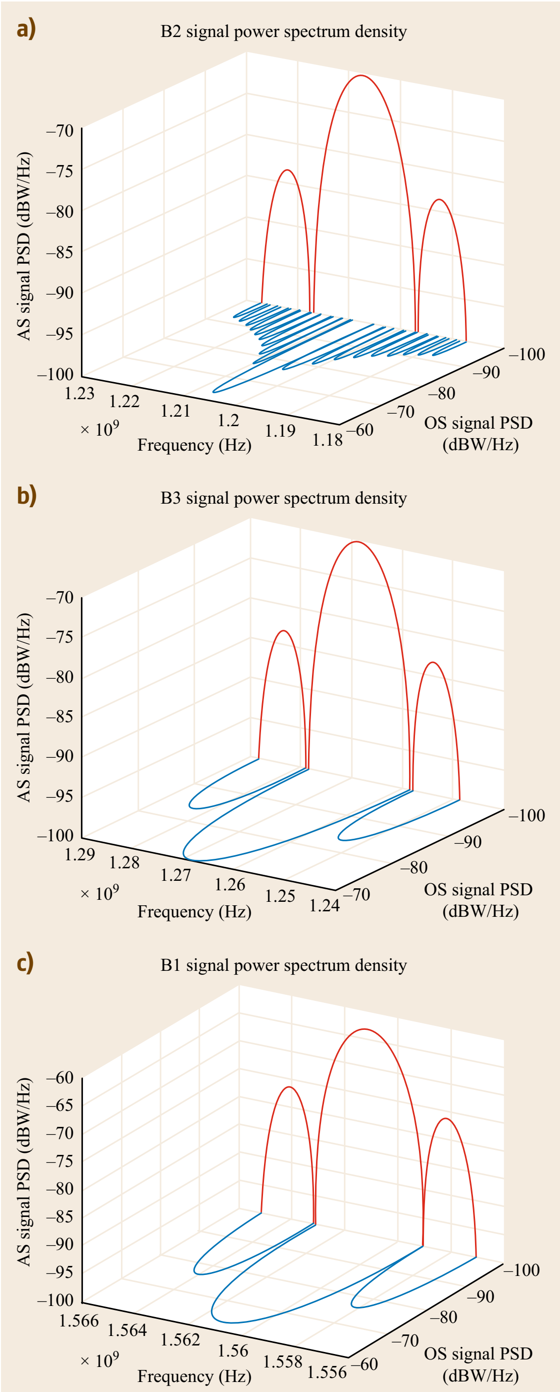

Fig. 10.12a–c Spectral characteristics of BeiDou (BDS-2) signals in the B2 **(a)**, B3 **(b)**, and B1 **(c)** frequency bands. Note the different scales of the individual plots

The in-phase components of the B1 and B2 signals are assigned to the BDS-2 open service [10.11],

Table 10.4 BDS-2 navigation signals. The BPSK(n) code chip rate is $n\times1.023$ Mcps

Band	Frequency (MHz)	Signal	Modulation	Service
B1	1561.098	B1-I	BPSK(2)	Open
		B1-Q	BPSK(2)	Authorized
B2	1207.14	B2-I	BPSK(2)	Open
		B2-Q	BPSK(10)	Authorized
B3	1268.52	B3-I	BPSK(10)	Authorized
		B3-Q	BPSK(10)	Authorized

while the remaining four signals are reserved for the authorized service. The open service is specified to offer signal-in-space range errors (SISREs) of better than 2.5 m and a horizontal and vertical positioning accuracy of better than 10 m at a 95% confidence level [10.10] within the BDS-2 service area shown in Fig. 10.11. A minimum received signal power of −163 dBW is ensured for the open service signal on each of the two frequencies.

Apart from the standard positioning and timing service available in the entire service area [10.10], the BDS-2 open service signals also support an improved, satellite-based augmentation systems (SBAS)-like positioning service based on near-real-time corrections transmitted through the GEO satellites. This service is freely available to all users, but limited to a smaller service area centered around the Chinese mainland.

The open service signals employ truncated Gold-codes with a length of 2046 chips and a chipping rate of 2 MHz. Similar to the GPS C/A-code, the BDS-2 open service (OS) codes are generated using a pair of 11-bit shift registers and a full family of codes is obtained through configurable selectors (Fig. 10.13). The native code length of the 11-bit registers amounts to $2^{11}-1=2047$ bits, but the sequence is reset after 2046 chips to obtain a pseudo-random noise (PRN) code of exactly 1 ms duration. Within the OS signal ICD, a total of 37 different open service PRN codes are defined, out of which 1–5 PRNs are reserved for the geostationary satellites. On a given satellite, the same PRN sequence is used for both the B1-I and B2-I OS signals.

Next to the primary ranging code, the open service signal of the IGSO and MEO satellites is multiplied with a secondary, or Neuman–Hofman (NH) [10.16] code. Each chip of the NH-code has a duration of 1 ms and is aligned with the start of the primary code. Depending on the sign of the secondary code chip, either the unmodified primary ranging code sequence or a sign-inverted version is transmitted. As discussed in [10.17, 18], the use of NH-codes helps to decrease narrow-band interference, improves the cross- and autocorrelation properties, and offers an increased robustness in the data bit synchronization. The BDS-2 NH-code (00000 10011 01010 01110) matches that of the GPS L5-Q signal. It has a length of 20 chips and repeats after 20 ms.

The B1-I and B2-I signals of all BeiDou-2 satellites are, furthermore, modulated with navigation data. For a given satellite, the same data are transmitted on both frequencies, but different formats and data rates are employed for the various types of spacecraft. In case of the MEO/IGSO satellites, the *D1* navigation message is transmitted with a rate of 50 bps (corresponding to a data bit length of 20 ms). The GEO satellites, in contrast, transmit the *D2* message at a 10 times higher rate of 500 bps. Here, the data bit length amounts to just 2 ms, that is, the duration of two consecutive ranging codes.

The overall modulation scheme for the two classes of BDS-2 satellites is illustrated in Fig. 10.14. While improved signal properties at the expense of a lower data are favored for the MEO/IGSO satellites, the GEO signal is optimized for the transmission of high data volumes. This different tradeoff reflects the specific role of the GEO satellites, which also provide real-time augmentation data to the BeiDou users as part of the navigation message (Sect. 10.2.3).

The choice of different signal structures for satellites of the same constellation is unique to BDS-2 and requires specific care in the receiver implementation. As pointed out in [10.19] and [10.20], inconsistent interpretations of the NH-code sign may result in a half-cycle intersatellite-type biases (ISTB) when forming double-difference carrier-phase observations between GEO and non-GEO BDS-2 satellites using different receiver types. Further aspects of BeiDou receiver design and the impact of the NH-code on acquisition and tracking of the MEO/IGOS signals are discussed in [10.21] and [10.22].

Even though only the B1-I and B2-I signals are officially declared as open service signals, basic properties of the (authorized) B3-I signal have also become public through inspection with high-gain antennas [10.23, 24]. The signal employs a primary ranging code of 10 230 chips with a chipping rate of 10.23 MHz and a resulting length of 1 ms as well as a 20-bit secondary code. Knowledge of the ranging code, which can be generated by linear feed-back shift registers, has enabled various manufacturers to provide geodetic-grade

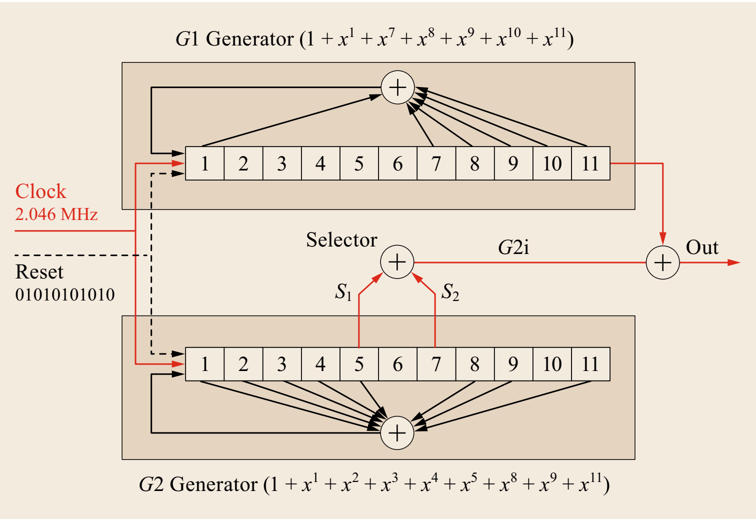

Fig. 10.13 Code generator for the B1-I and B2-I open service signals (after [10.11])

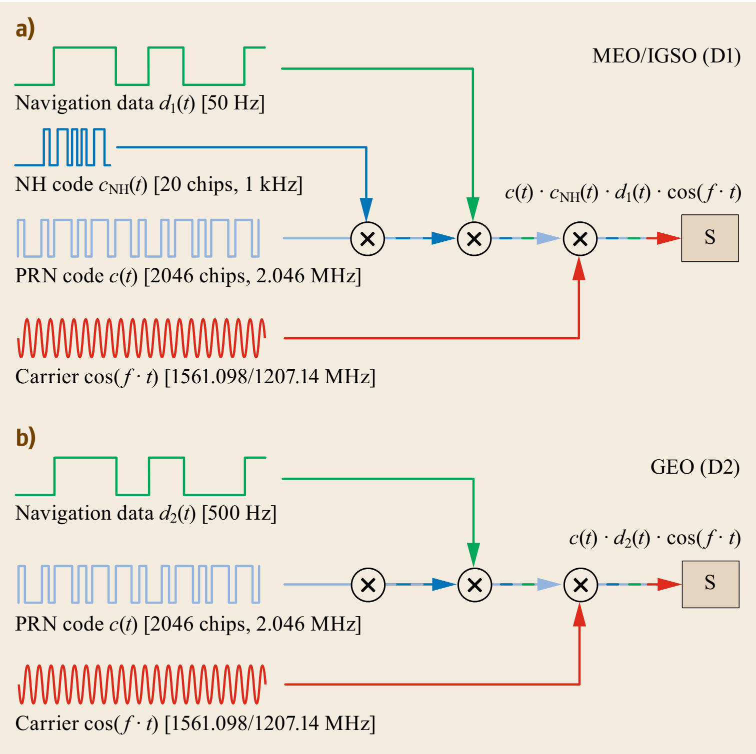

Fig. 10.14a,b Signal structure of the BeiDou-2 open service signals for MEO/IGSO **(a)** and GEO satellites **(b)**

triple-frequency BeiDou receivers. Access to more than two frequencies in BeiDou paves the way for various advanced GNSS processing techniques [10.25–28] with applications in surveying, precise point positioning and geodesy. It must be kept in mind, though, that tracking of the B3-I signal is not officially endorsed and may be inhibited at any time using explicit encryption of the B3-I ranging code.

10.2.3 Navigation Message

The D1 navigation message broadcast by the MEO and IGSO satellites resembles the legacy navigation message of GPS transmitted with the L1 C/A code signal. It employs the same data rate and provides basic navigation information such as almanac and ephemeris data for acquisition of visible satellites as well as positioning and timing. On top of these data, the high-rate D2 message of the BeiDou GEO satellites contains additional augmentation service information such as BDS integrity, differential corrections, and ionospheric grid data.

D1 Message Structure

The D1 navigation message is structured into a superframe made up of individual frames and subframes (Fig. 10.15). Each subframe is composed of 300 bits and takes 6 s to transmit. Five subframes make up a full frame, which is of 30 s duration. The superframe, finally, comprises 24 frames (i. e., one less than GPS) with a total of 36 000 bits transmitted in 12 min. Subframes 1–3 contain fundamental navigation data such as orbit and clock parameters for the transmitting satellite as well as ionospheric model coefficients. This information is updated at the start of each hour and repeated once every 30 s within this period.

Subframes 4 and 5 are commutated, that is, different *pages* are transmitted within consecutive frames. They contain the almanac information for up to 30 satellites (in pages 1–24 of subframe 4 and pages 1–6 of subframe 5) as well as constellation health data, the BDS time offset from UTC as well as the time offsets between BDT and other GNSS time scales (pages 7–10 of subframe 5). The entire information is repeated once every 12 min.

The 300 bits of each subframe are composed of 10 elementary 30-bit words. Each halfword contains 11 data bits as well as 4 parity bits encoded with a Bose–Chaudhuri–Hocquenghem (BCH) [10.29] code enabling single-bit error correction. Furthermore, the data and parity bits from two halfwords with each word are interleaved to protect against possible burst errors during the transmission.

D2 Message Structure

The D2 message is transmitted at a 10 times higher data (500 bps) than the D1 message and uses a different scheme to transmit the low-rate basic navigation data along with high-rate augmentation data. The superframe is composed of 120 frames, which are divided into five subframes of 300 bits length. A single subframe has a length of 0.6 s and a full frame is broadcast in 3 s. The entire superframe contains a total of 180 000 bits and takes 6 min to transmit (Fig. 10.16).

Subframe 1 provides basis navigation data such as orbit and clock information of the transmitting satellite and ionospheric model parameters in a series of 10 commutated pages. Apart from the different layout, the data are identical to subframes 1 and 3 of the D1 message. As in the case of the non-GEO satellites it, thus, takes a total of 30 s to receive the full ephemeris data of a GEO satellite despite the higher transmission rate. Within a superframe, the same set of 10 pages is repeated 12 times. The ephemeris information is complemented by almanac data (for up to 30 satellites) in pages 37–60 and 95–100 of subframe 5. One full almanac is transmitted per superframe and the information is repeated every 6 min.

Information on the integrity of BDS-2 satellites as well as differential correction data are provided to the users in subframes 2 and 3 of the D2 navigation message. Other than in traditional SBAS systems (Chap. 12), equivalent clock corrections are provided in the BDS-2 augmentation data. The scalar correction values Δt account for the combined effects of broadcast orbit and clock offset errors and are intended for users in China and adjacent areas. The user adds the value of Δt to the observed pseudorange. Updated values are provided once every 18 s. Within this period, six

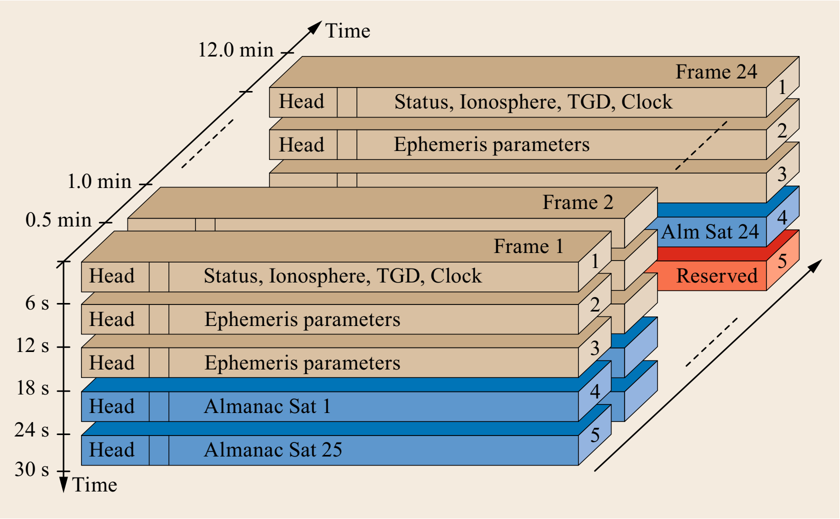

Fig. 10.15 Structure of the BeiDou D1 navigation message transmitted by the MEO and IGSO satellites. *Arrows* indicate the transmission order of individual subframes

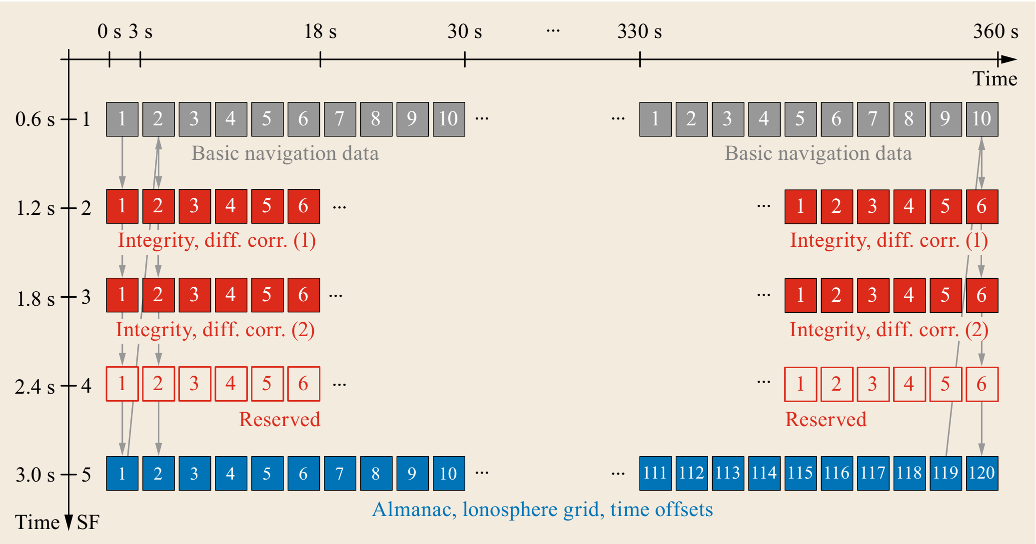

Fig. 10.16 Structure of the BeiDou D2 navigation message transmitted by the GEO satellites (after [10.30])

commutated pages of subframes 2 and 3 are transmitted, which provide integrity information and equivalent clock corrections for up to 18 different satellites. This covers the expected maximum number of BeiDou satellites jointly visible in the service area for augmentation data.

The differential ephemeris corrections are complemented by low-latency ionospheric corrections for single-frequency users provided in subframe 5. These data cover a service area from 70°E to 145°E longitude and 7.5°E to 55°E latitude and are provided in two subgrids of 5° × 5° resolution which are shifted by 2.5° in latitude (Fig. 10.17). In accord with the length of a superframe, the ionospheric grid data are updated once every 360 s. Depending on the availability and distribution of monitoring stations, the provision of valid correction data may be confined to a subset of points in the overall grid (typically the Chinese mainland).

Ephemeris Parameters and Models

The broadcast orbit and clock parameters as well as the standard ionospheric correction parameters in BDS-2 have been defined in close correspondence with those of the legacy GPS navigation message. A total of 16 orbit parameters for a perturbed Keplerian model and three parameters of a quadratic clock model are used to describe the satellite motion and clock offset variation within the ephemeris validity interval. Ionospheric path

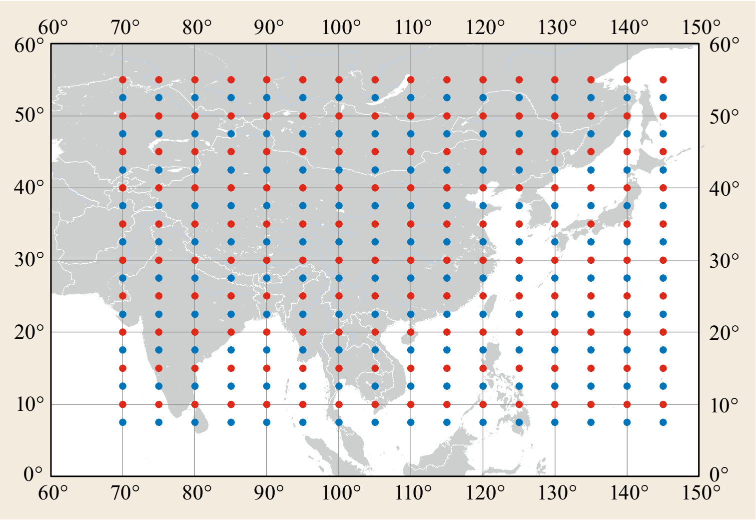

Fig. 10.17 Ionospheric correction data in the BeiDou-2 D2 navigation message are provided for two interleaved grids of 5° width with a 2.5° offset. The northern grid (*blue*) is transmitted in the first 3 min, followed by the southern grid in the second half of a superframe

delays are described through a Klobuchar-type model with eight parameters.

Despite obvious similarities, the models employed with the BDS-2 broadcast navigation message differ in various aspects from those of GPS [10.11, 30]. All information is referred to BDT (Sect. 10.2.8) and the BeiDou coordinate system (BDC) connected to China Geodetic Coordinate System (CGCS) 2000 (Sect. 10.2.7). Along with that, slightly different values for the gravitational coefficient ($GM_\oplus$) and the Earth rotation rate ($\omega_\oplus$) are employed in BeiDou.

With the above exceptions, the orbit model of BDS-2 matches that of GPS for MEO and IGSO satellites, but a different interpretation of the orbit parameters applies for the GEO satellites (Sect. 3.3.2). Since the geostationary orbits exhibit a very low (and potentially zero) inclination, large residuals and divergence problems may be encountered when determining the broadcast elements. To cope with this situation, a reference plane with a 5° inclination angle to the equator is adopted in the orbit determination of the GEO satellites. A complementary 5° rotation must, therefore, be applied when calculating the position and velocity for these satellites relative to the Earth equator.

Satellite clock offsets from BDT are described through a second order polynomial

$$\Delta T = a_0 + a_1(t - t_{oc}) + a_2(t - t_{oc})^2 + \Delta t_{rel} \tag{10.7}$$

with coefficients a_0, a_1, and a_2 providing offset, drift, and drift rate at the reference epoch t_{oc}, as well as periodic relativistic corrections

$$\Delta t_{rel} = -\frac{2}{c^2}(\boldsymbol{r}^\top \boldsymbol{v}) \tag{10.8}$$

depending on the spacecraft position $\boldsymbol{r}$ and velocity $\boldsymbol{v}$ in much the same way as for GPS and Galileo. However, the clock offsets are referred to single-frequency B3 observations rather than an ionosphere-free dual-frequency combination. All users of the open service BDS-2 signals must, therefore, account for additional satellite group delay corrections. For processing of single-frequency B1-I observations, a timing group delay parameter TGD_1 provided in the navigation message has to be added to the B3 clock offset value, while a linear combination of TGD_1 and TGD_2 is required for dual-frequency (B1-I/B2-I) observations [10.31].

For ionospheric correction of single-frequency observation users, the BDS-2 broadcast navigation message makes use of a Klobuchar-style thin layer correction model (Sect. 6.3.4). It involves a total of eight coefficients ($\alpha_0, \ldots, \alpha_3$ and $\beta_0, \ldots, \beta_3$) describing the amplitude and period of the daytime vertical total electron content variation. The ionospheric model is constructed in geographic latitude and longitude, rather than geomagnetic coordinates as used in GPS. The coefficients of this model are transmitted by all BDS-2 satellites and updated at hourly intervals. Even though the model is conceptually valid on a global scale, best results are obtained across the Chinese mainland due to currently limited distribution of monitoring stations [10.32].

10.2.4 Space Segment

The BeiDou regional navigation satellite system is composed of three groups of spacecraft, namely the GEO, IGSO, and MEO satellites. The satellites have a specified lifetime of eight years. The platform and navigation payload of all three satellites types are essentially similar, but various complementary payloads are accomodated on the GEO spacecraft.

Satellite Platform

The BDS-2 MEO/IGSO satellites (Fig. 10.18) adopt the DongFangHong-3 (DFH-3; *The East is Red*) platform, and a slightly modified version (DFH-3A) is employed for the GEO satellites spacecraft [10.14, 33]. The three-axis stabilized DFH-3 bus has been developed by the China Academy of Space Technology (CAST), Beijing, in cooperation with Messerschmitt–Bölkow–Blohm (MBB), Germany, and was used for various geostationary communications satellites since 1994 [10.34]. It is equipped with an apogee boost motor and liquid propulsion system for initial orbit insertion and orbit keeping purposes.

At a size of about $2.4 \times 1.7 \times 1.7\,\mathrm{m}^3$ (GEO) and $2.0 \times 1.7 \times 1.7\,\mathrm{m}^3$ (MEO/IGSO), the spacecraft have different masses of around 2.5 t at lift-off. The platform comprises subsystems for thermal control, power supply and distribution, tracking, telemetry and commanding (TT&C), as well as attitude and orbit control. The solar arrays with a total area of more than $20\,\mathrm{m}^2$ are based on silicon cells (MEO/IGSO satellites) and GaAs/Ge cells (GEOs) providing a minimum power of 2 kW and 2.5 kW, respectively. For power storage, all BDS-2 satellites are equipped with NiMH batteries offering capacities of 40–60 Ah [10.14].

Attitude control is performed through a combination of Earth and Sun sensors as well as four reaction wheels. These wheels are unloaded during station-keeping maneuvers or using magnetorquers to avoid unnecessary orbital perturbations. Outside the eclipse season, a continuous yaw-steering (Sect. 3.4) is performed by the MEO and IGSO satellites to maintain the antennas pointing to the center of the Earth while orienting the solar panels to the Sun [10.35]. The Earth-pointing accuracy is typically better than 0.25° and the nominal solar panel orientation is maintained with an

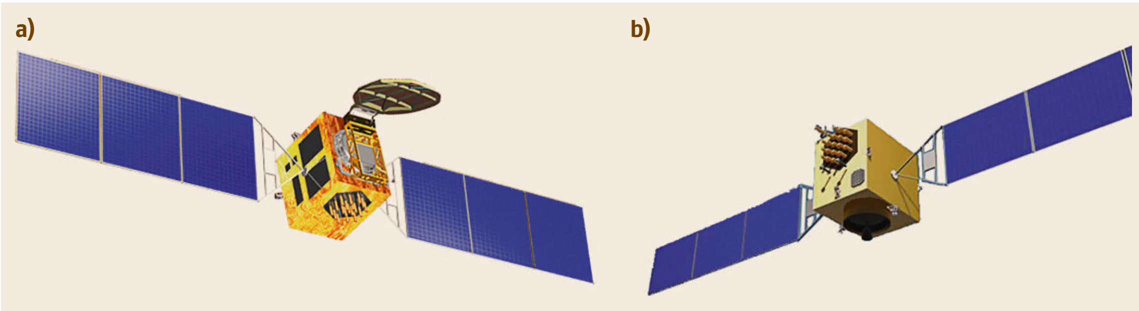

Fig. 10.18a,b GEO **(a)** and MEO/IGSO **(b)** satellites of the regional BeiDou Navigation Satellite System (BDS-2). Reproduced with permission of Beijing Satellite Navigation Center

uncertainty of less than 5° [10.14]. To avoid the need for rapid yaw-slews near Sun–spacecraft–Earth collinearity, an orbit-normal attitude is employed, whenever the elevation of the Sun above the orbital plane is less than about 4° [10.36, 37]. The orbit-normal mode is also adopted for all BeiDou GEO satellites. Measured yaw angles provided in the onboard telemetry were found to match the nominal attitude at a level better than 0.5–1° [10.38].

Satellite Payload

The RNSS navigation payload of the BeiDou satellites is mainly composed of the time and frequency subsystem as well as the navigation processor and signal generation unit.

The time and frequency subsystem is used to generate, maintain, and calibrate the primary reference frequency. It consists of Rubidium atomic frequency standards (RAFSs; Fig. 10.19) as well as supporting equipment such as a frequency multiplier, reference frequency synthesizer, and power-division/amplification network. The four clocks on each spacecraft comprise one active clock, a hot backup, and two cold backups. While the majority of clocks employed in the BDS-2 constellation is of indigenous origin, a limited amount of European RAFS has been procured for the BeiDou program and is used alongside the Chinese clocks on the various spacecraft [10.8, 14, 39]. The RAFS performance is further described in Sect. 10.3.2.

Following the modulation of the carrier with the ranging code and navigation message, the navigation signals are filtered and amplified in a traveling wave tube amplifier (TWTA). The phased-arrays antenna used for transmission of the signals covers a total of three frequency bands (B1, B2, and B3). Similar to GPS, a slightly higher gain in the off-boresight direction is used to compensate the increased distance and free-space loss for users at low elevations. The desired shape of the gain pattern is achieved by phase coherent combination of a central part with 6+1 helix antenna elements as well as an outer ring of 12 individual helix antennas.

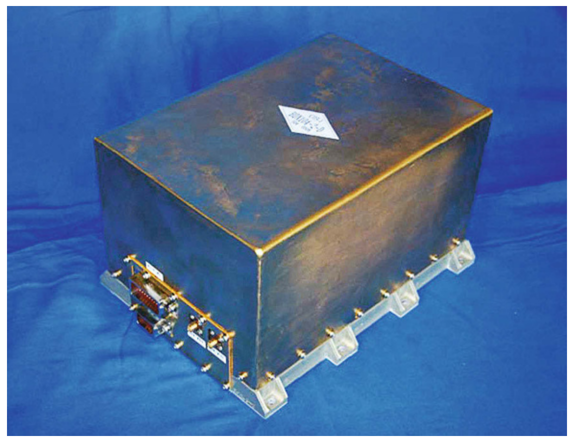

Fig. 10.19 Rubidium atomic frequency standard for BeiDou-2 satellites (after [10.40]). Reproduced with permission of Beijing Satellite Navigation Center

The upload of navigation information from the ground is handled by the uploading and ranging segment, which comprises an L-band uploading receiver and a spread spectrum ranging receiver for calibration of the two-way time delay.

In addition to the RNSS payload, which is common to all BeiDou-2 spacecraft, the geostationary satellites are equipped with an RDSS payload comprising an L-band/C-band inbound transponder and C-band/S-band outbound transponders for BDS-1-type navigation and short messaging (Sect. 10.1). Furthermore, the GEO satellites host a C-band transponder for time synchronization and data transmission between the ground control center and monitoring stations.

All BDS-2 satellites are equipped with a laser retroreflector array (LRA), which is used for precise orbit determination, and to assist the time comparison between satellites and ground stations. The LRAs were developed by Shanghai Observatory and consist

Part B | 10.2

of a planar array of individual prisms with a diameter of 33 mm. To account for the large distance, an LRA with a size of about $50 \times 40\,\mathrm{cm}^2$ and a total of 90 prisms is used onboard of GEO and IGSO satellites, whereas a smaller, 42-prism LRA is sufficient for the MEO spacecraft. Furthermore, the LRAs are slightly tilted on the GEO satellites, to improve the return signal strength for satellite laser ranging stations in China [10.41].

Complementary to satellite laser ranging (SLR), various BeiDou MEO/IGSO satellites support laser time transfer (LTT) through a dedicated onboard detector and timer connected to the atomic clocks [10.42]. The LTT system developed by the Technical University of Prague and Shanghai Astronomical Observatory [10.43] is based on a single photon avalanche diode (SPAD) and enables measurements of the ground-to-satellite signal travel time with subnanosecond (i. e., a few centimeter-level) precision. Independent of GNSS observations or traditional two-way time transfer (TWTT) equipment, LTT enables the precise monitoring and synchronization of the atomic frequency standards of the BeiDou satellites.

10.2.5 Operational Control System

The Operational Control System (OCS) of BDS, like that of other GNSSs, is a key segment for BDS operation. The research on the OCS of BDS demonstration system started as early as the 1980s. The OCS of BDS-2 has been in place since 2007, when the first BDS-2 satellite was launched.

The OCS of BDS provides command, control and operation capabilities for the three kinds of satellite constellations. The main functions of BDS OCS are:

- To establish and maintain coordinate reference datum
- To maintain time reference datum
- To measure time synchronization between satellites and ground stations
- To manage precise orbit determination and prediction
- To predict satellite clock offset
- To deal with augmentation data
- To process RDSS information
- To monitor, process, and predict ionospheric delay
- To monitor integrity
- To upload and download navigation message.

The workflow of the OCS can be simply described as collecting data related to the satellites and the ground stations, processing and analyzing the collected data, managing communication between satellites and ground stations, uploading operational commands to satellites, and broadcasting navigation messages to the users.

In the course of the BDS development, the OCS has evolved along with the increased number of satellites and complexity of the constellation. While the OCS in BDS-1 only controlled the two GEO satellites and one backup, the OCS in BDS-2 has to control three different types of satellites (GEO, IGSO, and MEO). The information, which the OCS has to process, has been enlarged dramatically. In addition, the services have been extended from RDSS to RDSS plus RNSS. Finally, the calibration stations have been replaced by the modern monitoring stations. There are high database and calibration stations with barometric altimeter for positioning in the OCS of BDS-1. The OCS of the BDS-2, however, no longer needs high database and some of the new monitoring stations are equipped with laser ranging system.

At present, the OCS of BDS-2 is composed of 1 MCS, 7 monitoring stations of Type A, which are mainly used for orbit and ionospheric delay monitoring, 22 monitoring stations of Type B, which are mainly used for augmentation service and integrity service, and 2 time synchronization/uploading stations (Fig. 10.20).

The frequency bands of the BDS-2 RDSS feeder and service links are the same as in BDS-1. The L-band is used in the BDS-2 RNSS service such as navigation message upload and download (Fig 10.21).

The OCS performance in BDS-2 is reflected by the general accuracy of the satellite orbits, the time datum, and the coordinate datum. The orbit determination accuracy as obtained from the regional monitor network is about 0.2 m, 1.2 m, and 0.6 m in radial, along-track, and orbital normal (N) directions, respectively. Satellite laser range measurements agree with the determined orbits to better than 1 m root-mean-square (rms) [10.38]. The user ranging error (URE) of 2-h orbit prediction is 1 m for GEO satellite, while UREs of IGSO and MEO orbit prediction are about 1 m at 6 h and 5 m at 16 h, respectively. The accuracy of satellite clock prediction ranges from 1.4 ns at 2 h to 12 ns at 10 h. Finally, the accuracy of ionospheric delay corrections by the broadcast Klobuchar model is better than 75%.

The updating strategy of the OCS involves mainly six parts: the least-squares adjustment of a polynomial model for the satellite clock using robust estimation [10.8]; generation of the ephemeris, which is presently updated each hour; adjustment of the coefficients for the Klobuchar ionospheric model, which is based on data from 32 monitoring stations; performance of the RDSS two-way service with a response time of less than 1 s; transfer of RDSS messages of up to 120 Chinese characters of 14 bit each; and issue of integrity warnings with a response time of less than 8 s.

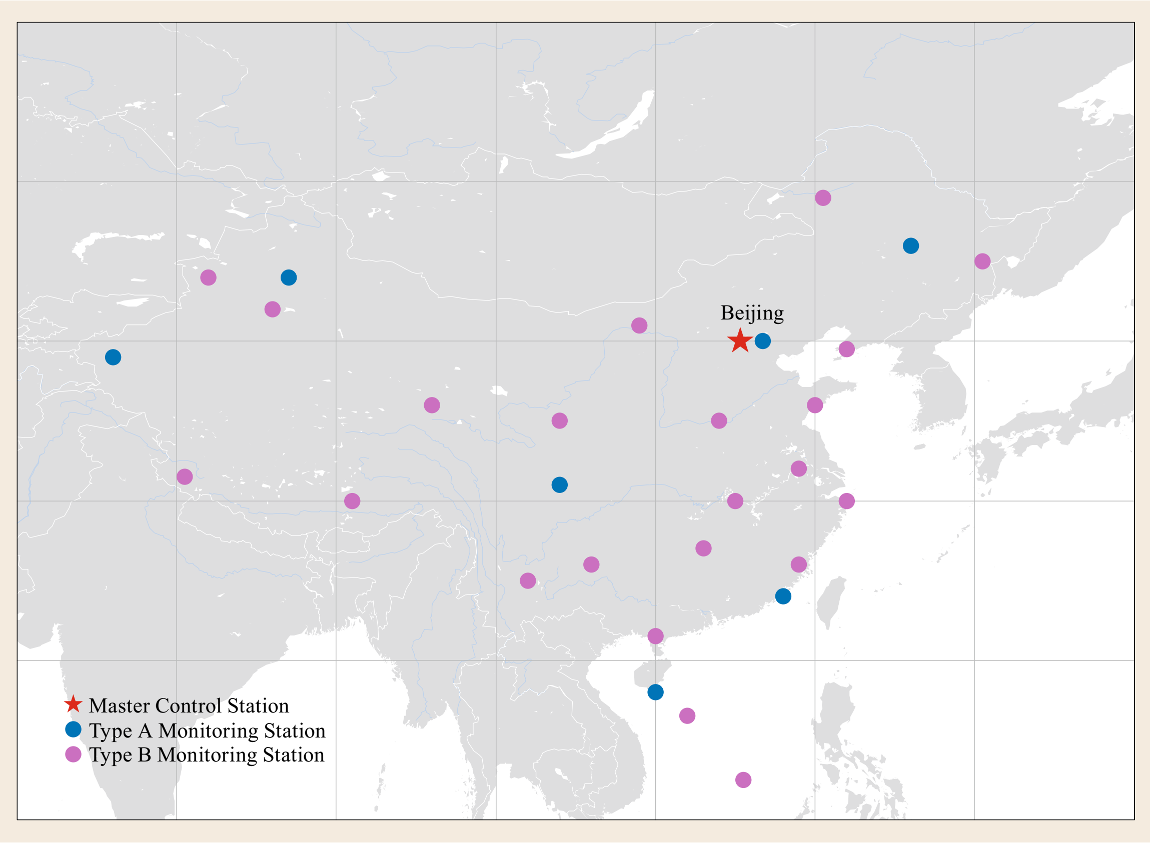

Fig. 10.20 Location of BeiDou Master Control Station and the type-A/B monitoring stations. Information courtesy of Beijing Satellite Navigation Center

As part of the ongoing BeiDou evolution to a fully global service, the OCS will be adapted to operate the next-generation of BDS satellites (MEO/IGSO/GEO) in an optimal and robust manner. The ground segment will be extended to upload navigation messages for the entire satellite constellation, to maintain an interoperable time datum based on reliable, stable, and accurate clocks, and to maintain the BeiDou coordinate system in real time using multi-GNSS observations.

10.2.6 BeiDou Satellite-Based Augmentation System

Unlike other SBASs (Chap. 12), which are separated from the navigation satellite systems, BDS and its OCS include the BeiDou Satellite-based Augmentation Services (BDSBAS, [10.44]) as an integral part.

After the BDS-1 was established, the first-generation of BDSBAS (BDSBAS-1) was embedded in 2003. It broadcasted augmentations for the GPS navigation signal using the GEO satellites. More than 20 monitoring stations were established for tracking and integrity monitoring. In each monitoring station, three receivers and one atomic clock were assembled. All the collected monitoring data were transmitted to the MCS, where the precise satellite orbit, grid ionospheric corrections, and the equivalent satellite clock corrections were processed. The corresponding corrections, the user differential range error (UDRE), and grid ionospheric vertical error (GIVE) were generated.

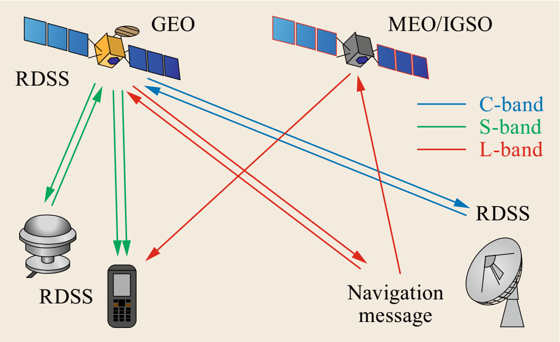

Fig. 10.21 Signal flow of satellites and monitoring stations

It was shown that the precision of differential positioning based on GPS L1 C/A was about 3 m, and the integrity, continuity, and availability were also improved.

In BDS-2, the basic navigation service and augmentation service have also been integrated [10.11], for which technical tests were started in December 2012. The differences of the BDSBAS-1 and BDSBAS-2 are as follows:

- The augmentation service of only GPS L1 C/A in BDSBAS-1 has been extended to include both GPS L1 C/A and BDS B1I, and possibly Galileo and other GNSSs in the future
- The service coverage area is enlarged in BDSBAS-2, because all five GEO satellites broadcast the augmentation information, as opposed to only two GEO satellites in the BDSBAS-1
- In the BDSBAS-1, the integrity was not included in the augmentation information, but it is included in the BDSBAS-2
- The number of monitoring stations in BDSBAS-2 has been increased to more than 30
- Scalar *equivalent satellite clock errors* were derived and broadcast in BDSBAS-1, while satellite clock errors and satellite orbit errors are handled separately in the BDSBAS-2.

The workflow of calculating the equivalent satellite clock errors is as follows:

- Geometric distances between the satellite and monitoring stations are calculated based on the broadcast ephemeris and the satellite clock corrections as well as the known coordinates of the monitoring stations.
- The differences between the geometric distances and measured pseudoranges which are corrected by the ionospheric influences are calculated; thus, the pseudorange residuals are obtained.
- The equivalent satellite clock correction is obtained as the average of the residuals corresponding to this satellite.

The augmentation data of B1I signal are monitored by the monitoring stations and then the monitored data are transmitted to the MCS and processed there. The corrections of ephemeris, satellite clocks (SCs), and grid ionosphere as well as UDRE/GIVE and integrity information are generated in the MCS and modulated in the navigation message. The augmentation information together with the normal navigation message is uploaded to the GEO satellites through the communication link between the MCS and the GEO satellites, on which the augmentation messages are modulated into the downlink signals and broadcast to the users. In the new test, the precision of differential positioning by B1I of BDS is better than 3 m.

10.2.7 Coordinate Reference System

The BDC system is connected to the China Geodetic Coordinate System 2000 (CGCS2000), which itself is aligned to the International Terrestrial Reference System (ITRS) [10.45].

CGCS2000 is realized by the China Terrestrial Reference Frame (CTRF). The definition of this coordinate system follows the criteria outlined in the 1996 conventions [10.46] of the International Earth Rotation and Reference Systems Service (IERS). The next generation of CGCS may be renewed following the new IERS conventions issued in 2010 [10.47].

CGCS2000 is a right-handed, orthogonal system. Its origin is the center of the mass of the Earth including the oceans and the atmosphere. Its scale is that of the local Earth frame, in the meaning of a relativistic theory of gravitation [10.45, 46]. The orientation is initially given by the orientation of the Bureau International de l'Heure (BIH) Terrestrial System at 1984.0, and the time evolution of the orientation is ensured by using a no-net-rotation condition with respect to the horizontal tectonic motions over the whole Earth. The unit of the length is meter. Its z-axis is the direction of the IERS Reference Pole (IRP). This direction corresponds to the direction of the BIH conventional terrestrial pole (CTP) at epoch 1984.0. The x-axis is the intersection of the IERS reference meridian (IRM) and the plane passing through the origin and normal to the z-axis. The IRM is coincident with the BIH Zero Meridian at epoch 1984.0. The y-axis, finally, completes a right-handed, Earth-centered Earth-fixed (ECEF) orthogonal coordinate system.

The CGCS2000 origin also serves as the geometric center of the CGCS2000 ellipsoid and the z-axis serves as the rotational axis of this ellipsoid of revolution. Parameters of the CGCS2000 reference ellipsoid are listed in Table 10.5.

Table 10.5 Fundamental parameters of the CGCS2000 system

Parameter	Value
Semimajor axis	$a = 6\,378\,137.0\,\mathrm{m}$
Flattening	$f = 1/298.257222101$
Gravitational coeff. (incl. atmosphere)	$GM_{\oplus} = 398\,600.4418 \cdot 10^9\,\mathrm{m^3/s^2}$
Angular velocity	$\omega_{\oplus} = 7.292115 \cdot 10^{-5}\,\mathrm{rad/s}$

10.2.8 Time System

The time reference for the BeiDou (Regional) Navigation Satellite System is BeiDou Time, BDT [10.8]. BDT is a continuous navigation time scale without leap seconds and with the SI second as its basic unit. BDT is commonly represented by the BeiDou week number (WN) and the seconds of week (SoW), ranging from 0 to 604 799. The zero point of BDT (i. e., WN = 0, SoW = 0) is January 1, 2006 (Sunday) UTC 00h 00m 00s. Similar to GPS and Galileo Time, BDT is aligned to UTC except for an integer second offset caused by the accumulated leapseconds.

The basic tasks of time keeping and timing service of the BeiDou system are to provide time and frequency signals in real time with continuity, stability, high accuracy, and reliability. Here, *continuity* reflects that time (frequency) is differentiable and the ability of the time system to run without interuption; *stability* refers to the variation of frequency over time and is commonly expressed by the Allan deviation (ADEV); *accuracy* means the consistency of the time (frequency) signal with the nominal value, which is often denoted by relative time bias (frequency bias); and *reliability* means the ability to provide the time and frequency signals under given conditions over the envisaged period of operation. In fact, there is no single atomic clock, which can provide time and frequency signals meeting the above criteria. Multiple Hydrogen maser clocks are, therefore, employed to collectively provide the BeiDou system time and frequency with the desired performance and reliability.

BDT is maintained by the Time and Frequency System (TFS) and aligned to the UTC realization UTC(BSNC) of the Beijing Satellite Navigation Center (BSNC). The TFS is mainly composed of five parts shown in Fig. 10.22. The clock ensemble (CE) comprises about 10 Hydrogen masers, which are used to form a *composite clock* in a robust estimation process. The intermeasurement element (IME) provides measurements of the original time and frequency signals from the clock ensemble and outputs the clock differences both in time and frequency in a regular pattern. The outer comparison element (OCE) provides the deviation of BDT from other time scales, especially from UTC and that of NTSC (National Timing Service Center of Chinese Academy of Science). The data processing element (DPE) carries out the calculation with the given algorithm based on all the information from IME and OCE, to give a relative uniform time scale, which is called BDT and works as the time reference for the whole navigation system. The signal generation element (SGE), finally, exerts frequency adjustments to the signals of the master clock (MC), and generates physical time and frequency signals for the MCS.

The algorithm performed in BDT calculation is well designed to form a good composite clock. The frequency offset, drift, and instability of each clock have been taken into account. The weights of clocks are determined by their Allan variances in which the frequency drift is taken off. The equivalent weights are also used based on the robust estimation principle [10.48, 49]. In order to be as consistent as possible with UTC, BDT may be steered with an interposed frequency adjustment after a period of time (more than 30 days) if the bias between the BDT and UTC is beyond the appointed threshold, but the quantity of the interposed frequency adjustment is not allowed to be more than $5 \cdot 10^{-15}$.

In order to align BDT with UTC, a time and frequency transfer chain between the MCS and the NTSC has been established. It makes use of two-way satellite time and frequency transfer (TWSTFT) via the geostationary BeiDou satellites as well as BDS and GPS common view (CV) observations [10.50]. Fiber chains between BSNC and National Institute of Metrology

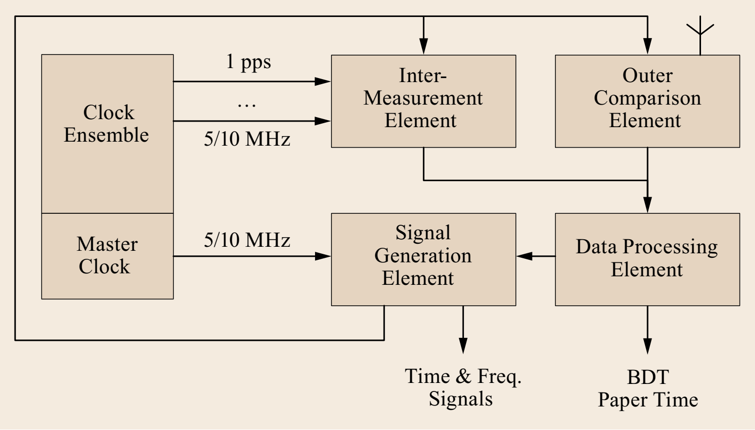

Fig. 10.22 The composition of the time and frequency systems (after [10.8])

Part B | 10.2

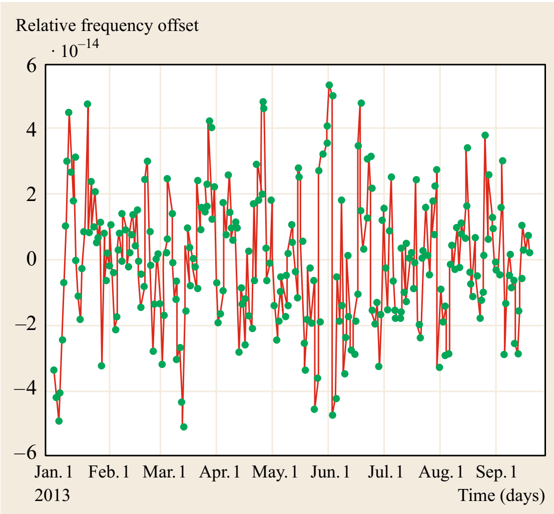

Fig. 10.23 Frequency bias of BDT relative to UTC(BNSC)

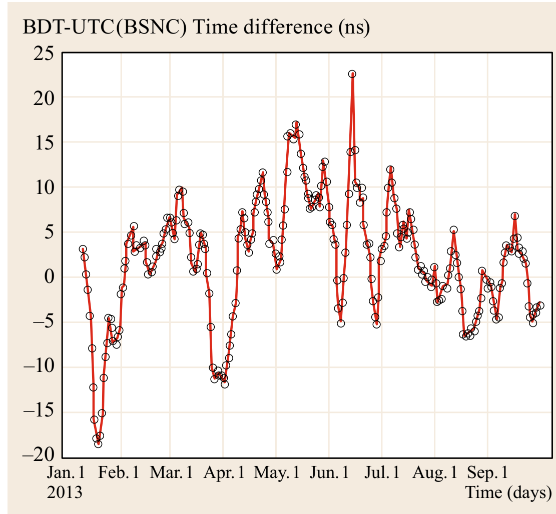

Fig. 10.25 Difference of BeiDou system time with respect to UTC(BNSC)

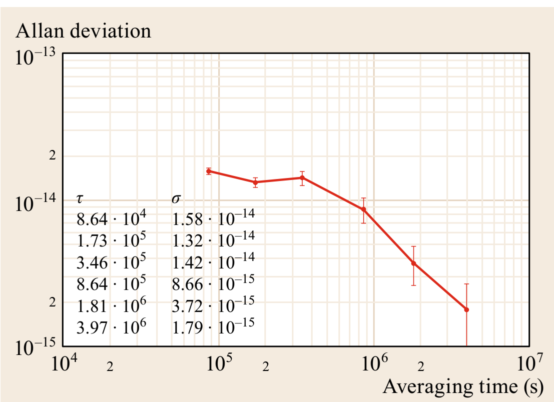

Fig. 10.24 Frequency stability of BDT shown by ADEV

Table 10.6 BeiDou system time performance

Patameter	Value
Time (frequency) accuracy	$< 1.0 \cdot 10^{-13}$
Time (frequency) stability	$< 2.0 \cdot 10^{-14}$ /1d $< 1.0 \cdot 10^{-14}$ /7d
Time deviation BDT-UTC	< 100 ns (modulo 1 s)

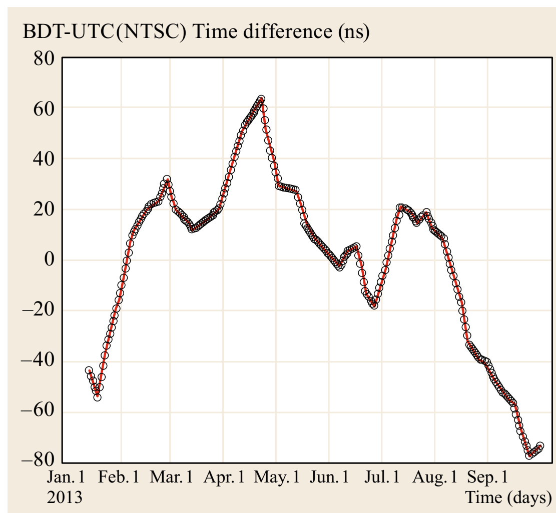

Fig. 10.26 Difference of BeiDou system time with respect to UTC(NTSC)

(NIM) as well as BSNC and NTSC will be established. Apart from the indirect links, a direct determination of the BDT-UTC time offset through TWTFFT and GNSS CV measurements between the BSNC and the Bureau International des Poids et Mesures (BIPM) is under preparation. For further reference, Figs. 10.23 and 10.24 show the frequency offset and ADEV of BDT in comparison with the realization of UTC provided by the BSNC. The overall offset between BDT and UTC(BSNC) as well as UTC(NTSC) (which is closely aligned with UTC and GPS time) is shown in Figs. 10.25 and 10.26 over a 10-month period in 2013. All graphs are based on data of the BeiDou MCS.

The current performance of BDT is summarized in Table 10.6. It may be noted that the performance of BDT after running several years is not as good as its original state shown in [10.8].

10.3 Performance of BDS-2

During the construction of BDS-2, the performance of satellite clock, ranging, positioning accuracy, and reliability has been validated gradually. Tests performed by different communities [10.38, 51] demonstrate that the performance of BDS-2 in positioning, navigation, and timing (PNT) has reached or even exceeded the design specification.

10.3.1 Service Region

Broadcast ephemeris date for January 22–29, 2013 was used in [10.51] to assess the number of visible satellite and position dilution of precision (PDOP) [10.52, 53] for global users and the Asia-Pacific area shortly after the start of the regional operational service.

For areas between latitude 70°S–70°N and longitude 40°E–180°E, the number of visible satellite is more than five (Fig. 10.27) and the PDOP is smaller than 12 (Fig. 10.28), which satisfies the basic navigation requirements. More reliable navigation is available between latitude 60°S–60°N and longitude 70°E–150°E, where the number of visible satellite is more than seven and the PDOP is less than five. For areas between latitude 50°S–50°N and longitude 85°E–135°E, the number of visible satellite is finally larger than eight and the PDOP is between 2 and 3. Higher accuracy and a more reliable navigation service can be provided in these areas.

The number of visible satellites is above seven in China, and the availability (as defined by a PDOP value of less than <6) exceeds 97.5%. The service region of BeiDou system reaches the design requirement, and the availability of BeiDou system is close to 100% in the designated coverage area (Fig. 10.29).

10.3.2 Performance of Satellite Clocks

The performance of BeiDou SCs directly affects the accuracy and reliability of the users' positioning and navigation results. From the measurements between the BeiDou satellites and the ground uplink stations, the onboard clock offsets from BDT and the clock stabilities can be evaluated. In addition, the performance can also be evaluated through the satellite orbit and clock determination process. Results from both approaches are consistent with each other and show that the uncertainties of the measured satellite clock offsets are less than 2 ns.

In order to transmit correct navigation signals, the clock offsets are controlled within 1 ms. Between adjustments, the offset exhibits a dominant linear trend over time (i. e., a frequency offset) and a superimposed quadratic variation (i. e., a frequency drift), which is common for Rubidium atomic frequency standards. By means of an example, Fig. 10.30 shows clock offset variation of a geostationary BeiDou satellite after lin-

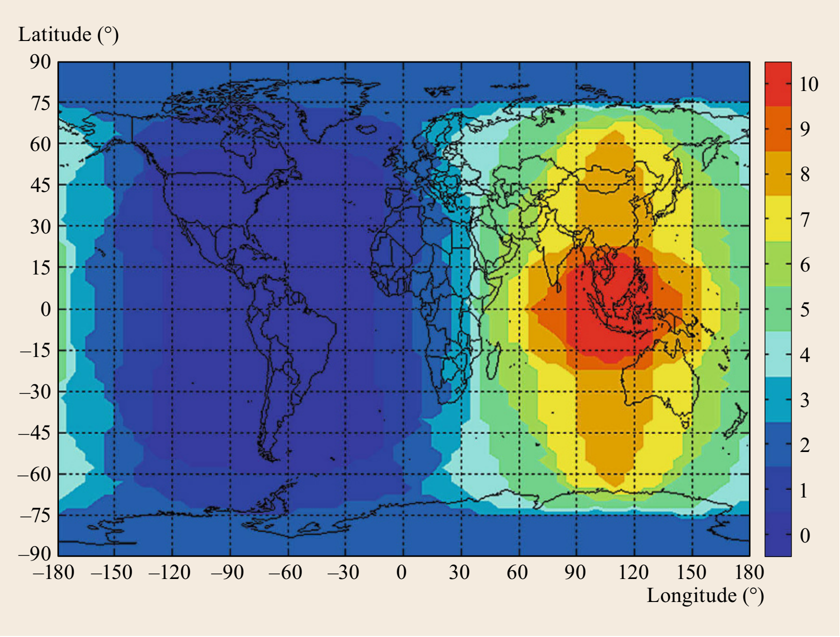

Fig. 10.27 Number of visible BeiDou satellites (95%) in January 2013 considering a cut-off elevation of 5° (after [10.51])

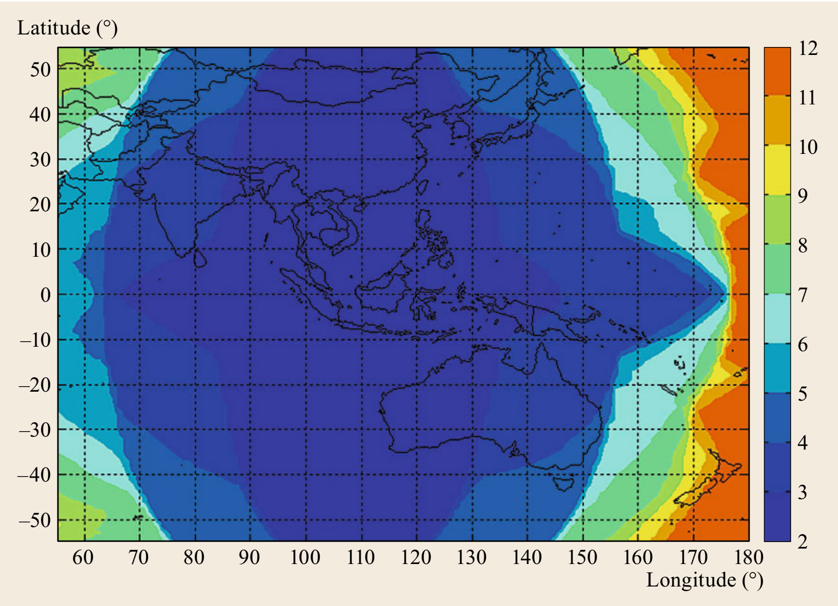

Fig. 10.28 PDOP value (95%) in Asia-Pacific area (after [10.51])

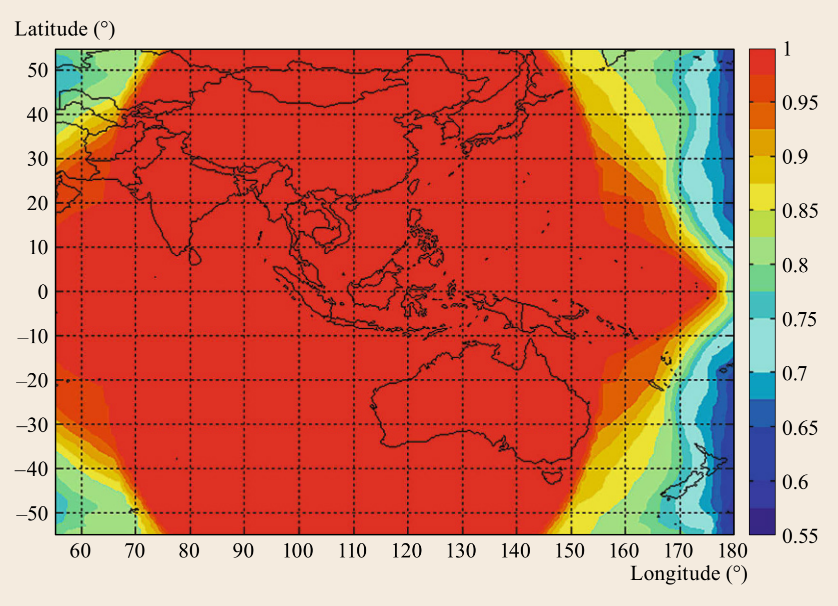

Fig. 10.29 Availability of BeiDou in Asia-Pacific area (PDOP<6) (after [10.51])

ear and quadratic detrending over a 2-month interval in 2014.

Frequency offsets, drifts, and stabilities (i. e., ADEV for 1-day intervals) as obtained from TWTT [10.54–56] between the satellites and the seven type-A monitoring stations are summarized in Table 10.7 for all BeiDou-2 satellites. The satellite clocks (SCs) from three different companies are symbolized as SC1, SC2, SC3, and SC4, respectively. As can be seen, the performances of the four clocks are comparable, only the accuracy of SC1 is slightly lower.

The frequency stability as obtained from the TWTT observations over time scales from 1s to several days is illustrated in Fig. 10.31. Here, ADEV values of $2–8 \cdot 10^{-14}$ over one day are obtained for most satellites, while a stability of about $5 \cdot 10^{-11}$ is obtained near 1 s. However, the measured ADEV is dominated by the noise of the employed ranging measurements and

Table 10.7 Performance of BDS satellite clocks in April 2013. Satellites are identified by their type (*G*, *I*, and *M* for GEO, IGSO, and MEO satellites, respectively) as well as the PRN number of the transmitted signal. The last column indicates, which of the four clocks of each satellite was activated during the analysis period

Sat	PRN	Frequency offset (10^{-11})	Drift (10^{-13}/d)	Stability (at 1 day) (10^{-13})	Clock
G1	C01	+1.935	−0.351	0.741	SC3
G6	C02	−4.147	+2.299	3.671	SC2
G3	C03	+0.513	+0.272	0.385	SC2
G4	C04	+0.769	+0.279	1.123	SC4
G5	C05	−5.271	−1.450	0.704	SC1
I1	C06	−1.208	+0.060	1.792	SC1
I2	C07	+1.158	+0.331	1.359	SC3
I3	C08	+0.890	+0.698	2.698	SC4
I4	C09	+2.778	−0.352	0.493	SC1
I5	C10	+2.929	−0.752	0.702	SC3
M3	C11	+0.144	−2.448	0.508	SC1
M4	C12	+1.047	−0.445	0.187	SC2
M5	C13	+5.969	+3.679	1.116	SC1
M6	C14	+0.858	+5.752	2.412	SC2

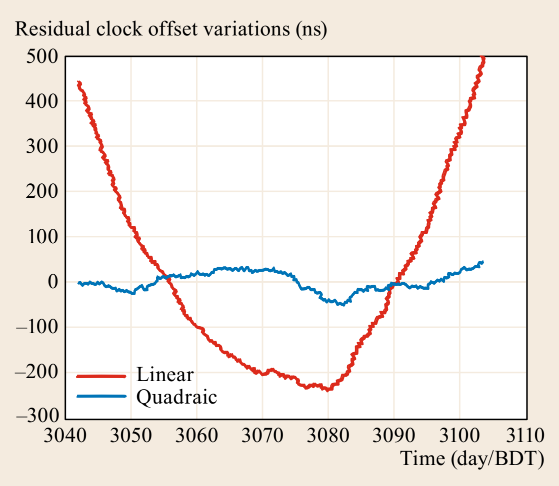

Fig. 10.30 Residual clock offset variations of GEO-3 satellite clock after linear and quadratic detrending from May 1 to July 1, 2014

does not reflect the actual onboard clock performance below an averaging time of 1000 s [10.55]. Independent analyses of one-way carrier phase observations reported in [10.57] and [10.58] have actually demonstrated a short-term stability of about $0.5 \cdot 10^{-11}$ at 1 s intervals. Modified ADEVs of less than $1 \cdot 10^{-14}$ at daily time scales are reported in [10.59].

10.3.3 Positioning Performance

The BDS-2 positioning performance following the start of the regional service has been assessed in [10.51]. Single-point position solutions were obtained from measurements collected with a geodetic receiver in Beijing from December 27, 2012 to March 20, 2013 (including a 13-day unavailability due to receiver update and maintenance). The employed B1I pseudorange observations exhibit a noise level of 0.2–0.4 m and the BeiDou Klobuchar model was used for compensating ionospheric path delays. Observations were limited to a 5° cut-off elevation.

The resulting 95% (2σ) position errors relative to the surveyed antenna location are illustrated in Fig. 10.32 over the 71-day time interval. Complementary to these, the horizontal, vertical, and PDOP (95% values) of every day are shown in Fig. 10.33. On most days, the 95th percentiles of the horizontal, vertical, and total position error are smaller than 6 m, 10 m, and 12 m, respectively, which is in good accord with the open service performance specification [10.10].

The average single-point positioning accuracy of 10 m at a mean PDOP of 3 indicates a users range error (URE) of about 3.5 m 2σ. This value includes user equipment related contributions (noise, multipath, and uncompensated atmospheric delays) as well as the SISRE, which characterizes the contribution of broadcast orbit and clock errors. Independent comparisons of broadcast ephemerides with postprocessed precise orbit and clock determination results indicate a SISRE value of about 1.5 m (rms) on average over the entire BDS-2 constellations [10.60–62].

Apart from standard positioning applications, BeiDou has found widespread use for precise point positioning in stand-alone or multiconstellation mode. Precise orbit and clock products for BeiDou are rou-

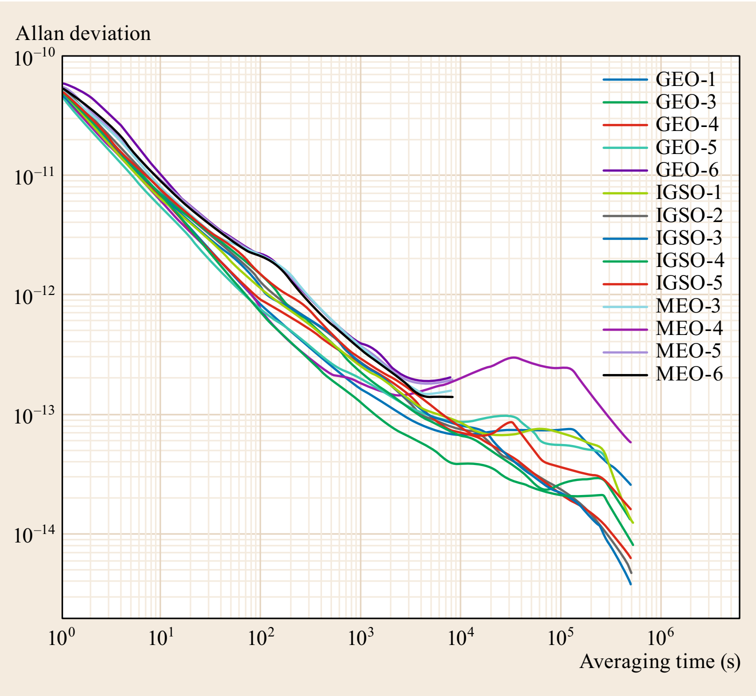

Fig. 10.31 Frequency stability (ADEV) of BeiDou satellite clocks based on two-way time transfer (after [10.55])

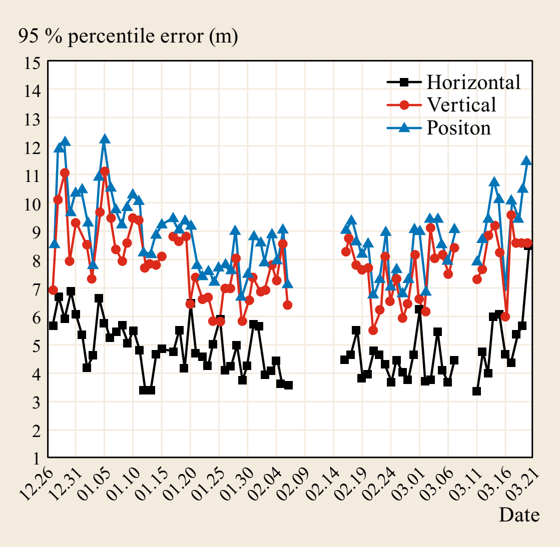

Fig. 10.32 Positioning performance of BeiDou-only navigation in Beijing after start of the BDS-2 regional service from December 2012 to March 2013 (after [10.51])

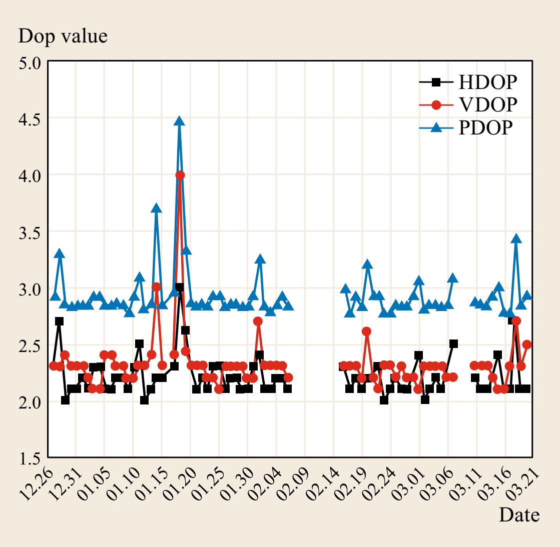

Fig. 10.33 Horizontal (HDOP), vertical (HDOP) and PDOP of BDS-2 in Beijing between December 2012 and March 2013 (after [10.51])

tinely generated by a variety of analysis centers [10.59, 63, 64] and publicly made available through the International GNSS Service.

A comprehensive assessment of the BeiDou tracking performance and the associated positioning performance conducted in [10.51] is summarized in Fig. 10.34. Using a geodetic grade receiver, code and carrier phase observations with noise levels of about 10 cm and 0.5 mm, respectively, were collected. While the code-only position exhibit rms errors of 6 m and 10 m in horizontal (H) and up (U) directions, respectively, the cancellation of common errors in differential

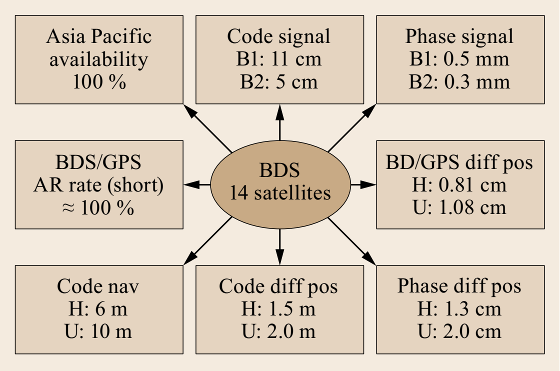

Fig. 10.34 Performance of BDS-2 service in Beijing area (after [10.51]). See text for further explanations

code positioning enables an accuracy better than 2 m in each direction. Using carrier phase observations, differential positions with centimeter-level accuracy and an ambiguity resolution (AR) rate of about 100% are obtained at short baselines. Combining BDS and GPS, the carrier phase-based differential relative navigation accuracy can further be improved by a factor of 2.

10.3.4 Application Examples

Starting with the successful implementation of the BeiDou Navigation Satellite Demonstration System in 2003, BDS has been used for a wide range of applications and created substantial social and economic benefits [10.4]. BeiDou terminals and receivers developed by Chinese industry are employed for land and maritime navigation, provide precise timing for critical infrastructure, contribute to weather services, and are widely employed for emergency services. Prominent examples highlighting the benefits of BeiDou for the Chinese society include the use of BDS navigation during the Beijing Olympic Games and the Shanghai World Expo as well as as BDS navigation and communication in earthquake and snow disaster relief.

Use of the BeiDou Navigation Satellite System in the transportation sector has been promoted through pilot projects such as the Demonstration System of Monitoring Management Services in Priority Transportation, the Highway Infrastructure Safety Monitoring System [10.65, 66], and School Bus Safety Monitoring [10.67]. In the maritime sector, an integrated information service platform has been established to provide vessel localization and monitoring, rescue and information services as well as harbor access management for fishing boats [10.4, 68].

Apart from the navigation related applictaions, BeiDou is an important element for the reliable distribution of precise time information. Key technologies such as long-distance fiber technology and an integrated satellite-based timing system have been developed as part of the BeiDou two-way timing demonstration program [10.69, 70]. Similarly, a pilot project for power system time synchronization provided the basis for monitoring and protection of electric power grids [10.71].

The pilot project for *Monitoring and Warning in Atmospheric, Oceanic and Space* has addressed the automatic data transmission among China's meteorological stations and a real-time hydrological monitoring system has been established to support flood and drought control [10.4]. Further studies in this field include the assessment of precipitable water vapor from ground-based BeiDou observations in a precise point positioning approach [10.72] as well as the estimation of typhoon wind speeds using reflected signals from BeiDou GEO satellites and the transfer of related information using the BeiDou short message mode [10.73].

BeiDou also plays a vital role in diverse forms of emergency and disaster relief services. Among others, forest fire monitoring terminals based on BDS have been designed and produced by Chinese industry [10.74]. They have been successfully used in a forest fire prevention system [10.75], which benefits from the combination of the BeiDou positioning and short message communication services. This unique feature of BeiDou is also utilized within the nationwide disaster relief management system, where BeiDou has greatly improved the efficiency of emergency operations and decision-making processes [10.4, 76, 77].

Finally, with the ongoing proliferation of navigation satellite systems, BeiDou has become an important contributor to multi-GNSS. With the availability of more satellites and signals, precision and reliability of parameter estimation improves, as well as convergence times, position availability and robustness of ambiguity resolution [10.78–80].

10.4 BeiDou (Global) Navigation Satellite System

The BeiDou Navigation Satellite System with global coverage (BDS-3) will be completed by 2020. The space constellation will consist of five GEO satellites (positioned at 58.75°E, 80°E, 110.5°E, 140°E, and 160°E) as well as as 27 MEO satellites and three IGSO satellites. The current satellites will be a part of the constellation that forms the BeiDou global navigation satellite system. Future MEO and IGSO satellites will have the same orbit as the current ones, that is, they will be placed in orbits with an inclination of 55° at altitudes of 21 500 and 36 000 km, respectively. The three IGSO satellites orbit the Earth in three different planes but exhibit a common ground track with its ascending node at 118°E.

BDS-3 will provide an open service and an authorized service in four frequency bands, including B1 (1559–1610 MHz), B2 (1164–1219 MHz), and B3 (1240–1300 MHz) with center frequencies of 1575.42 MHz, 1191.795 MHz, and 1268.52 MHz. A new S-band signal, Bs (2483.5–2500 MHz), is also broadcasted by the newly launched satellites. Compared to the regional BeiDou system, new and advanced signal structures are employed for better performance, compatibility, and interoperability with other GNSSs [10.81]. Key characteristics of these signals as presented in [10.82–84] are summarized in the following.

The B1 frequency has two signals, named B1-A and B1-C. B1-A is an authorized signal and employs a BOC(14,2) binary offset carrier modulation. The open service B1-C signal, in contrast, utilizes a MBOC(6,1,1/11) multiplexed binary offset carrier modulation. It consists of two components, namely the B1-CD data channel and the B1-CP pilot channel, which are transmitted in phase quadrature. The B1-CD component is modulated with a 50 bps (100 sps) binary navigation data stream.

On the B2 frequency, an AltBOC(15,10) modulation is used, which generates two side lobes at 1176.45 MHz (B2a) and 1207.14 MHz (B2b), respectively, and comprises four individual signal components for the open service. B2a consists of a data channel (B2a-D) and a pilot channel (B2a-P) in phase quadrature. The binary navigation data stream on B2a-D is transmitted at a rate of 25 bps (50 sps). Similarly, the upper sideband comprises the B2b-D data channel (with twice the data rate of the B2a-D channel) and a B2b-P pilot channel in phase quadrature.

In the B3-band, two authorized signals (B3 and B3-A) with a total of four individual components are transmitted at a common center frequency of 1268.52 MHz. The B3I and B3Q signals are modulated in quadrature phase shift keying (QPSK) with a 10.23 Mchips/s PRN code and a 500 bps binary navigation data stream. The B3-A signal is modulated in BOC(15,2.5) and consists of two components, B3-AD and B3-AP, in phase quadrature. The B3-AD data channel is modulated with a 50 bps (100 sps) binary navigation message.

The Bs signal, finally, is modulated in BPSK(8) and transmitted at a central frequency of 2492.028 MHz. It consists of two components, designated as Bs-D and Bs-P. The Bs-D component is modulated with a 50 bps (100 sps) binary navigation data stream.

Between March and September 2015, the first four satellites of the third generation BeiDou system (including two IGSO and two MEO satellites) have been launched. Initial test signals transmitted by these satellites for system validation purposes are described in [10.85]. As of December 2015, the final structure of the BDS-3 signals has not officially been published and minor modifications of the aforementioned signal properties might still be performed for further optimization. However, as China had claimed before, the ICD of the global open signal will be published as soon as possible once the new signal system assessment is accomplished [10.81].

10.5 Brief Introduction of CAPS

The Chinese Area Positioning System (CAPS) is an alternative, regional radio navigation system that has been developed since the early 2000s under the lead of the Chinese National Astronomical Observatories and the NTSC. It implements the concept of a *transponder satellite communication navigation and positioning system* [10.86] utilizing spare capacities of existing geosynchronous communication satellites. While traditional GNSS concepts are build on a dedicated satellite constellation, which generates and transmits the navigation signals in orbit, CAPS makes use of communication satellites, which relay navigation signals generated on ground to the users. The reuse of existing space infrastructure offers considerable cost savings along with great flexibility and redundancy [10.87–89].

CAPS has been involved in the testing of signals, time synchronization, and orbit determination of the BeiDou system. In the future, CAPS will contribute to the performance monitoring of BeiDou and serve as an experimental platform for the integration of navigation and communication services.

10.5.1 CAPS Concept and System Architecture

Similar to other spacebased navigation systems, the CAPS system can be divided into a space segment and a ground segment (Fig. 10.35).

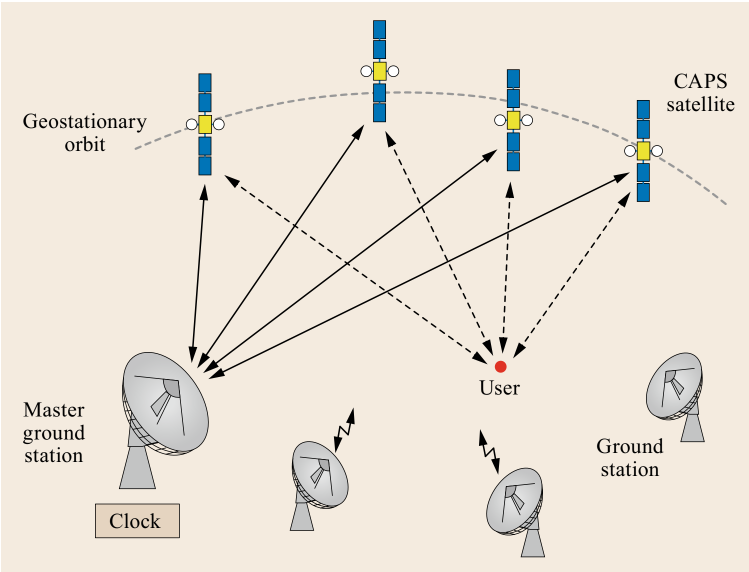

Fig. 10.35 The CAPS system architecture comprises various satellite in near-geostationary orbit as well as a master ground station and multiple remote stations for orbit determination

The space segment is made up of multiple communications satellites in geosynchronous orbits, which offer continued visibility from the regional service area. Apart from satellites in a tightly controlled GEO, the CAPS includes decommissioned GEO (DGEO) satellites which no longer perform a north–south station keeping and attain a slightly inclined geosynchronous orbit (SIGSO). The use of highly inclined geosynchronous orbits has, furthermore, been suggested to improve the geometric distribution of visible satellites and the overall dilution of precision (DOP) in CAPS-based positioning [10.87]. The satellites do not require a dedicated navigation payload and high performance atomic clock, but merely a standard transponder to relay a signal between a ground based transmitter and a receiver. As such, CAPS offers great flexibility in the choice of satellites for its space segment.

The CAPS ground segment consists of a master ground station and various remote ground stations. All stations are equipped with large dish antennas for transmitting a modulated ranging signal to the satellites and can simultaneously receive signals from other stations returned through the satellites' transponders. The master station hosts the primary time and frequency reference. It generates the CAPS system time, which itself is synchronized to the realization of Universal Coordinated Time provided by the National Time Service Center (UTC(NTSC)) [10.90].

The master station also serves as the ground navigation center, which determines the orbits and transponder delays of the CAPS satellites from the measured measures transmission times between stations, and broadcasts this information to the user as part of the navigation message. In addition to orbit and clock information, the CAPS navigation message includes near real-time temperature and pressure data collected by meteorological stations across China. Along with barometers in the user terminals, this information can be used to infer the altitude of the user and to support a robust three-dimensional positioning.

Users receiving ranging signals from multiple CAPS satellites, can determine their position using the measured signal travel times, and, optionally, barometric height information. Even though, at first sight, CAPS resembles the first-generation BeiDou system (Sect. 10.1), it employs a completely passive navigation technique. No signals need to be returned by the user to the control center and all positions are computed in the end-user equipment rather than a central navigation facility.

CAPS utilizes C-band links for all signals exchanged between ground stations, satellites and users. This choice is partly driven by the wide availability of C-band transponder capacity on geostationary communication satellites, but also motivated by a general interest to avoid the crowded L-band spectrum for new navigation systems. As discussed in [10.91], the higher frequency induces increased free-space losses and a higher attenuation due to rainfall, but is substantially less affected by ionospheric path delays. Also, C-band supports the use of wide-band navigation signals with beneficial noise and multipath properties.

To avoid interference at the satellites, different frequencies need to be employed for the uplink and downlink. For ionospheric correction, the satellites of the CAPS trial system described in Sect. 10.5.3

transmit dual-frequency navigation signals at $f_{C1} = 4143.15\,\text{MHz}$ and $f_{C2} = 3826.02\,\text{MHz}$ to its users. The ground stations, in contrast, use carrier frequencies of $f_{C1} = 6368.15\,\text{MHz}$ and $f_{C2} = 6051.02\,\text{MHz}$ for the uplink. The uplink and downlink signals are separated by a constant offset of 2225 MHz, which is generated by a local oscillator onboard the satellites [10.92]. Since the onboard oscillator exhibits only a moderate stability, an active alignment of the uplink frequency is performed in the master station to compensate the frequency shift of the transponder. In this way, CAPS can also be used to determine the user velocity based on observed Doppler shifts at the receiver.

Through the inherent combination of navigation and communication, CAPS offers unique advantages over traditional navigation-only satellite systems. Possible applications of these features include the provision of differential corrections and integrity information but also various forms of search and rescue or disaster management services. The design and application of a CAPS user-terminal supporting joint navigation and communication functions for land and marine use is, for example, discussed in [10.93].

10.5.2 Positioning Principle of CAPS

Navigation as well as orbit determination and time synchronization in the CAPS are performed through measurements of signal travel times between the transmitting ground station and the user receiver. The signal path involves an uplink from the ground station at $\boldsymbol{r}_g$ to the transponding satellite at $\boldsymbol{r}_s$ and a subsequent downlink to the user at $\boldsymbol{r}_u$. Denoting the transmit and receive times by t_g and t_u, respectively, the two-leg pseudorange is given by

$$\begin{aligned} p_{gsu} &= c \cdot (t_u + dt_u - t_g) \\ &= ||\boldsymbol{r}_s - \boldsymbol{r}_g|| + ||\boldsymbol{r}_u - \boldsymbol{r}_s|| \\ &\quad + c\tau_s + cdt_u + T_{gs} + T_{su}\,. \end{aligned} \tag{10.9}$$

Here, τ_s is the satellite transponder delay and dt_u denotes the offset of the receiver clock from CAPS system time, which is defined by the master ground station. The tropospheric delays of the uplink and downlink paths are denoted by T_{gs} and T_{su}, respectively. They can be taken into account through meteorological measurements at the ground station and tropospheric models for the receiver location. Ionospheric delays are eliminated through the use of a ionosphere-free dual-frequency combination and have, therefore, been ignored in the pseudorange model.

Equation (10.9) describes the basic relation among the measured signal travel times, the satellite, and station coordinates as well as the user position and clock offset. Depending on the specific application, different alternative formulations can be employed. First, the relations

$$\begin{aligned} p_{gsg} &= 2||\boldsymbol{r}_s - \boldsymbol{r}_g|| + c\tau_s + 2T_{gs} \\ p_{gsg'} &= ||\boldsymbol{r}_s - \boldsymbol{r}_g|| + ||\boldsymbol{r}_{g'} - \boldsymbol{r}_s|| \\ &\quad + c\tau_s + cdt_{g'} + T_{gs} + T_{sg'} \end{aligned} \tag{10.10}$$

are obtained for pseudorange observations collected by the master ground station as well as pseudorange observations between the master station (g) and the remote ground stations (g′). These can essentially be used to measure the instantaneous distance between each station and the satellite, and also to determine the three-dimensional satellite position. They also enable calibration of the satellite transponder delay and (by comparison of $p_{gsg'}$ and $p_{g'sg}$) a clock synchronization of the remote stations with the master ground station.

Second, (10.9) may be rephrased as

$$\begin{aligned} p_{su} &= p_{gsu} - c \cdot \tau_{VCLK} \\ &= ||\boldsymbol{r}_u - \boldsymbol{r}_s|| + cdt_u + T_{su}\,. \end{aligned} \tag{10.11}$$

Within this *virtual clock* (VCLK) concept [10.94]

$$\begin{aligned} c \cdot \tau_{VCLK} &= c \cdot (t_s - t_g) \\ &= ||\boldsymbol{r}_s - \boldsymbol{r}_g|| + c\tau_s + T_{gs}\,. \end{aligned} \tag{10.12}$$

denotes the difference between the uplink time t_g at the ground station and the time t_s of retransmission at the satellite. The VLCK correction is determined at the ground station from the known satellite orbit and calibrated time delays. It is then transmitted to the user via the CAPS navigation message and can be used to remove the uplink contribution from the measured pseudorange. As a result, the measurement model (10.11) attains the well-known form of traditional navigation satellite systems using one-way pseudorange observations. The user position and receiver clock offset can then be determined from a minimum of four corrected pseudorange observations. While a closed-form solution is possible for exactly four observations, the measurement model is commonly linearized with respect to the user coordinates and solved in an iterative manner.

Due to the regional distribution of the ground stations as well as the large distance and small orbital inclinations of the near-geostationary satellites, CAPS suffers from an unfavorable dilution of precision (DOP) as compared to traditional GNSSs. The use of barometric measurements is, therefore, considered as a pseudo-observation to better constrain the user position [10.95].

Making use of a barometer in the user terminal as well as broadcast meteorological data (ground pressure and temperature) for the region of interest, the receiver's height above the reference ellipsoid can be determined with an accuracy ranging from 3–5 m for terrestrial users to 10–20 m for aviation users [10.90].

10.5.3 Trial CAPS System

Following the governmental approval in 2005, a trial system was established in the course of two years at a cost of about 20 million USD to validate the working principle and performance of the CAPS.

The trial constellation consists of two GEO satellites (Zhongwei/ChinaStar-1 and Sinosat-1) located at 87.5°E and 110.5°E, as well as two decommissioned GEOs (Apstar-1A and Apstar-1), located at 130°E and 142°E, respectively. The master ground station of the CAPS prototype is located at Lintong in central China and hosts a total of six 7 m antennas for uplink and downlink to/from the geosynchronous satellites [10.89]. Four additional ground stations at Urumqi, Shanghai, Changchun, and Kunming provide the necessary measurements for orbit determination.

Each of the two carriers (C1 and C2) is modulated with two ranging signals namely a coarse-and-acquisition (C/A) with a 1.023 MHz chipping rate and an encrypted precise (P) code at 10.23 MHz [10.90, 96]. The CAPS navigation message is transmitted at a rate of 50 bps and comprises 44 frames with a length of 1500 bits.

Static and dynamic performance tests were performed in various regions throughout the China mainland. In addition to the actual navigation signals, barometric altimetry is employed as a virtual satellite. Following [10.87], horizontal positioning accuracies of 15–25 m and 5–10 m were achieved using the coarse and precise ranging signals, respectively, while the velocity accuracy attained values in the range of 0.1–0.3 m/s.

As of 2015, this system is used as a preliminary operational system, and a complete system with three GEO, three DGEO, and three IGSO is pursued.

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