

The principle of a navigation constellation composed of SIGSO communication satellites

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Abstract The Chinese Area Positioning System (CAPS), a navigation system based on geostationary orbit (GEO) communication satellites, was developed in 2002 by astronomers at Chinese Academy of Sciences. Extensive positioning experiments of CAPS have been performed since 2005. On the basis of CAPS, this paper studies the principle of a navigation constellation composed of slightly inclined geostationary orbit (SIGSO) communication satellites. SIGSO satellites are derived from GEO satellites which are near the end of their operational life by inclined orbit operation. Considering the abundant frequency resources of SIGSO satellites, multi-frequency observations could be conducted to enhance the precision of pseudorange measurements and ameliorate the positioning performance. A constellation composed of two GEO satellites and four SIGSO satellites with an inclination of 5° can provide service to most of the territory of China with a maximum position dilution of precision (PDOP) over 24 h of less than 42. With synthetic utilization of the truncated precise code and a physical augmentation factor in four frequencies, the navigation system with this constellation is expected to obtain comparable positioning performance to that of the coarse acquisition code of the Global Positioning System (GPS). When the new method of code-carrier phase combinations is adopted, the system has the potential to possess commensurate accuracy with the precise code in GPS. Additionally, the copious frequency resources can also be used to develop new anti-interference techniques and integrate navigation and communication.

Key words: astrometry and celestial mechanics — astronomy application — artificial satellite — satellite navigation constellation

1 INTRODUCTION

The Global Positioning System (GPS) of the US and the Global Navigation Satellite System (GLONASS) of Russia can provide position, velocity and time (PVT) services for users with global coverage and all-weather capacity. The Chinese system Compass has been extending its coverage and is scheduled to be a global satellite navigation system around 2020¹. The European Galileo is

¹ http://en.wikipedia.org/wiki/Beidou_navigation_system

in the initial phase at present and will launch positioning applications on a global scale as early as 2020². Several regional navigation systems have also emerged recently, such as the Quasi-Zenith Satellite System (QZSS) of Japan and the Indian Regional Navigational Satellite System (IRNSS). All of the above GPS-like systems require the launch of specific navigation satellites to constitute constellations. In 2002, a group of astronomers at Chinese Academy of Sciences (CAS) presented a new concept for navigation, to constitute a positioning system using geostationary orbit (GEO) communication satellites³, which is fundamentally different from the GPS-like systems in that navigation signals are generated on a ground station and then transmitted by transponders on communication satellites, while receivers decode the signals and achieve positioning, measurements of velocity and time, and communication.

Under the guidance of this pioneering idea, researchers organized by CAS successfully developed the Chinese Area Positioning System (CAPS). Compared to GPS-like systems, some advantages are introduced in CAPS: (1) the cost is much lower and the deployment cycle is notably shorter by resorting to available GEO satellites instead of launching specific navigation satellites; (b) a more accurate and reliable atomic clock can be employed to provide time reference as navigation signals are generated on the ground; (3) inherent communication functions of GEO satellites can be embedded in navigation applications to realize the integration of navigation and communication (Ai et al. 2008, 2009b; Shi et al. 2009b; Ma et al. 2012a). In 2005, a demonstration system of CAPS was tested in six cities in China, which successfully passed acceptance and adequately displayed the features of CAPS. CAPS was then included in the guidelines on the national medium- and long-term program for science and technology development (2006–2020) as an important part of the Chinese second generation satellite navigation system. Subsequent to the successful development of CAPS, the Boeing Company began to make use of the Iridium communication system to enhance GPS and carry out navigation-related applications in 2007⁴. The Iridium system consists of 66 operational satellites positioned in six Sun-synchronous orbital planes. It works in the L-band for voice data communications and offers much stronger signals received by users on the ground than GPS does because its satellites are in low orbits. These features enable the Iridium system to enhance GPS.

A constellation with only GEO satellites cannot achieve three-dimensional (3D) positioning because the satellites are located in a coplanar orbit over the equator. In the CAPS demonstration system, GEO satellites and a specific barometric altimeter were combined to realize altitude-aided 3D positioning (Ai et al. 2009a). In this paper, slightly inclined geostationary orbit (SIGSO) satellites are recommended to be deployed in the navigation system. Owing to various perturbations, orbital elements of a GEO satellite vary constantly (Ma et al. 2011b). The orbital position of the operational GEO satellite should be maintained at a certain precision. When a GEO satellite approaches the end of its life, inclined orbit operation is implemented to save propellant fuel and prolong its service life, which means the fuel is only consumed for east-west station-keeping and attitude control. Under inclined orbit operation, a GEO satellite near the end of its life in effect becomes a SIGSO satellite⁵. SIGSO satellites can make radical improvements to the geometric configuration of a navigation constellation by introducing north-south components and further enable the navigation system to offer 3D positioning services. Furthermore, by exploiting plentiful frequency resources of SIGSO satellites, positioning with high performance can be acquired, as well as the new anti-interference techniques and integration of navigation and communication (Shi et al. 2009a; Han et al. 2009; Cui et al. 2009; Ma et al. 2011a).

The principle of constituting a navigation constellation by employing SIGSO communication satellites is studied in this paper. Perturbations and SIGSO communication satellites are introduced

² http://en.wikipedia.org/wiki/Galileo_%28satellite_navigation%29

³ National Astronomical Observatories, CAS; National Time Service Center, CAS, Transponder satellite communication and positioning system, Ai, G. X., Shi, H. L., et al. PRC Patent, No. 200410046064.1, 2004

⁴ http://www.coherentnavigation.com/press/2007.04.11_ee_times.pdf

⁵ <http://www.satsig.net/satellite/inclined-orbit-operation.htm>

in Section 2. We establish observation equations for the system based on communication satellites and perform analyses of position dilution of precision (PDOP) values in Section 3. Section 4 gives an overview of the navigation performance. Finally, several issues are further investigated pertaining to the navigation system based on SIGSO satellites.

2 PERTURBATIONS AND SIGSO COMMUNICATION SATELLITES

2.1 Perturbations

A GEO satellite is subject to various perturbing forces, mainly arising from the Earth's nonspherical gravity, lunisolar gravitational force and solar radiation pressure. Due to the perturbations, motions of the satellite no longer follow the two-body dynamic equations and its inclination, orbital period, eccentricity and Right Ascension of the Ascending Node (RAAN) constantly change (Ma et al. 2011b).

Mass distribution in the Earth is uneven and its shape is also irregular. The polar radius is approximately 23 km shorter than the equatorial radius. The equatorial plane shows a slight oval shape (difference between semi-major axis and semi-minor axis is about 68 m). The GEO satellite consequently gravitates both in the tangent and normal directions of the orbit, and the magnitude depends on the satellite's position and distance from the Earth. The longitudes of the minor axis of the equator are at about 75°E and 105°W , which have a difference of 90° with that of the major axis. The Earth's equatorial ellipticity has a long-term accelerating effect on the longitude of the sub-satellite point. As points on the minor axis are stable and points on the major axis are unstable in a GEO, the equatorial ellipticity produces perturbations which cause the satellite to drift back and forth in an east-west direction around the points of the minor axis.

As revolution of the Earth is in the ecliptic plane, movements of a GEO satellite are related not only to gravity acting upon the satellite by the Earth, the Sun and the Moon, but also to gravity imposed on the Earth by the Sun and the Moon. Lunisolar gravitational force is the most important factor causing changes of inclination. Because the lunar orbit has an angle between $23.5^\circ \pm 5.1^\circ$ relative to the equatorial plane, the drift of the satellite's inclination varies every year and its value depends on the average value of the lunar orbit's inclination over a period of 18.6 years. The annual drift rate is from 0.75° to 0.95° , and its direction alters in different years as the pole of the lunar orbit changes. Since a SIGSO satellite does not have station-keeping in a north-south direction, the satellite's orbit rotates with a 52-year cycle, centered on a pole which has an angle of 7.5° with respect to the terrestrial pole. If the initial inclination of a SIGSO satellite is 0° , the inclination will reach the maximum value of about 15° after 26 years and then decrease annually.

The GEO satellite is also exposed to the Sun's radiation. One part of the radiation is absorbed and the other part is reflected. The conversion of energy involved is known as solar radiation pressure which is the largest non-gravitational perturbation on the satellite, and hence can have a significant influence on its orbital dynamics. Solar radiation pressure mainly affects orbital eccentricity. The movement of the eccentricity vector relies on the area-to-mass ratio of the satellite and the endpoint of the vector forms an ellipse with a period of one year.

2.2 SIGSO Communication Satellites

Because of the above perturbations, a GEO communication satellite continuously drifts. An operational GEO satellite must be kept in a control box in order to meet the requirements of anti-interference and isolation with adjacent communication satellites. A GEO satellite therefore always carries propellant fuel which is consumed to conduct attitude control, and produce east-west velocity corrections to the nonspherical gravity and the solar radiation pressure, as well as the north-south velocity increment for the lunisolar perturbation.

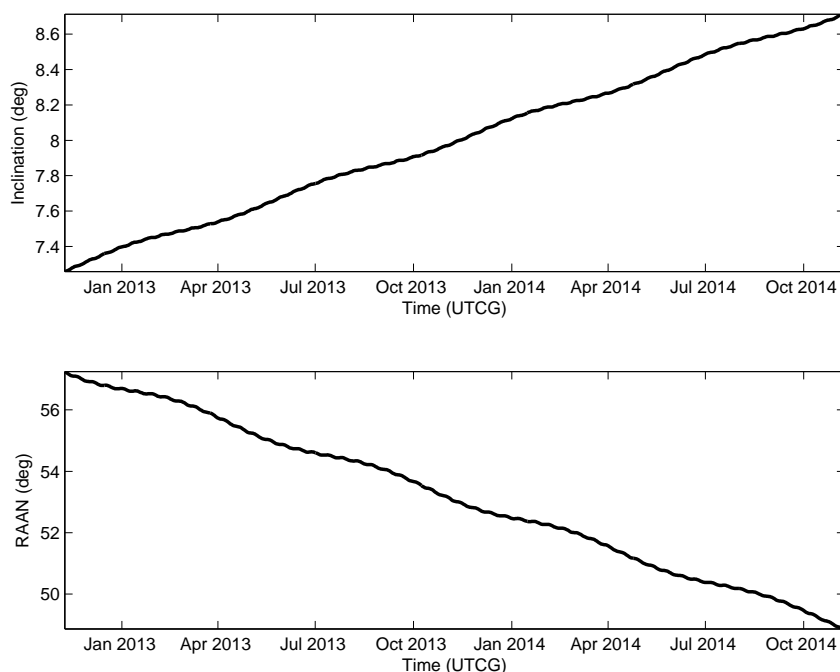


Fig. 1 Orbital evolution of a SIGSO satellite under perturbations (Ma et al. 2011b).

Most of the fuel on a GEO satellite is expended to maneuver its position to correct disturbances in the north-south direction. As each satellite carries a restricted quantity of fuel, the satellite will come close to the end of its life after some years of operation. Generally, the design life has a certain redundancy, so the solar battery and signal transponders on a GEO satellite near the end of its operational life can still maintain service for several years. When attitude control and east-west maneuvering of an end-of-life GEO satellite are still maintained, the satellite in fact becomes a SIGSO satellite. Since the fuel is no longer used for maintaining the orbital position in a north-south direction, and only a small portion is needed for east-west station-keeping and attitude control, the remaining lifetime of a SIGSO satellite can be greatly extended before being placed into a graveyard orbit (Shi et al. 2009a; Ma 2011). This technique of maneuvering end-of-life GEO satellites to SIGSO satellites is known as an inclined orbit operation.

The evolution of inclination and the RAAN of a certain SIGSO satellite are illustrated in Figure 1. Further studies reveal that phase differences (time differences passing the equatorial plane) of two SIGSO satellites are determined by their differences in RAAN and differences in longitude of the sub-satellite point. Seeing that SIGSO satellites follow the same evolution of inclination and RAAN, the phase differences are mainly determined by the differences in longitude of the sub-satellite point.

2.3 Advantages and Applications of SIGSO Communication Satellites

The cost of renting or purchasing end-of-life GEO satellites and then maneuvering them to become SIGSO satellites is obviously lower than that of developing and launching new satellites. By deploying SIGSO satellites, one can reduce the period and the expense of constructing a navigation system, and make communication satellites play an important role in navigation and communication appli-

cations. As SIGSO satellites have figure-8 ground tracks and accordingly can effectively improve the geometric configuration by introducing north-south components, a navigation system deploying a certain number of SIGSO satellites can provide 3D positioning services.

Due to the plentiful frequency resources of SIGSO satellites, multi-frequency observations can be performed to achieve pseudorange measurements with centimeter precision and to augment positioning accuracy. Since there are transponders covering almost the whole C-band on SIGSO satellites, frequency-switching techniques can be carried out to reinforce anti-interference ability. Because each SIGSO communication satellite has a frequency band up to 300 MHz or more, information transmission service based on position, time and status can be provided in addition to the positioning service. Moreover, SIGSO satellites can preserve precious GEO resources (Shi et al. 2009a).

3 OBSERVATION EQUATIONS AND PDOP ANALYSES FOR THE CONSTELLATION BASED ON SIGSO COMMUNICATION SATELLITES

3.1 Observation Equations

In a navigation system based on communication satellites, navigation signals are generated on a ground station and transmitted via satellite transponders to users. Using the virtual clock technique, generation time of navigation signals can be converted to transmission time at the satellite antenna's phase center (Li et al. 2009a). To obtain three positions and clock bias, at least four satellites should be simultaneously observed by users. The pseudorange observation equation based on the code phase from the i th satellite can be modeled as

$$\rho^i = r^i + I_\rho^i + T_\rho^i + c \cdot \delta t_u + c \cdot \tau_{\text{VCLK}}^i + M_\rho^i + \epsilon_\rho^i, \tag{1}$$

where $i = 1, 2, \dots, M$, and M is the number of observed satellites; ρ_i denotes the pseudorange from the antenna phase center on the ground station to the antenna phase center of the receiver; r^i is the geometric distance between the receiver antenna's phase center at signal reception time and the satellite antenna's phase center at signal transmission time; I_ρ^i and T_ρ^i are the ionospheric and tropospheric propagation delays, respectively; c is the speed of light; δt_u is the receiver clock offset; τ_{VCLK}^i stands for the virtual clock parameter, which is broadcasted in the navigation messages; M_ρ^i and ϵ_ρ^i account for multipath effects and measured errors, respectively. We denote by ρ_c^i the pseudorange obtained after modifying the virtual clock and propagation delays, and compensating for the multipath effects in the measurements. Equation (1) is then rewritten as

$$\rho_c^i = r^i + c \cdot \delta t_u + \epsilon_\rho^i. \tag{2}$$

To characterize the quality of the positioning estimates, the model for the measurement error in Equation (2) is simplified as (Misra & Enge 2006)

$$E(\epsilon_\rho) = 0, \text{Cov}(\epsilon_\rho) = \sigma^2 I, \tag{3}$$

where $E(\cdot)$ represents the mean value, $\text{Cov}(\cdot)$ denotes covariance, I is the identity matrix, and σ is the common standard deviation of the user range error for each of the visible satellites. Let Δx and Δb denote the estimates of position and clock bias in the local east-north-up (ENU) coordinate frame respectively, then the covariance matrix can be written as

$$\text{Cov} \begin{bmatrix} \Delta x \\ \Delta b \end{bmatrix} = \sigma^2 [G^T G]^{-1} = \sigma^2 H, \tag{4}$$

where $H = (G^T G)^{-1}$; G is an $M \times 4$ matrix with each row composed of three elements of direction cosine vectors represented in the ENU coordinate frame, and an entry of 1 in the last column. The

Dilution of Precision (DOP) parameters are defined as (Misra & Enge 2006)

$$\text{Geometric DOP (GDOP)} = \sqrt{H_{11} + H_{22} + H_{33} + H_{44}}, \quad (5a)$$

$$\text{Position DOP (PDOP)} = \sqrt{H_{11} + H_{22} + H_{33}}, \quad (5b)$$

$$\text{Horizontal DOP (HDOP)} = \sqrt{H_{11} + H_{22}}, \quad (5c)$$

$$\text{Vertical DOP (VDOP)} = \sqrt{H_{33}}, \quad (5d)$$

$$\text{Time DOP (TDOP)} = \sqrt{H_{44}}. \quad (5e)$$

The DOP parameters provide a simple characterization of the geometric configuration of the constellation. The positioning error mainly depends upon the measurement geometry and pseudorange measurement error. The quality of the estimates can be described as (Kaplan & Hegarty 2006)

$$\sigma_j = (\text{DOP})_j \cdot \sigma, \quad (6)$$

where $(\text{DOP})_j$ designates GDOP, PDOP, HDOP, VDOP or TDOP; σ_j is the corresponding estimation errors. It is more common to investigate the PDOP distributions, since the quality of 3D position estimates generally receives extra attention from users.

3.2 PDOP Analyses

Considering that the coverage of the constellation based on SIGSO satellites has a north-south symmetry, regions of China are taken as an example to investigate the constellation configuration. Ten cities in China, which could be considered as several representative stations in a geographical distribution, are then selected to analyze PDOP distributions. Daily PDOP distributions in the ten cities are computed using two GEO satellites situated at 87.5°E and 110.5°E and four SIGSO satellites at 59°E, 71.7°E, 125°E and 142°E respectively. All six satellites are controlled by stations within mainland China. In the simulation, we presume that navigation signals can be continuously uplinked to these communication satellites. Inclination of the four SIGSO satellites is assumed to be 5° and the elevation mask angle is 10°. The PDOP values are computed one minute apart over a 24-hour period and presented in Table 1.

To give a comparison with GPS, the daily distributions of PDOP for the constellation of six satellites and the constellation of GPS observed from Beijing, Taipei, Kunming and Kashgar are shown in Figure 2.

It can be noted from Table 1 that the maximum PDOP value over 24 h for all of the stations is below 42. Moreover, the PDOP values will get better and better because inclination angles of the SIGSO satellites constantly increase as time goes on.

Table 1 Daily Distributions of PDOP for the Ten Cities

City	Latitude	Longitude	PDOP		
			max	min	mean
Beijing	39.90°N	116.47°E	38.3	15.3	23.1
Shanghai	31.20°N	121.43°E	37.7	15.2	22.7
Changchun	43.89°N	125.31°E	40.9	15.5	24.7
Taipei	25.05°N	121.51°E	37.3	15.1	22.5
Sanya	18.20°N	109.50°E	36.5	14.9	22.1
Kunming	25.05°N	102.70°E	36.8	14.9	22.3
Lhasa	29.66°N	91.13°E	37.1	15.1	22.6
Kashgar	39.45°N	75.98°E	41.3	15.5	25.6
Urumchi	43.77°N	87.60°E	38.4	15.5	23.3
Xi'an	34.25°N	108.92°E	37.6	15.2	22.7

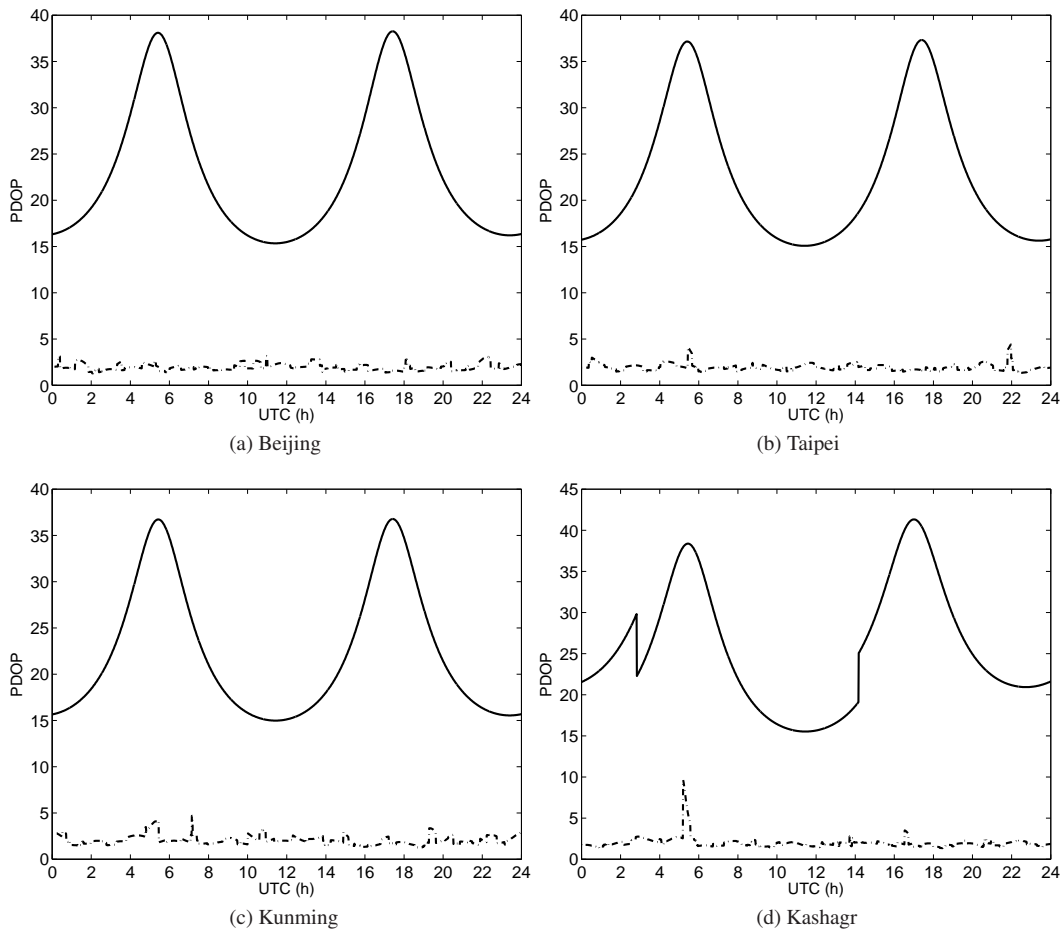


Fig. 2 Daily distributions of PDOP for the four stations. *Solid line*: constellation based on SIGSO satellites, *Dash-dotted line*: constellation of GPS.

4 AN OVERVIEW OF POSITIONING PERFORMANCE

4.1 Multi-frequency Observations

Considering the profuse frequency resources of SIGSO communication satellites, Ai et al. (2011) proposed a new method of code-carrier phase combinations. In the new method, three frequencies are selected to structure linear combinations of code phase and carrier phase. As positive linear combinations and negative linear combinations both have ionospheric terms with approximately the same magnitude but opposite sign, integer ambiguity can be fixed fast, and ionospheric delays can be quickly corrected due to their large differences between the two selected carrier phase combinations (Ai et al. 2011). The new approach of code-carrier phase combinations possesses the high dynamics of code phase measurements as well as the high precision of carrier phase measurements. To further take advantage of the plentiful frequency resources of SIGSO satellites, navigation signals are transmitted at multiple frequencies from each satellite and users independently measure the cor-

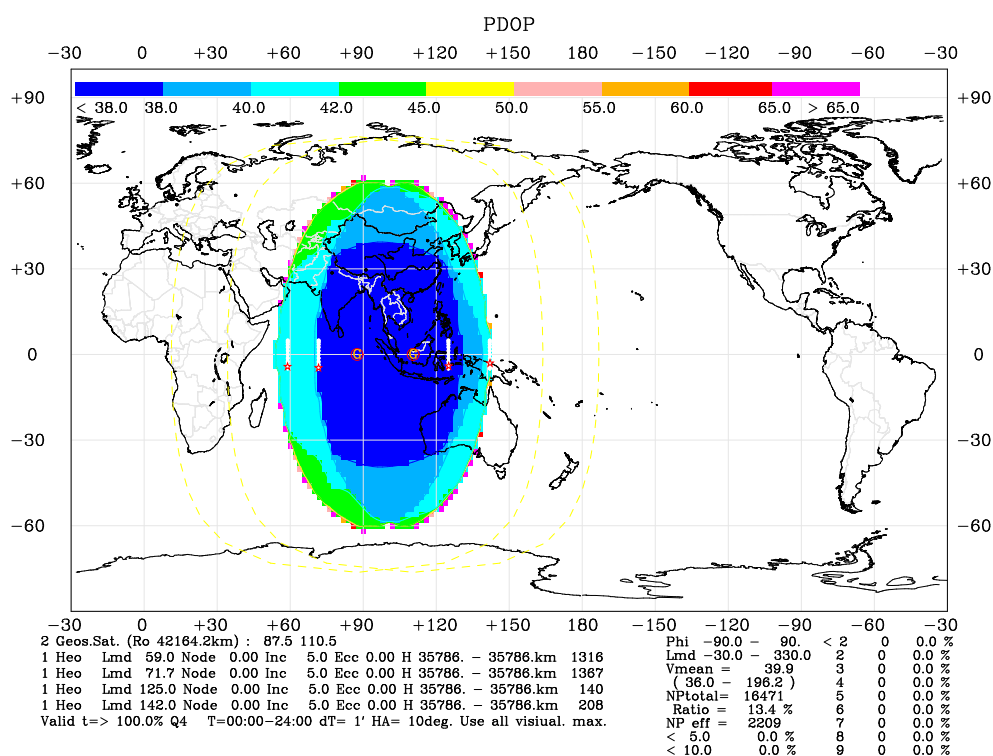


Fig. 3 The global distribution of maximum PDOP value over 24 h.

responding multiple pseudoranges, which can significantly enhance the positioning accuracy. This method is referred to as Physical Augmentation Factor of Precision (PAFP)⁶ (Ai et al. 2012).

4.2 Performance Evaluation

The above analyses suggest that positioning accuracy rests on geometric DOP and physical PAFP, and pseudorange measurement accuracy.

The global distribution of maximum PDOP value over 24 h for the constellation with the two GEO satellites and four SIGSO satellites is illustrated in Figure 3. As for China, more than 95% of the area can gain a maximum PDOP value smaller than 42 over 24 h. The constellation provides 92% of the area with an average PDOP value below 25. The minimum PDOP value in 95% of the area is less than 16.

The combined effect of error sources in pseudorange measurement is referred to as the user equivalent range error (UERE). It is reasonable to model these errors due to the satellite clock and ephemeris, atmospheric propagation, multipath, and receiver noise as being uncorrelated, and then the UERE can be defined as the root-sum-square of these components (Misra & Enge 2006). Using the transmitted orbit determination method, an accuracy of about 1.0 m in orbit determination could be obtained (Li et al. 2009a,b). As the first-order ionospheric effect is inversely proportional to the square of the carrier frequency, the ionospheric effect in the C-band navigation system based on SIGSO satellites is much less than in GPS. For tropospheric correction, it is suggested to establish

⁶ National Astronomical Observatories, CAS, A method of improving positioning precision in satellite navigation systems, Ai, G. X., Ma, L. H., Shi, H. L., Ji, H. F., PRC Patent, No. 201210090864.8, 2012

observation stations on grid points over a large area to collect atmospheric pressure, temperature and humidity. These actual atmospheric parameters could be used to construct a time-variable tropospheric delay model (Ai et al. 2011). The root-mean-square (rms) residual error attributed to atmospheric propagation models is then assumed to be 0.5 m. The truncated precise (TP) code with a period of one millisecond and a chip rate of 10.23 Mcps is adopted in the navigation system based on SIGSO communication satellites. The TP code, having a similar signal structure to GPS precise (P) code, is almost ten times more precise than the coarse acquisition (C/A) code in GPS, so the rms range error due to receiver noise and multipath is assumed to be 0.5 m. The UERE in the navigation system based on SIGSO satellites is about 1.2 m.

If the TP code is utilized to measure pseudoranges, and PAFP in the case of four frequencies is used to reduce PDOP twice, the system with the previous constellation can be expected to have a matching performance with that of GPS C/A code by combining the transmitted orbit determination method, the virtual clock technique and high-accuracy corrections of tropospheric delays and multipath effects (Li et al. 2009a,b; Cheng et al. 2012). The more the frequencies are used by SIGSO satellites to transmit navigation signals, the greater the improvement in PDOP values and accordingly the better the positioning performance. When the new method of code-carrier phase combinations is adopted, the system even has the capability to provide equivalent positioning accuracy as P code in GPS.

5 CONCLUSIONS

Due to a variety of perturbations, GEO communication satellites near the end of their operational life will drift to become SIGSO satellites under inclined orbit operation. SIGSO satellites are favorable for being deployed in a constellation to achieve 3D positioning. When SIGSO satellites have relatively large inclination angles (e.g., 5°) and four-frequency PAFP is enforced, the system composed of SIGSO communication satellites is capable of obtaining approximately equal positioning performance with C/A code in GPS. If the new method of code-carrier phase combinations with three frequencies is further employed, the positioning accuracy will be remarkably enhanced and would be as good as that of GPS P code.

6 DISCUSSION

6.1 Contributions of IGSO Satellites to Constellation Configuration

In the navigation system based on SIGSO communication satellites, if several inclined geosynchronous orbit (IGSO) satellites are launched, the configuration will be greatly improved. One IGSO satellite is not adequate to obtain a satisfactory improvement in PDOP for the reason that users at higher latitudes will fail to receive signals when the satellite is in the other hemisphere (Ma et al. 2011a). We then adopt a configuration of three IGSO satellites, with an inclination of, for instance, 55° and cross node of 118°E , and the six previous satellites to assess the contributions of IGSO satellites. The amelioration of PDOP values contributed by the three IGSO satellites is noticeable. Ninety-three percent of the area in China can get a maximum PDOP value over 24 h of less than 6.2 and that fraction of the area obtains an average PDOP value below 4.8. The minimum PDOP value in 95% of the area is smaller than 3.5. The global distribution of maximum PDOP value over 24 h is shown in Figure 4.

However, it should be pointed out that when only four satellites are observable, the PDOP value is inversely proportional to the volume of a tetrahedron described by unit vectors from the receiver to each of the four satellites. If endpoints of the four unit vectors are nearly coplanar, the PDOP value is infinitely large. For the constellation with three IGSO satellites and one GEO satellite, there are several time intervals in a day when the volume of the tetrahedron is close to zero and a continuous 24-hour 3D positioning is thus not achievable. Further details can be found in Ma et al. (2012b).

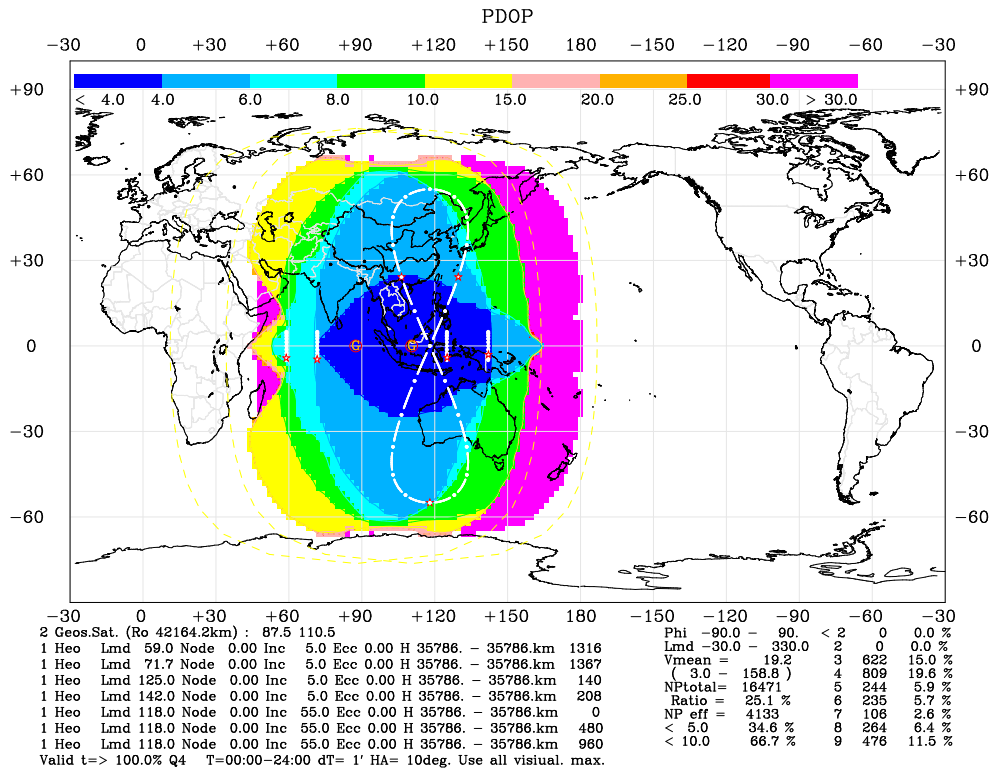


Fig. 4 The global distribution of maximum PDOP value over 24 h with three IGSO satellites.

6.2 New Techniques for Coping with Interference

Interference is one of the greatest technical challenges that satellite navigation systems face. The received signal power is lower than natural noise contained in the bandwidth. If artificial interference is added to natural noise, then the situation quickly becomes bleak (Kaplan & Hegarty 2006; Misra & Enge 2006).

Navigation frequencies are commonly set when the system is designed and as a consequence there is no margin for switching frequencies in applications. As for a navigation system based on SIGSO communication satellites, all C-band frequencies are available for navigation. New techniques such as frequency-switching, code-switching and satellite-switching can therefore be employed to enhance anti-interference performance. Frequency-switching only requires the corresponding change of receiving frequency when uplink frequency on the ground station is altered. In a code-switching technique, the receiver backs up several optional codes and applies the code adopted in the navigation signal to track the signal and demodulate messages. To utilize a satellite-switching technique, the ground station redirects antennas to other satellites and uplinks navigation signals, while users receive the transmitted signals to accomplish positioning.

6.3 Integration of Navigation and Communication

Besides PVT services, the transmission of position and time information is provided in the system based on SIGSO communication satellites. A satellite link budget, as an elemental optimized de-

sign, trades off various attenuation and gains in transmission links. It involves system capability and reliability, as well as investment in the ground station. Navigation transmission link includes both uplink and downlink, and downlink power is limited. An optimal design is requisite in order to guarantee successful reception and demodulation of navigation signals. A communication transmission link deserves more careful treatment as power is limited in two-way links. In addition, many system parameters should also conform to the International Telecommunication Union (ITU) requirements (Cui et al. 2009).

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