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Beyond life-cycle utilization of geostationary communication satellites in end-of-life

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1. Introduction

In 2002, we proposed an idea that carrier signals with ranging codes and navigation data from ground navigation master station are transmitted in transponders of geostationary (GEO) communication satellites and then ground users receive those signals and realize passive navigation. In 2003 we began to lease transponders of GEO communication satellites to carry out experimental verification, and a success was achieved in 2005^[11, 12].

The most challenging problem in the verification is that all rental GEO communication satellites are located in GEO orbit and therefore three dimensional positioning is impossible. To improve geometric configuration of satellites constellation and positioning precision, we hope that several inclined geosynchronous orbit (IGSO) satellites can be adopted except for GEO satellites to constitute the constellation. Considering the long designing period of IGSO satellite, a concept that we try to utilize IGSO satellites was proposed. Unfortunately, those efforts are in vain, and therefore we proposed the concept turning GEO communication satellites in end-of-life to IGSO by regulation.

Communication satellites running in GEO orbit with altitude of 35786 km above equator are maintained in fixed track with up to about ± 0.1 degree precision and some even with better than about ± 0.05 degree precision. However, because of the perturbation from other celestial bodies, the position of GEO satellites are changing relative to the Earth, and the drift of satellite's fixed position relative to the equator are constantly increasing and even exceeds more than the ITU fixed-point drift value. In order to control the satellite's drift, we must adjust the satellite's orbital position and attitude, which will inevitably consume fuel, when fuel in the satellite is consuming step by step, the satellite's service life will come to end. We call such a geostationary communications satellite "late-life" or "end-life" GEO satellite. In fact, the life of satellite's solar battery and signal transponders has a certain redundancy and it can still work for many years, just because the remaining fuel in satellite has almost run out, this satellite with heavily investment in the process of development and launch has to been abandoned. To ensure custom's business is not interrupted, satellites company must launch a new satellite to replace the GEO communication satellite in end-of-life. According to the IADC's suggestion on retiring GEO communication satellites, the satellite solar power

and related equipment have to be closed and satellite's must be pulled up about 200 ~ 300 km to the grave orbit and then those retired satellites become space junk^[14, 15].

According to IADC's monitoring, there have been approximately more than a thousand satellites in the vicinity of GEO orbit within about 60 km, but only about 300 satellites work normally^[16]. Increasing space junks seriously affect the space environment, especially the valuable space environment near the equatorial orbit. How to extend the life of the satellite in orbit and thereby turning waste into wealth has become one of important topics for space technology researchers.

To this end, according to concept of modern design and advanced manufacturing technology, we explored the issue of reusing satellite in end-of-life^[1, 9, 13]. Specifically, with use of remaining fuel resources in retired satellites in end-of-life, gradually turning GEO satellite in end-of-life to slightly inclined geostationary orbit (SIGSO) satellite by control of satellite attitude. Utilizing those SIGSO satellites to constitute a new navigation and positioning constellation is for the purpose of improving the navigation and positioning accuracy of the transmitting satellite navigation system. In addition, the abundant transponders resources in those satellite can also be used to carry out satellite communication business or open up new satellite communication services, that is to say, it is possible to develop a second life-cycle of the satellite in end-of-life.

2. Orbital dynamic analysis of GEO communication satellite orbit

In order to explore the issue of reusing the GEO satellite in end-of life, we must thoroughly understand and analyze the dynamic theory of GEO satellite^[34].

2.1 Description of GEO orbit

GEO is a special orbit, on which the satellites rotating around the Earth has the same rotation cycle with Earth's rotation period and its nadir position in the Earth's surface should be fixed. Generally speaking, GEO has the following three characteristics:

- (1) the shape of orbit is circular, eccentricity $e = 0$;
- (2) orbit is located in the Earth equatorial plane, the inclination $i = 0$;
- (3) orbit's spin cycle is same with the earth rotation cycle, $T = 2\pi / \omega_e = 23$ hours 56 minutes 4.1 seconds; the orbit altitude is 35786 km, or semi-major axis $a = 42164$ km, where ω_e is for the Earth's rotation angular velocity.

However, due to the Earth's non-spherical gravity, moon and sun gravitational perturbation and solar light pressure, satellite orbit elements (including a , e , i) are constantly changing and deviating from the fixed location of the satellite.

2.2 The relationship between deviation of satellite orbital elements and drift

Semi-major axis deviation causes long-term east-west direction drift, At t time, sub-satellite point longitude λ is:

$$\lambda = \arctan(\cos i \tan u) + \Omega - \omega_e(t - t_0) - s_{g0} \quad (2.1)$$

Where, s_{g0} is GMT at t_0 time; u is satellite longitude argument, $u = \omega + f$, namely the angle between satellite and ascending node; ω is perigee argument, namely the angle between orbit ascending node and perigee; ω is true anomaly, that is, angle between satellite and perigee; Ω is RAAN, namely angle between ascending node and the equinox.

When $i = 0$, $e = 0$, we have $f = M$, at t time, sub-satellite point longitude is:

$$\lambda = \omega + M + \Omega - \omega_e(t - t_0) - s_{g0} = \omega + M_0 + n_e(t - t_0) + \Omega - \omega_e(t - t_0) - s_{g0} \quad (2.2)$$

In initial time t_0 , satellite longitude λ_0 is

$$\lambda_0 = \omega + M_0 + \Omega - s_{g0} \quad (2.3)$$

And then can be simplified as

$$\lambda = n_e(t - t_0) - \omega_e(t - t_0) + \lambda_0 \quad (2.4)$$

When semi-major axis a has no error, we have

$$n = \omega_e \quad (2.5)$$

$$\lambda \equiv \lambda_0 \quad (2.6)$$

And when semi-major axis has error, there is

$$\Delta n = -\frac{3}{2}n_e \frac{\Delta a}{a} \quad (2.7)$$

Therefore, when a has deviation Δa , satellite drift in east-west direction is

$$\dot{\lambda} = -0.012806 \cdot \Delta a \text{ (}^\circ/\text{day)} \quad (2.8)$$

When $\Delta a > 0$, $\dot{\lambda} < 0$, satellite drifts to west; when $\Delta a < 0$, $\dot{\lambda} > 0$ satellite drifts to east.

2.3 Oscillation in east-west direction caused by eccentricity deviation

The instantaneous sub-satellite point longitude can be denoted as:

$$\lambda = \lambda_0 + 2e \cdot \sin M \quad (2.9)$$

where λ_0 is central point longitude, M is mean anomaly; when $e \neq 0$, satellite swings periodically around the center of λ_0 , the largest Oscillation argument is $2e(\text{rad})$, Oscillation cycle is equal to satellite orbit period.

2.4 Oscillation in north-south and east-west direction caused by Orbit inclination deviation

When $\Delta a = 0, e = 0$, if satellite orbital plane deviates from the earth equator, namely there is deviation Δi .

Satellite geocentric longitude is

$$\sin \phi = \sin \Delta i \sin u \quad (2.10)$$

While Δi is small, then

$$\phi = \Delta i \sin u \quad (2.11)$$

The former equation indicates that when $\Delta i \neq 0$, satellite swings in latitude direction with the period of one day, and the argument in south-north direction is i . u is latitudinal argument, with the range from 0° to 360° in one day. When inclination is not zero, satellite will have oscillation both in south-north direction and east-west direction, and now sub-satellite point longitude is

$$\lambda = \arctan(\tan u) - \frac{i^2}{4} \sin 2u + \Omega - \omega_e(t - t_0) - s_{g0} = \lambda_0 - \frac{i^2}{4} \sin 2u \quad (2.12)$$

The former formulation denotes: when the inclination is not zero, satellite has oscillation with a half-day period in longitude direction, and argument of oscillation is $i^2 / 4$, the track of sub-satellite point has "8" shape which is shown in figure 2.1.

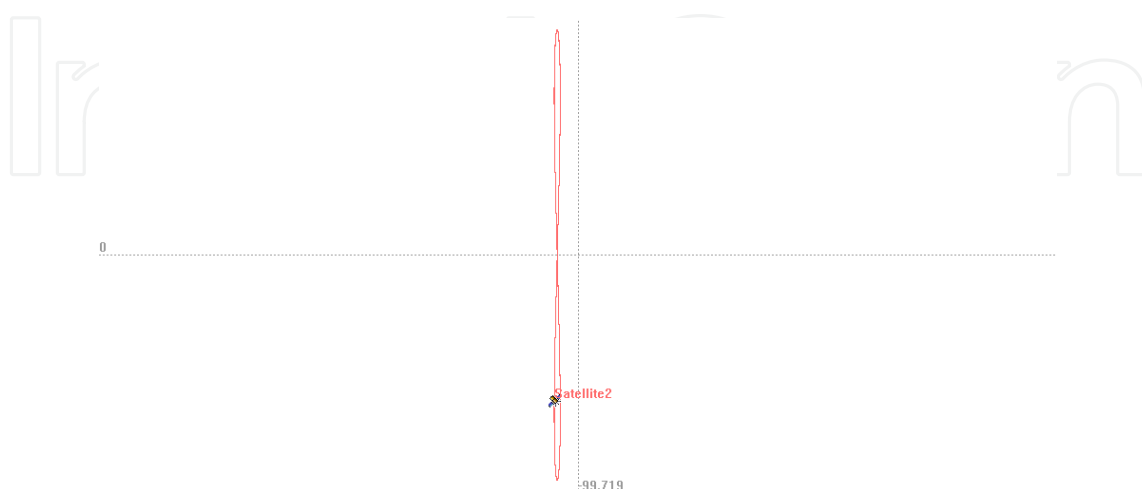


Fig. 2.1 Diagram of sub-satellite point "8" shape due to the change of GEO satellite orbital inclination

Due to various perturbations, GEO satellite position relative to Earth is not absolutely static, in the actual project implementation; it needs to continually and periodically modify its orbit^[34, 35], restricting its motion in a small area around its specified location. Figure 2.2 shows that of Canada Anik-C3 satellite still has typical latitude and longitude changes after position maintenance^[7].

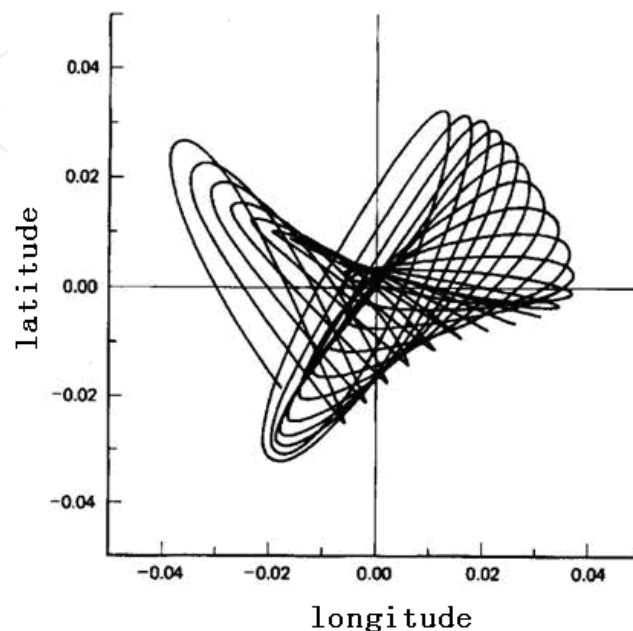


Fig. 2.2 Typical track of GEO satellite's sub-satellite point

2.5 GEO satellite orbit perturbations

GEO satellites are subject to various perturbations, including: additional gravitational force caused by non-spherical shape and the uneven quality of the earth, the sun and the moon's gravity and solar radiation pressure. Under the perturbations, satellite orbit no longer follows the two-body orbital motion law, the period, eccentricity, RAAN and inclination are constantly changing, and thereby causing satellite orbit drift. The details of these perturbations are as follows:

- 1) Earth's non-spherical gravitational perturbation
Earth's non-spherical gravity will mainly cause changes in sub-satellite point longitude; especially Earth's equatorial ellipticity has a long-term accelerating effect on sub-satellite point longitude. The difference between semi-major axis and semi-minor axis is about 68 meters, the short axis pointed at west longitude 75 degrees and west longitude 105 degrees, the long axis point and short point axis has a 90 degrees in longitude direction. As in the geostationary orbit, semi-minor axis point is stable and the semi-major axis point is not, so the equatorial ellipticity will bring about perturbation which will cause the satellite drift back and forth near the center of semi-minor axis point in east-west direction.

Considering the first 4-order harmonic field perturbation primarily, the average longitude perturbing acceleration can be described as follows^[39]:

$$\ddot{\lambda} = 0.00168 \sin 2(\lambda - \lambda_{22}) - 7.79 \times 10^{-5} \sin(\lambda - \lambda_{31}) + 2.34 \times 10^{-4} \sin 3(\lambda - \lambda_{33}) - 8.95 \times 10^{-6} \sin 2(\lambda - \lambda_{42}) + 1.14 \times 10^{-5} \sin 4(\lambda - \lambda_{44})^\circ / d^2 \tag{2.13}$$

Where λ_{lm} is defined as phase longitude^[40], data of λ_{lm} is presented in Table 2.1

Table 2.1 Data table^[51] for λ_{lm}

λ_{22}	λ_{31}	λ_{33}	λ_{42}	λ_{44}
-14.91°	7.0°	21.1°	31.2°	30.65°

In the east longitude 0° ~ 180°, the average longitude perturbing acceleration caused by the Earth's gravitational perturbation is shown in Figure 2.3. As can be seen from the diagram, average longitude drift acceleration reaches the maximum value of about -0.00197° / day² near east longitude 118° and equals to zero in the vicinity of east longitude 75° and 165°.

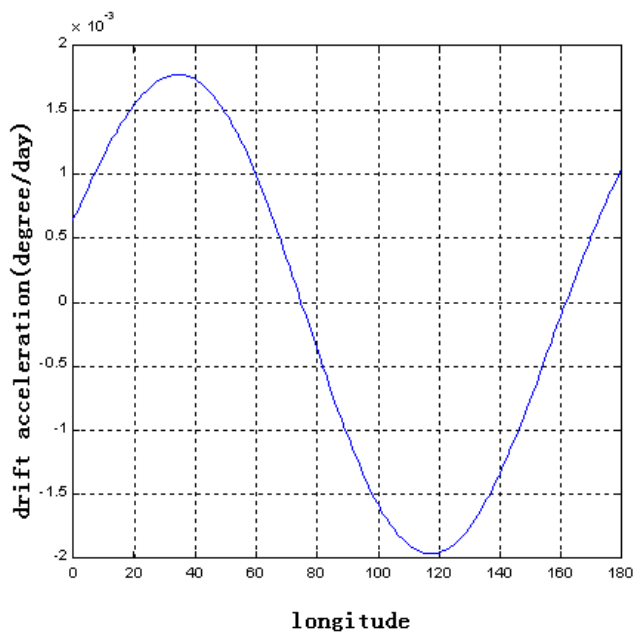


Fig. 2.3 Mean longitude perturbing acceleration caused by the Earth's gravitational perturbation

- 2) The sun light pressure perturbation
Sun light pressure perturbation mainly affects eccentricity of geostationary satellites orbit. Eccentricity vector components is defined as:

$$e_x = e \cos(\Omega + \omega) \tag{2.14}$$

$$e_y = e \sin(\Omega + \omega) \tag{2.15}$$

where Ω is RAAN, ω is perigee argument.

The trajectory of eccentricity vector Endpoint forms an ellipse with one-year cycle, its semi-major axis and semi-minor axis are as follows:

$$a_e = 0.0114 \frac{A}{m}$$

(2.16)

$$b_e = 0.0105 \frac{A}{m}$$

(2.17)

Where A is surface area of satellite, m is satellite quality. The eccentricity vector caused by visible sun light pressure is mainly depends on the ratio of surface area to mass. Figure 2.4 shows the changes of eccentricity vector curve caused by various factors in one year. The value of eccentricity equals the distance between the point in the figure and the origin, the size of large circular curve mainly caused by the pressure of sunlight, large wavy lines caused by the lunar gravity, and small zigzag line is derived from several factors such as the Earth's gravity, solar gravity, and lunar gravity.

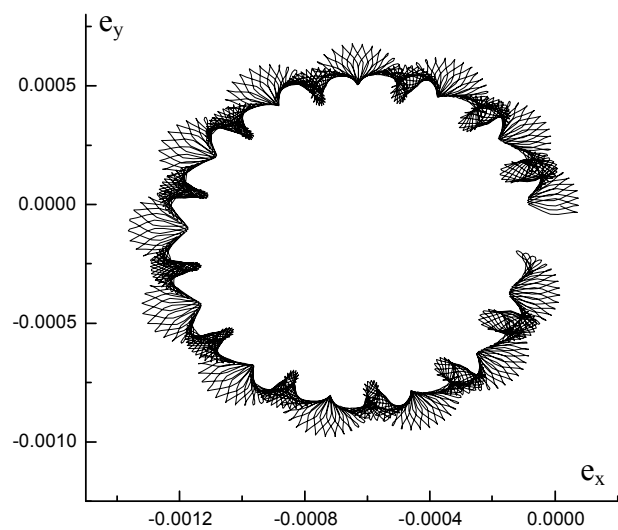


Fig. 2.4 Various perturbations’ affects on eccentricity in one year

- 3)
- Sun and Moon gravitational perturbation
- Sun and Moon gravitational perturbation is most important factor causing the changes of GEO orbit inclination. Orbital inclination vector (or orbital polar) is defined as the unit vector for the normal direction of orbital plane. Under the combined effect of gravity field J_2 items of the sun, the lunar and the earth (the earth with harmonic coefficients), the normal direction has gradually deviated from the Arctic. Orbital normal direction generally rotates around a certain direction which is in the Arctic pole plane and ecliptic pole plane, between the ecliptic pole and the Arctic pole, and has an angle of about 7.5° from Arctic pole. With a 52 years cycle, orbital inclination reached its maximum value of about 15° in about 26 years and back to zero 52 years later which means normal direction meets Arctic Pole again.

As the lunar orbit has an angle between $23.5^\circ \pm 5.14^\circ$ relative to equatorial plane, the drift of satellite's inclination is changing every year, the specific value of which depends on the 18.6-year -cycle average value of lunar orbit inclination. Drift rate ranges from $0.7^\circ / \text{year}$ to $0.95^\circ / \text{years}$ and its direction varies in different years as the lunar orbit pole varies. The most maximum value of drift occurred in 2006, the lunar orbit inclination reached maximum value at the same time.

Figure 2.5 is two-dimensional inclination vector diagram for the satellite, the moon and the sun. As can be seen from the figure, the angle between terrestrial pole and the ecliptic pole is 23.5° , the angle between the lunar orbital pole and ecliptic pole was 5.14° . Lunar orbital plane is not fixed, its orbital pole regress around ecliptic pole with a period of 18.6 years. If we don't maintain satellite position in north-south direction, the satellite's orbit rotates around the pole which has a 7.5° angle with terrestrial pole and a period of about 52 years. If the initial orbit inclination satellite is 0° , the orbital inclination will reach the maximum value of about 15° and then gradually decreasing with year.

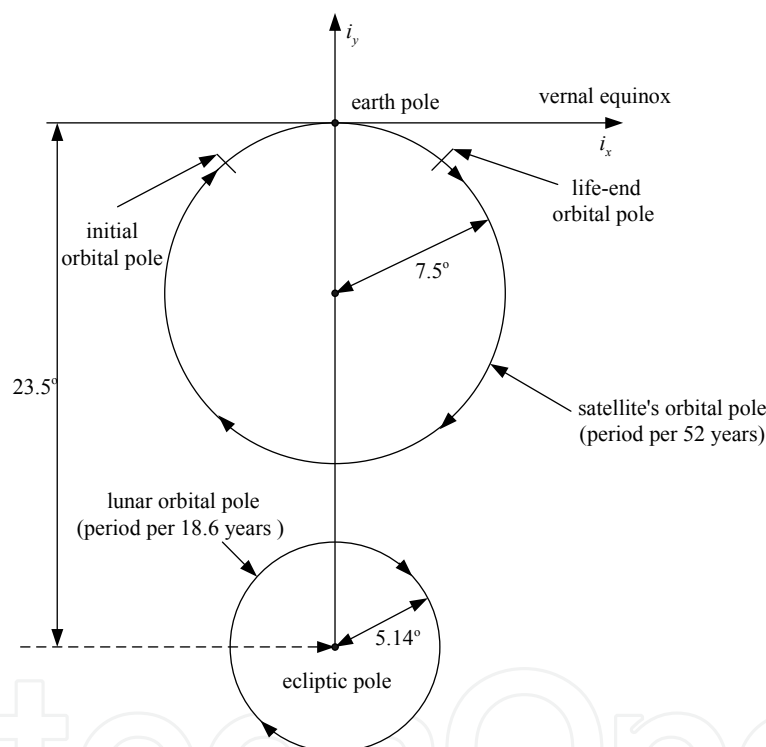


Fig. 2.5 Two dimensional diagram of GEO satellite orbit, moon's path and ecliptic

The effects on inclination vector caused by solar gravity, lunar gravity and the Earth's non-spherical gravitational perturbations vector can be defined as

$$i_x = \sin i \cos \Omega \quad (2.18)$$

$$i_y = \sin i \sin \Omega \quad (2.19)$$

Lagrangian perturbation equation defined with i is as follows^[40]:

$$\begin{aligned}\frac{di_x}{dt} &= -n_e(5.21i_y - 0.099\sin\Omega_m)\times 10^{-5} \text{ rad / s} \\ \frac{di_y}{dt} &= n_e(-4.93 i_x + 0.074\cos\Omega_m + 0.648)\times 10^{-5} \text{ rad / s}\end{aligned}\tag{2.20}$$

Where n_e is the average angular velocity of the earth’s rotation, namely:

$$n_e = \sqrt{\frac{Gm_e}{r_e^3}}\tag{2.21}$$

Here Ω_m is ecliptic longitude of ascending node of lunar orbit. Based on AGI's STK, the following Table 2.2 and Table 2.3 gives the changes of i and Ω for the perturbed geostationary orbit in the situation of different RAAN, with the initial inclination 0.1° and 0.5° .

Table 2.2 Changes of orbit in varied RAAN (Ω) with initial inclination 0.1°

Ω		3 monthes	6 monthes	1 years	2 years	3 years	4 years
0°	i	0.266	0.58	1.04	1.89	2.82	3.79
	Ω	80.45	82.35	84.6	82.86	79.4	75.1
45°	i	0.334	0.65	1.02	1.97	2.91	3.86
	Ω	87.07	85.36	86.3	83.54	79.6	75.26
90°	i	0.368	0.678	1.05	2.01	2.96	3.90
	Ω	98.242	91.389	90.05	85.5	80.86	76.2
135°	i	0.359	0.66	1.03	1.99	2.93	3.89
	Ω	110.15	97.73	94.12	87.60	82.35	77.36
180°	i	0.31	0.60	0.97	1.93	2.89	3.83
	Ω	120.14	101.82	96.58	88.88	83.12	78.03
225°	i	0.24	0.52	0.90	1.86	2.82	3.75
	Ω	123.24	100.88	95.29	88.46	82.92	77.86
270°	i	0.18	0.48	0.85	1.81	2.39	3.71
	Ω	109.77	93.61	91.72	86.44	83.56	76.93
315°	i	0.19	0.50	0.88	1.83	2.78	3.72
	Ω	86.25	85.15	86.76	84.13	80.08	75.77

Table 2.3 Changes of orbit in varied RAAN (Ω) with initial inclination 0.5°

Ω		3 months	6 months	1 years	2 years	3 years	4 years
0°	i	0.510	0.656	1.020	1.900	2.816	3.736
	Ω	29.48	43.09	61.70	70.81	71.149	69.070
45°	i	0.682	0.882	1.321	2.249	3.176	4.101
	Ω	63.19	66.41	73.314	75.52	73.618	70.536
90°	i	0.766	0.975	1.449	2.408	3.363	4.294
	Ω	93.168	89.463	88.211	83.986	79.487	74.990
135°	i	0.745	0.918	1.380	2.333	3.286	4.231
	Ω	122.480	112.562	103.53	93.111	86.022	80.131
180°	i	0.623	0.723	1.129	2.048	2.987	3.938
	Ω	153.281	135.878	116.831	99.877	90.641	83.681
225°	i	0.427	0.419	0.758	1.665	2.610	3.560
	Ω	190.385	160.25	122.407	100.05	90.39	83.450
270°	i	0.245	0.055	0.460	1.420	2.369	3.317
	Ω	253.177	199.55	99.09	89.273	83.618	78.605
315°	i	0.304	0.328	0.635	1.534	2.465	3.397
	Ω	341.197	18.153	62.185	74.94	74.757	72.170

As can be seen from the above results, for the geostationary orbit whose initial inclination is in the vicinity of 0° , the general trend is that its orbital inclination is to increase. However, in the different case of RAAN, there are still some slight differences in the changes of orbital inclination. Specifically, for $\Omega = 90^\circ$, orbital inclination will directly increase, and for $\Omega = 270^\circ$, the inclination will decrease first and then increase. Ω is to change in the direction of 90° with a 52-year period. to the specific, Ω will be 90° from the first beginning 0° after 26 years and 270° after 52 years (in 52 years, the changing law of Ω is $90^\circ \rightarrow 0^\circ, 360^\circ \rightarrow 270^\circ$). This variation does not change with sub-satellite point longitude.

2.6 Orbit control scheme for GEO satellite

To maintain GEO satellites in the fixed position with the required accuracy, it is necessary to regulate the position of satellite’s orbit periodically based on the characteristics of the orbit’s change. In order to keep GEO satellites operating in the designated area, it is required to increase the velocity by jet to overcome various perturbation imposed on satellite. For GEO satellites, the velocity increment in north-south direction resulting from north-south position maintenance is to overcome satellite inclination’s changes due to the sun and moon gravity, and while the velocity increment in north-south direction resulting from east-west position maintenance is to overcome the changes of eccentricity caused by solar light pressure and satellite’s drift in east-west direction caused by harmonic perturbation of the Earth's gravitational field. East-west position maintenance for the GEO satellite is to change inclination by control of orbital normal direction in the vicinity of RAAN. Taking a longer time interval for East-west position maintenance into account, RAAN should be adjusted to

270 ° at the same time of controlling orbital inclination. Velocity increment for north-south position maintenance has a relative large value of about 42 m/s ~51m/s every year. East-west position maintenance for the GEO satellite is mainly to overcome the long-term accelerated drift of average longitude caused by the tangential perturbation resulted from the Earth's non-spherical gravity. Through the control method with limit cycle^[40], satellite can be restricted to do the long term limit cycle oscillatory movement near the fixed-point. Control mode of drift limit cycle will be introduced in the following via typical cycle of east-west amendments (as shown in Figure 2.6).

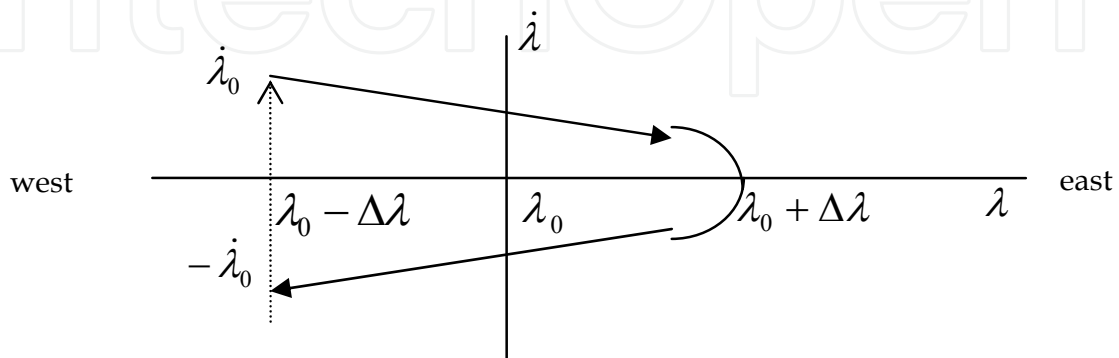


Fig. 2.6 Limit cycle of east-west position maintenance

Supposed λ_0 is sub-satellite point, $\Delta\lambda$ is the allowed longitude deviation, $\ddot{\lambda}$ is for the longitude drift acceleration which is a function of longitude (in China's space, $\ddot{\lambda} < 0$). If Satellite's longitude is λ_0 at time t_0 , Satellite's longitude will be as followings at time t :

$$\lambda = \lambda_0 + \dot{\lambda}_0 t + \frac{1}{2} \ddot{\lambda} t^2 \quad (2.22)$$

where $\dot{\lambda}_0$ is initial drift velocity. Due to $\ddot{\lambda}$, satellite will have drift velocity. Specifically, satellite will have westward drift when $\dot{\lambda}_0 < 0$ and eastward drift when $\dot{\lambda}_0 > 0$. as in the vicinity of china area $\ddot{\lambda} < 0$, control is usually implemented in the western boundary of the limit cycle to give the satellites a long running time within the fixed-point accuracy (such as $\pm 0.1^\circ$ the east-west direction), which will equip the satellite an eastward drift velocity. In the role of $\ddot{\lambda}$, the velocity of satellite will gradually slow down during the eastward drift until satellite drifts to the east boundary of limit cycle. At that time, the satellite will have westward drift velocity and then drift to west continuously by the effect of $\ddot{\lambda}$. When the satellite reaches the western boundary of limit cycle $\lambda_0 - \Delta\lambda$, it can be equipped with drift velocity $\dot{\lambda}_0$ by the control of executive organization and thereby drifts to the east again. A drift cycle has been formed after several repetition of former process.

Velocity increment for east-west position maintenance each year is generally less than 2 m/s, especially in the equilibrium point $\ddot{\lambda}$ will be close to zero and here the required velocity increment is also approaching zero.

2.7 issue of GEO orbital phase

For geostationary orbit with a certain inclination, the satellite phase we actually call refers to Greenwich sidereal time when satellite passes the RAAN. As can be seen from $\lambda = \omega + M + \Omega - s_g$, if $\omega + M = 0$, while satellite passing the RAAN, there will be, $\phi = s_{g(M+\omega=0)} = \Omega - \lambda$. Therefore satellite phase can be denoted as $\Omega - \lambda$, where λ is sub-satellite point longitude and Ω is RAAN. When there is no north-south position maintenance for GEO satellites, they generally have the same law for the changes of orbital inclination and RAAN. Therefore their phases more depend on the differences of fixed position. For the two satellites with 10° difference in fixed position, their phase difference will be about 10° . The change of two satellites' phase-difference can be seen from $\phi = \Omega - \lambda$ and realized by altering their Ω or λ .

3. Technical scheme on altering control mode of the satellite's attitude

In precious section, we have explored the characteristics of IGSO satellite orbit and its running law. In this section, technical scheme on altering control mode of satellite's attitude in end-of-life will be introduced.

3.1 Technical schemes on regulating GEO satellite in end-of-life into IGSO satellite

Known from the previous section, due to various perturbations such as gravity of sun and moon, GEO satellite's inclination will change. Satellite will gradually deviate from the original position and drift in both east-west and north-south direction which is more apparent. There is 0.269° increase in IGSO satellite's inclination each year caused by solar gravity and $0.478^\circ \sim 0.674^\circ$ increase caused by lunar gravity. The inclination drifts $0.75^\circ \sim 0.95^\circ$ in north-south direction each year under joint effects of sun and moon. The inclination changes periodically with period of 18.6 years and its largest range ability is about 14.67° . After implementing the new control model, GEO satellite will become a new kind of satellite, namely SIGSO whose inclination is between 1° and 10° .

So if there is just east-west position maintenance and no north-south position maintenance which means satellite can drift in latitudinal direction freely, the retired GEO satellite can become half-controlled SIGSO satellite. As the fuel that north-south position maintenance consume is 9 times as much as the fuel that east-west position maintenance consume, the using time of remained fuel in retired satellite can be prolonged about 10 times with the new orbit regulation model. As mentioned earlier, the satellite's electronic equipment such as solar cells, signal transponders has a relative longer service life, SIGSO satellites can service for many years in transmitting navigation and positioning satellite system. Meanwhile, due to retire GEO communications satellites are no longer bear the original communication and broadcasting tasks, they can be regulated to other required and available track in a larger range in accordance with the requirements about formation of navigation constellation. The

satellite management departments regulating the orbits in this way has some technical difficulties, but much easier than developing and launching new satellites, and the satellite transponder lease costs is much less than the costs of developing and launching dedicated navigation satellites. Therefore the formations of navigation constellation composed of the SIGSO satellites which are regulated from GEO satellites make retired GEO communications satellites playing a role in improving the accuracy of navigation. The usage of the retired GEO satellites can not only shorten the time and saves a lot of money to organizing a navigation system, but also delays the time of satellites into space junk which will pollute the space environment. CAPS verification system using SIGSO satellites^[1, 9, 10, 13] which is deviated from regulating retired satellites has proven effective.

Of course, utilizing this kind of satellites need regulate the SIGSO satellites to required orbits and meet the provisions of the ITU about anti-interference. It also has extremely high demand of orbits determination since the orbits of satellites are the resources for navigation. CAPS project team using two-way time transfer technology and code-related disspreading demodulation makes satellite ranging accuracy better than 1 cm and orbit observation residuals less than 9 cm^[3, 17] which can meet the requirement of transmitting satellite navigation and positioning system.

3.2 Antenna's direction and its Isotropic Radiated Power

After retired satellites regulated to the new orbit, the ground beacons should be re-established or technology of geocentric point mode should be adopted. To meet the navigation's requirement on the effective coverage area and power distribution, effective coverage area of the satellite's antenna and EIRP allocation should be altered by adjusting antenna's direction.

3.3 The method of changing sub-satellite point longitude λ

For more than two satellites, their intervals in longitude direction must be drawn away. Method of the operation is not complicated, as long as one of the satellites has been drifted away, the purpose of changing the fixed-point longitude could be achieved, since changes in phase is consistent with changes in longitude. About 5~6m/s velocity increment is enough for drifting satellite and drift speed is 1°/ day. giving the scope of China's territory, drift of the longitude range can be limited to 50° E ~ 170° E. when satellite is in the new position, it is also necessary to consider electromagnetic compatibility of other satellites nearby.

3.4 The method of changing RAAN

As described above, each satellite's orbital inclination i has the same change with its RAAN when there is no north-south position maintenance. If there is some time difference in suspending the two satellite's north-south position maintenance, a certain Right Ascension difference will be retained during process of change. As is shown in Table 2.2, when the first satellite has been no north-south position maintenance for four years and the second satellite 2 years, there will be 10° difference in Right Ascension of the two satellites.

Changing the satellite's RAAN usually consumes a large amount of fuel. Taking two satellite with inclination 3° and RAAN 75° for example, velocity increment of 55m/s is required to bring about 20° difference in RAAN and velocity increment of 55m/s for 60° difference in RAAN, which is unrealistic for the huge cost. The initial inclination is about 0°

in the beginning of suspending north-south position maintenance, and therefore RAAN is meaningless and thereby setting Right Ascension difference is relatively easy. To set the Right Ascension of two satellites arbitrarily, the only thing need to do is that one of satellite has been established a non-zero angle at a certain time. For example, when satellite passes Right Ascension 90° , RAAN of satellite can be changed to 90° with north direction position maintenance. But the Right Ascension we have set will decrease generally during the following perturbed evolution, the extent of decrease depend on the inclination when setting the RAAN.

For example, RAAN of the two satellites were set to 0° and 180° respectively and inclination is controlled to 0.1° , velocity increment is about 5.5m/s and thereby consuming less fuel. Table 2.2 shows the subsequent changes, as can be seen from Table 2.2, the RAAN of the satellite with the initial RAAN 0° will change to 84.6° in a year and 79.4° in three years, and the RAAN of the satellite with the initial RAAN 180° will change to 96.6° in a year and 78° in three years. The right ascension difference will decrease to 12° in one year from the beginning 180° and to 1.4° three years later. If the inclination of the two satellites is set to 0.5° , while the RAAN is still set to 0° and 180° respectively, the reducing trend of right ascension difference will slow down.

The subsequent evolution of the situation is shown in Table 2.3, the RAAN of the satellite with the initial RAAN 0° will change to 61.7° in a year and 71.7° in three years, and the RAAN of the satellite with the initial RAAN 180° will change to 116.8° in a year and 90.6° in three years. The right ascension difference will decrease to 55° in one year from the beginning 180° and to 15.5° three years later. However, if the inclination has been set too larger, the consumption of propellant will have a substantial increase which is equal to the amount of half-year's consuming fuel and velocity increment will have to be about 27m/s. If we further increase the initial inclination, the reduction of the two satellite's RAAN difference will further slow down but the consumption of propellant will have a substantial increase, which can be seen from the table 2.3, 2.5, 2.5.

3.5 Conclusions

Based on the above analysis, we can obtain the following conclusion:

1. GEO satellite's orbital inclination and RAAN have a 52-year cycle of change due to solar and lunar perturbations, right ascensions reducing from about 90° to 0° , then to 270° , and at last to 270° directly. Therefore, GEO satellites without north-south position maintenance have same changes in their orbital inclination and RAAN.
2. There are two ways to change the time when the two retired satellites pass the equator: one is changing sub-satellite point longitude difference $\Delta\lambda$ between the two satellites, the other is to change the satellite's RAAN difference $\Delta\Omega$.
3. Altering the time when the two retired satellites pass the equator by changing the sub-satellite point longitude can improve navigation performance via the improvements of satellites constellation;
4. It is easier to change the sub-satellite point longitude with control volume $5 \sim 6\text{m/s}$; consider the scope of China's territory, drift in the longitude range can be limited to $50^\circ\text{E} \sim 170^\circ\text{E}$. However, we should note that the re-coordination of the orbit is required;
5. Altering the orbital phase by the change of the RAAN can improve navigation performance actually via increasing geocentric angles of two satellites, but in case of small

inclination, geometrical distribution can't be significantly improved because the increasing amount of the geocentric angle is not more than the sum of two satellites' inclination;

6. The method that we alter the orbital phase by the change of the RAAN can be optimized in different initial conditions. But even so, the control volume has the same amount of the normal north-south position maintenance and the initial set of orbital phase differences will gradually reduce and have the same value eventually.

4. Contribution of SIGSO satellite for transponder satellite navigation constellation

In this section, through simulation analysis, we will discuss the SIGSO communications satellites in the transponder satellite navigation system how to affect the navigation and positioning constellation structure and improve the navigation and positioning solutions.

4.1 Requirements of positioning on the constellation structure

Generally, position accuracy in satellites navigation system can be represented as:

$$\sigma_x = \text{GDOP } \sigma_p \quad (4.1)$$

Where $\sigma_x = \sigma_{(x,y,z,t)}$ is positioning and time service error, σ_p is pseudo-range measurement error. GDOP (Geometric Dilution of Precision) is an important index to describe the quality of the space section of a positioning system, and its value determines position accuracy^[42, 49, 53, 56].

An excellent positioning system requests PDOP value to be small in effective covering region in any time. The GPS system is formed by more than thirty satellites and corresponding PDOP value in covering region is smaller than 4 or less^[26].

When GEO communications satellites are used in constellation of regional navigation system, the system needs three communications satellites with the large orbital inclination (IGSO) too. Thus the coverage of the system will be of about one-third of the earth. Three such regional systems can cover the whole world.

In 2003, the problem existing in CAPS test system is that we have not appropriate IGSO satellites to apply in the system. Therefore, we propose to use GEO satellites which are going to be retired for solving the problem. That is, using new mode to control thus GEO satellites to become SIGSO satellites for navigation and positioning. However, the improvement of constellation structure when SIGSO satellites are used should be studied in depth. In this section, by calculating the distribution and variation of constellation PDOP within a certain coverage we mainly analyze quality of the constellation.

4.2 Improvement to PDOP value in satellites navigation system by SIGSO satellites

Based on the theoretical analysis of the constellation and PDOP changing with time, we developed a set of application software of calculation and analysis on PDOP change. For the navigation and positioning constellation includes some satellites with different orbital parameters, the software can calculate the PDOP change in any place on the ground at any time, calculate the PDOP change in the designated area within a certain period, and can

produce various charts of PDOP by the time and distribution of regional areas for simulation and analysis constellation quality.

(1) Analysis of the impact of SIGSO satellites for navigation constellation PDOP

We will analyze the function of SIGSO satellite through studies of distribution and variation of PDOP values for various constellation structures. In simulation, the satellite number of constellation is designed to be six, including the GEO satellites and SIGSO satellites. The number of SIGSO satellite changes from one to six, and number of GEO satellite changes from five to zero correspondingly. The longitude of the satellites is 57° , 87.5° , 103° , 122° , 142° and 163° respectively, and the least of the satellite's elevation for users is 5° . The orbit inclination of SIGSO satellite is 3° and 5° . For each $2^\circ \times 2^\circ$ grid point to calculate the 10-minute intervals PDOP values, and plotted PDOP distribution. If the PDOP values of a grid point is always less than 1000 in the required effective period (such as 95%, 98% or 100% of the day), the points will be called effective grid points and they will compose the effective coverage area. Effective area of the PDOP calculated respectively the minimum, maximum and average. The figures and data will be used in analysis of the function of SIGSO satellites.

(a) Constellation including SIGSO and GEO satellites can achieve three-dimensional navigation.

If the positioning system only uses GEO communication satellites without other assistant methods, it cannot do the 3-D positioning since these satellites are all in the earth's equator plane. The calculations show that the DOP value of this constellation is too large for navigation and positioning. For example, when using only the six GEO satellite, the PDOP value of Beijing area approximately is one million or more. Supposing an retired GEO satellite (such as at 110.5° E) has been controlled to be a SIGSO satellite with $i = 3^\circ$, the effective time is 95% of one day, the calculated PDOP distribution is shown in Figure 4.1. In the scope of about 60° E– 160° E and about 65° S– 65° N, PDOP minimum is 57.1, and average is 76.2, PDOP <60 in the center of the covered area and PDOP <70 in a considerable area. Although the effective time has not yet reached whole day, and the value of PDOP is also larger, the significant change is the 3-D positioning equation could be solved and fundamentally change the situation that the equation cannot be solved when GEO satellites are used only.

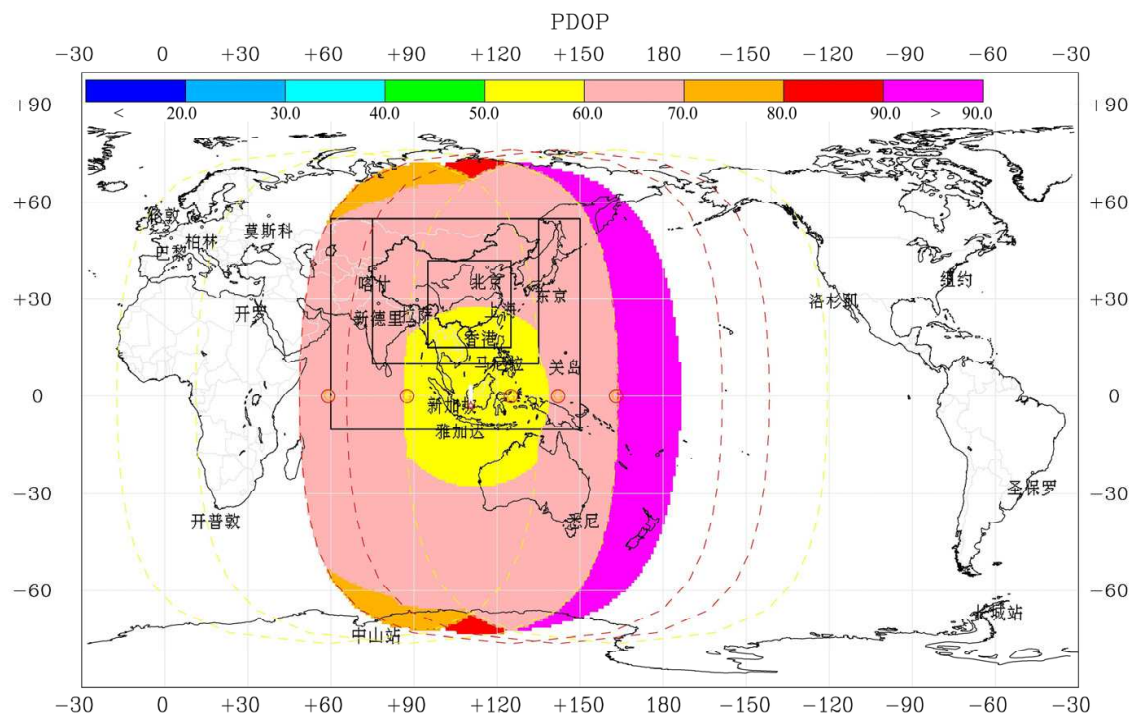


Fig. 4.1 Distribution of PDOP equal-value-area of the constellation of one IGSO ($i=35^{\circ},e=0$) and five GEO satellites.

Notes: Different color stands for the distribution grade levels of the PDOP daily mean and the same color area is called the equal-value-area. The circumscription value of the equal-value-area is marked on the top of the figure, such as PDOP<20 in the blue area and on the analogy of this. The red circles marked with 'G' along the equator are the ground projecting of GEO satellite, the corresponding coverage boundary are shown by dotted lines. The '8' shaped ground track of IGSO satellite is plotted with white dash-dot line, on which the red star represents the position of IGSO satellite, while those white points are the positions at every hour. The three key areas marked by the black line, they are Chinese hinterland, most of the territory and surrounding areas, and it is the same below.

(b) Increase in the number of SIGSO satellite PDOP of constellation can be improved.
Improvement of the PDOP value of constellation is relatively obvious along with the increasing in the number of SIGSO satellites. Based on above case, if retired GEO satellite at 142° E is also controlled to be a SIGSO satellite with $i = 3^{\circ}$, that is the combination of 4 GEO satellites and 2 SIGSO satellites is formed, the PDOP is improved obviously. In the cases of effective time is 98% of one day, the minimum reduces from 57.1 to 36.0 and the average decrease to 47.3 from 76.2 in the entire covered region, and the largish region will reach PDOP <50. Assuming an retired GEO satellite at 87.5° E is controlled to be a SIGSO satellite with $i=3^{\circ}$ and the combination of 3 GEO and 3 SIGSO satellites will be formed and ask the ratio of effective time to reach to 100% of one day, the PDOP distribution is shown in Figure 4.2. PDOP minimum further reduces to 15, average of the entire coverage region reduces to 28.6, the largish region reaches to PDOP <17.
Further assuming the retired GEO satellite at 125° E is controlled to be a SIGSO satellite with $i=3^{\circ}$ and the combination of 2 GEO and 4 SIGSO satellites will formed, the PDOP is further improved (see Figure 4.3). The minimum will reduce to 12.8, average of the entire coverage

region will reduce to 16.6, the largish region will reach to PDOP <14. If the number of controlled SIGSO satellite increases again, for example, all 6 GEO satellites are controlled to SIGSO ones with $i = 3^\circ$, PDOP minimum will further reduce to 11.9. For comparison, simulated PDOP values of some constellations are listed in Table 4.1 (i stands the orbital inclination, T is the percentage of effective coverage time in a whole day, min, max and mean show minimum, maximum and regional averages of daily average PDOP respectively, H means using atmospheric pressure altimeters).

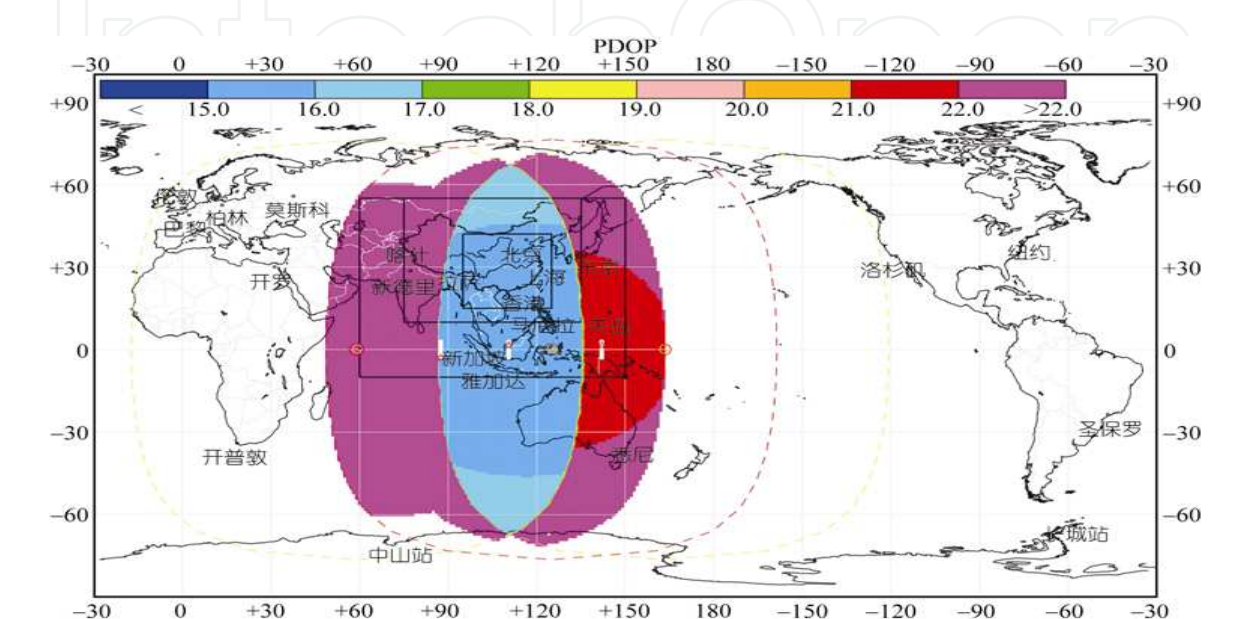


Fig. 4.2 Distribution of PDOP equal-value-area of the constellation of three GEO and three SIGSO satellites with $i=3^\circ$.

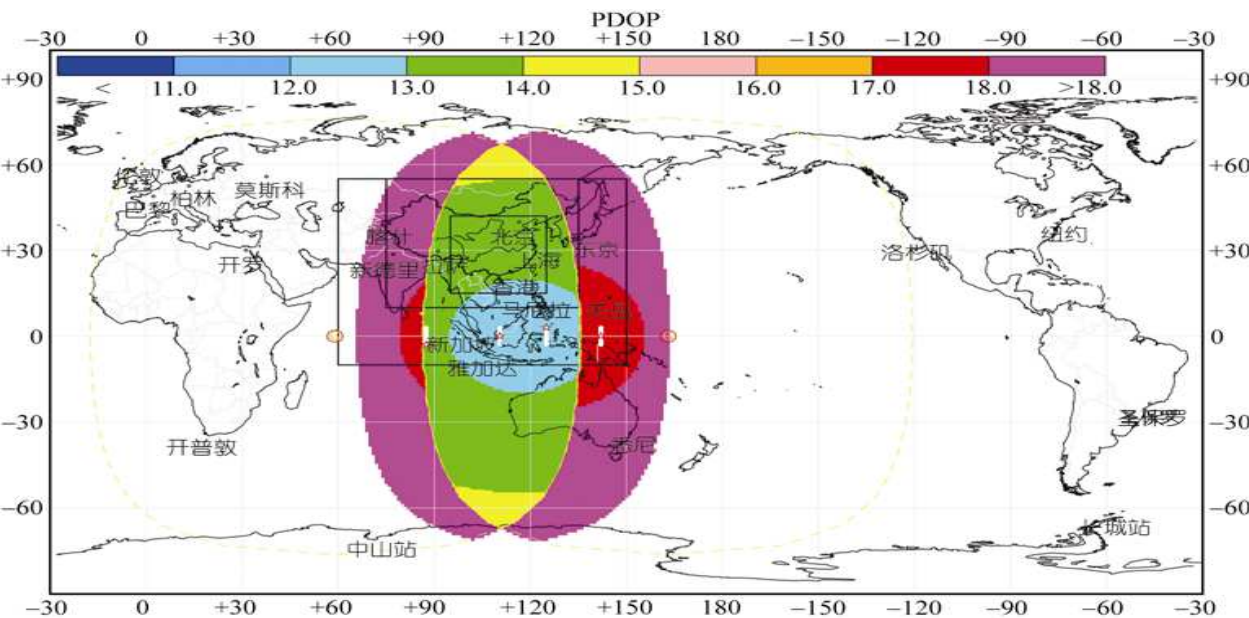


Fig. 4.3 Distribution of PDOP equal-value-area of the constellation of two GEO and four SIGSO satellites with $i=3^\circ$.

It should be noted that PDOP maximum became larger for the two groups of using atmospheric pressure altimeters in the table 4.1. It is the reason that the effective coverage area increases and the PDOP is relatively large in the marginal parts of the effective coverage area. As the parts are smaller, the impact on the average is also small, and it will not adversely affect the largish region we care about.

Table 4.1 PDOP values of various constellations
(The minimum elevation of satellite is 5°)

Table 4.1 PDOP values of various constellations (min elevation 5 degree)						
constellation	<i>i</i>	<i>T</i> %	Min	Max	mean	备注
5GEO+1SIGSO	1°	95	139.0	170.4	151.8	
	3°	95	57.1	149.1	76.2	
4GEO+2SIGSO	3°	98	36.0	75.1	47.3	
	3°	100	15.0	64.0	28.6	
3GEO+3SIGSO	3°+H	100	2.9	108.3	12.2	
	3°	100	12.8	33.4	16.6	
2GEO+4SIGSO	5°	100	7.9	23.5	10.5	
	7°	100	5.9	18.9	8.0	
1GEO+5SIGSO	5°	100	12.1	61.5	18.8	satellite phase 60°
	5°	100	9.1	35.8	13.3	satellite phase 75°
0GEO+6SIGSO	3°	100	24.0	77.2	36.6	
	5°	100	14.7	55.9	22.3	
	5°+H	100	3.1	106.4	12.8	satellite phase 60°
	7°	100	10.8	40.4	16.4	satellite phase 120°
	5°	100	6.6	51.7	11.8	

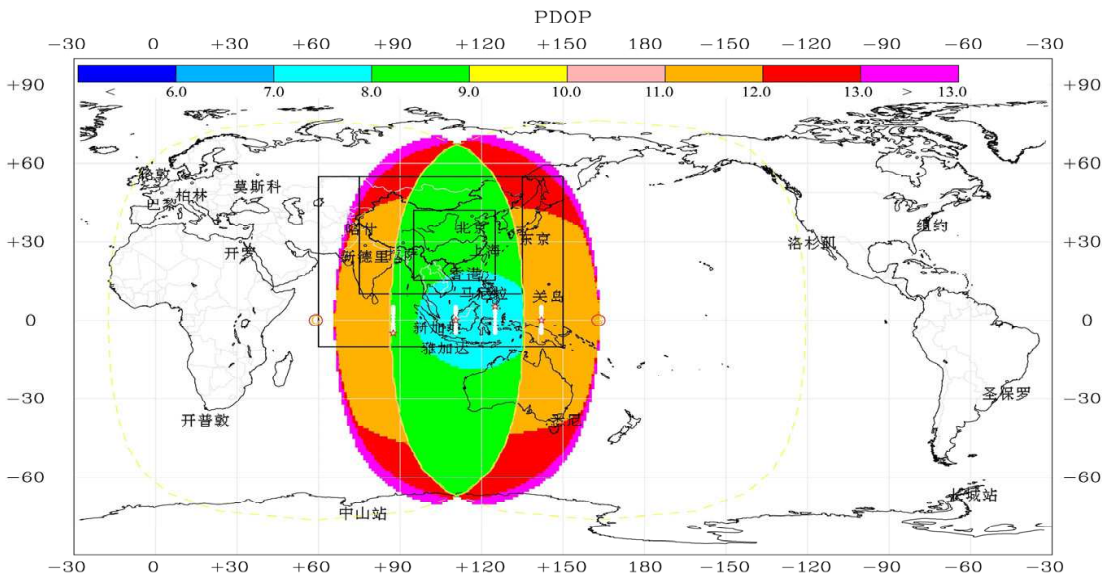


Fig. 4.4 Distribution of PDOP equal-value-area of the constellation of two GEO and four SIGSO satellites with *i*=5°.

(c) The relatively greater inclination of the SIGSO satellite is, the greater the degree of improvement of PDOP value is.

Simulation shows that even if only one SIGSO satellite exists and the orbital inclination i increases to 3° , the PDOP minimum will reduce to 57.1. Here we use the combination of two GEO and four SIGSO satellites to further display the impact of the orbital inclination on PDOP. Four SIGSO satellites locate at 87.5° E, 110.5° E, 125° E and 142° E and i changes from 3° to 5° and 7° for the simulation. The result of $i=3^\circ$ has been showed in Figure 4.3. The results of $i=5^\circ$ and 7° , respectively, are showed in Figure 4.4 and 4.5. The comparison of results in Table 4.1 and Figures 4.3, 4.4 and 4.5 show that PDOP value is obviously improved along with the increasing of inclination of SIGSO. The minimum PDOP reduces from 12.8 to 7.9 then to 5.9 and the average decreases from 16.6 to 10.5 and then to 8.0. At the same time, when $i = 5^\circ$, 4/5 of Chinese domain achieves PDOP <9. The change curves of PDOP per minute in 24 hours of some representative locations are in Figure 4.6. The results show that the variation of PDOP per minute is relatively stable and the value is relatively small except for the PDOP is relatively large in north-west marginal region of China which cannot observe 163° E satellite. Using SIGSO satellites are from retired GEO satellites to form constellation and then get such improvements of PDOP that may be not imagine before. In Figure 4.5, we can see that 4/5 of Chinese domain achieves PDOP<7 when $i = 7^\circ$. However it needs a longer time that SIGSO is controlled to be the orbital inclination of 7° , and there should be more of remaining fuel, as well as solar battery and the transponder has a long working life.

In the simulation, if three SIGSO satellites are used and their orbit inclination is about 5° , the PDOP average will be about 15.7, PDOP <12 in a majority of the satellite coverage area and a larger area of PDOP <10 appears in the middle (see Figure 4.6). When using four IGSO satellites, PDOP reduced to an average of 11.8, and the area of PDOP <8 appears in the middle (see Figure 4.7). Compared with the combination of the number of IGSO satellites of $i = 3^\circ$, the improvement of PDOP is obvious when the SIGSO satellites are used, of course, the navigation and positioning accuracy will be improved significantly (as shown in Figure 4.4).

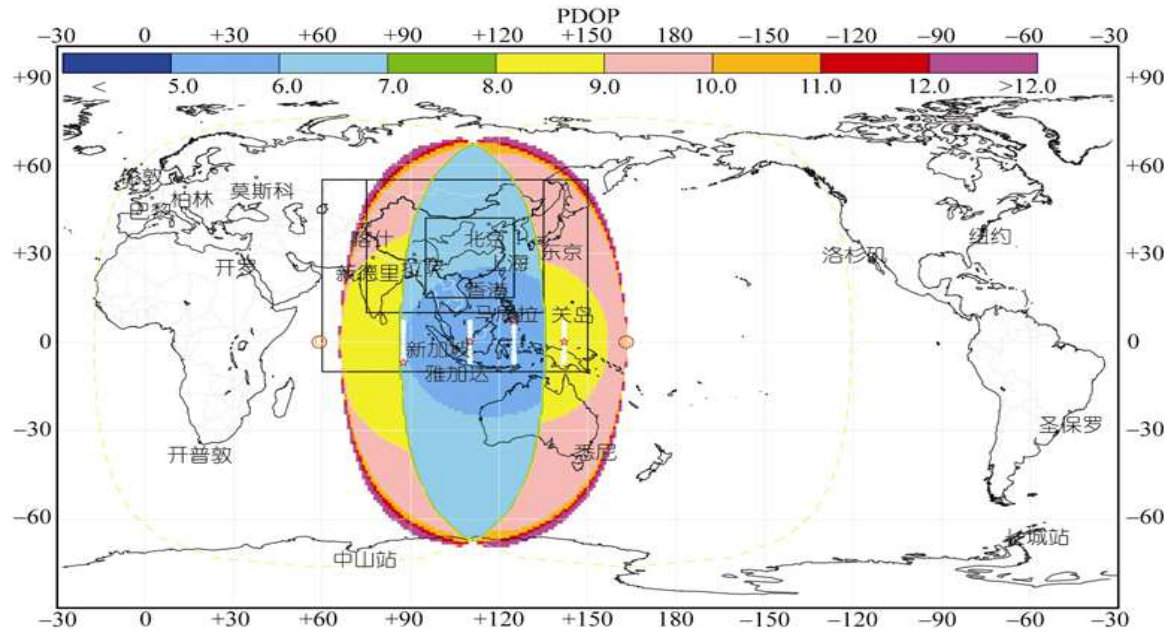


Fig. 4.5 Distribution of PDOP equal-value-area of the constellation of two GEO and four SIGSO satellites with $i=7^\circ$.

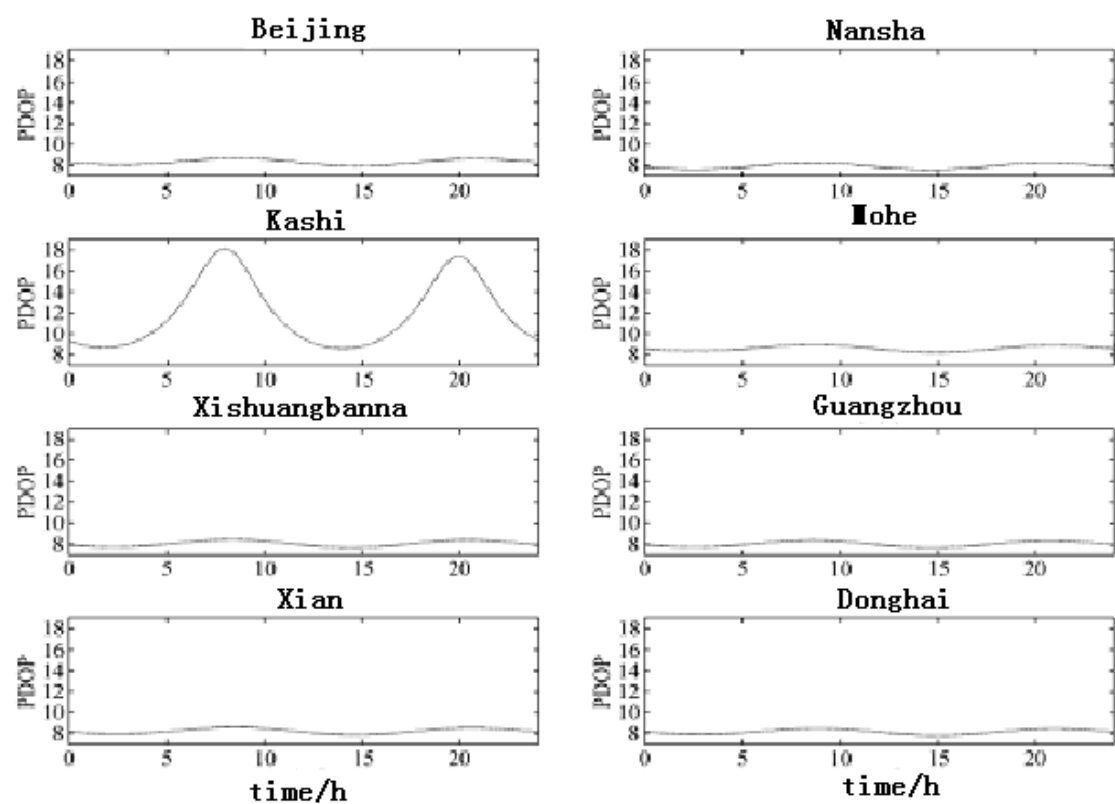


Fig. 4.6 the PDOP value per minute of a constellation with two GEO and four SIGSO ($i=5^\circ$) satellites in different sites in Chinese.

In order to make better use of contribution of SIGSO satellites for improving the distribution of satellite constellation, it is needful to take into account the phase difference of the SIGSO satellites. These GEO satellites have the same ascending node when they are launched, there are two ways to change their phase. We can adjust the phase directly, of course this way will consume more fuel and it is not advisable since SIGSO satellites have a spot of fuel. Another way is to move SIGSO satellites in the longitude direction in order to increase the interval between satellites and then their phase difference will be increased and the satellite coverage will be increased.

In summary, joining of SIGSO satellites changed the situation that the three-dimensional positioning cannot be made if only use GEO satellites, the three-dimensional positioning can be actualized. More SIGSO satellites and greater orbital inclination, the improvement of PDOP is more obvious. To increase the phase difference between SIGSO satellites, can be used pull SIGSO satellite in longitude direction interval.

(2) SIGSO satellites for improvement of PDOP value of CAPS validating system

The coverage of CAPS focuses on Chinese land and coastal areas, considering there should be a certain redundancy for the coverage, the simulation will be extended to Chinese surrounding areas ($60^\circ\text{ E} - 150^\circ\text{ E}$, $0^\circ - 65^\circ\text{ N}$). The GEO satellites involved in CAPS are at 87.5° E , 110.5° E , 125° E and 142° E , their span in west-east direction is relatively small. We suppose to launch new GEO communication satellites at 59° E and 163° E , or retired GEO satellites are controlled to become SIGSO ones and moved there (here we mainly consider Chinese existing GEO communication satellites and the possible new ones, as well as SIGSO

satellites from the retired GEO satellites). For the above-mentioned 6 satellites, they gradually enter the end of the life and become SIGSO satellites in sequence, their orbital inclination will reach to 1°, 3° and 5° etc., and minimum altitude angle of satellite is 5°. Under these assumptions, the simulation will provide PDOP value every 10 minutes, at each 1° × 1° grid (latitude × longitude) in the effective coverage area, as well as the daily average and minimum value of PDOP. For regional navigation and positioning system, we are concerned about the value of PDOP in the region and its distribution, so we draw the value of PDOP distribution in different levels. At the same time, in order to fully understand the details of the PDOP changes and further comparative analysis, we calculate PDOP changes per minute in one day and draw PDOP curve for some selected representative sites within the coverage area. Through the analysis of the change and distribution of PDOP, we can get the following results:

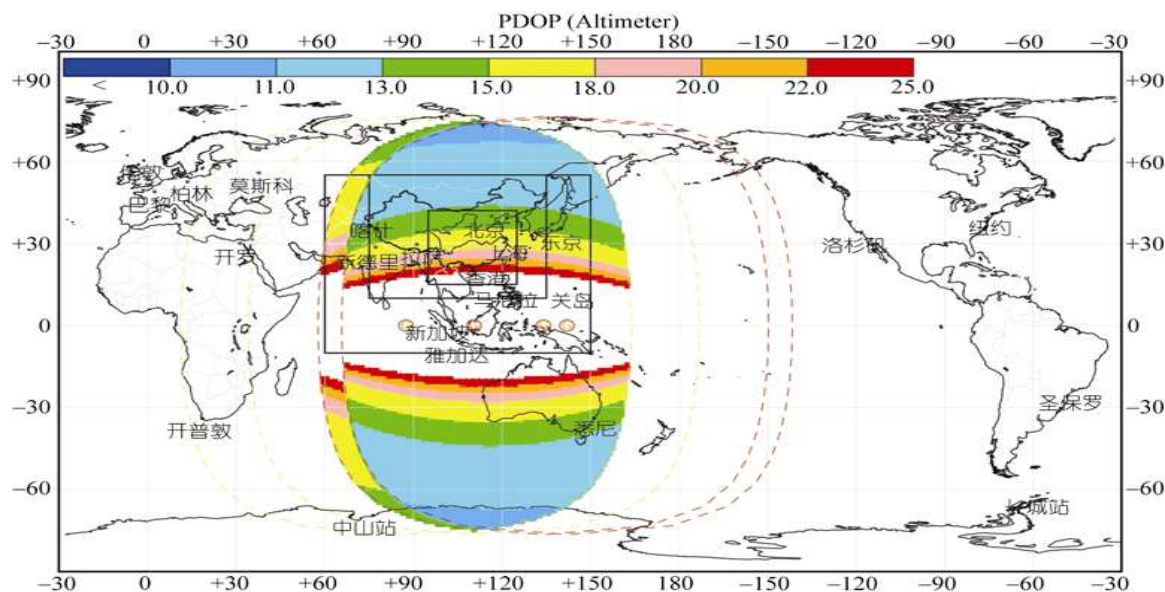


Fig. 4.7 Distribution of PDOP equal-value-area of the constellation of CAPS validating system formed by four GEO satellites and atmospheric pressure altimeters are used.

To verify the function of retired satellites used in the CAPS validating system, based on the situation of using atmospheric pressure altimeters we simulate the constellation is formed by above-mentioned 4 GEO communication satellites, as well as the constellation when GEO satellites at 134° E and 138° E retired and are controlled to be SIGSO satellites with $i=3^\circ$ respectively. The results are shown in Figures 4.7 and Figures 4.8. In absence of retired satellites, the average, minimum and maximum of PDOP value is 43.0, 10.9 and 970.8 (in Figure 4.7, the part for $PDOP>25$ is set to be white, and the same below). When two satellites retired and became SIGSO ones with $i=3^\circ$, these values of PDOP are improved as 19.4, 10.9 and 131.8, respectively (see Figure 4.8). It is obvious that retired satellite is certain valuable for improving PDOP value of CAPS validating system. With their orbital inclination increases, the improvement on PDOP will be relatively more pronounced. When the orbit inclination of the two satellites is about 5°, these PDOP values are 14.7, 10.8 and 124.7 (see Figure 4.9). We could see that, although the minimum of PDOP unchanged with the increase of the orbital inclination, the change of the average is obvious, the region with smaller PDOP expanded. For example, the south boundary of the region of $11 < PDOP \leq 13$ is at the

north of Beijing at first, and then it extends to the southern of Beijing when $i = 3^\circ$, then the boundary extends to Hainan island, and the region of $PDOP \leq 11$ exists in the eastern part of China when $i = 5^\circ$. Therefore, using relative more SIGSO satellites are from retired GEO satellites, and the orbital inclination is greater relatively, the improvement for the PDOP of CAPS validating system is relatively more pronounced.

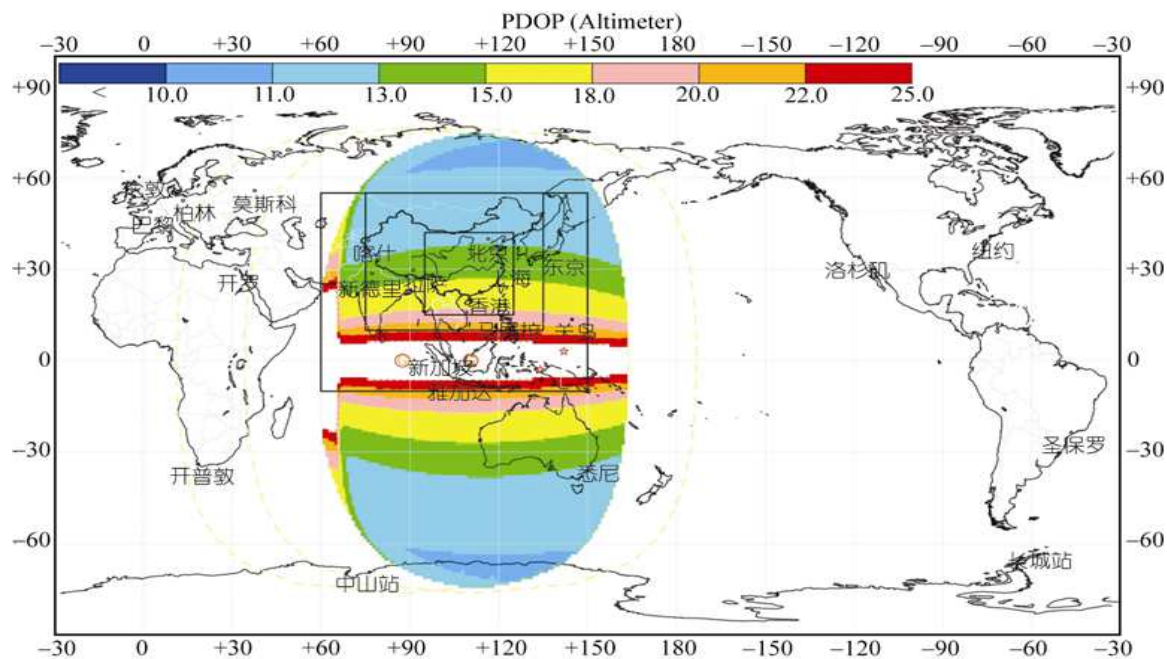


Fig. 4.8 Distribution of PDOP equal-value-area of the constellation of CAPS validating system formed by two GEO satellites and two SIGSO satellites with $i=3^\circ$ and atmospheric pressure altimeters are used.

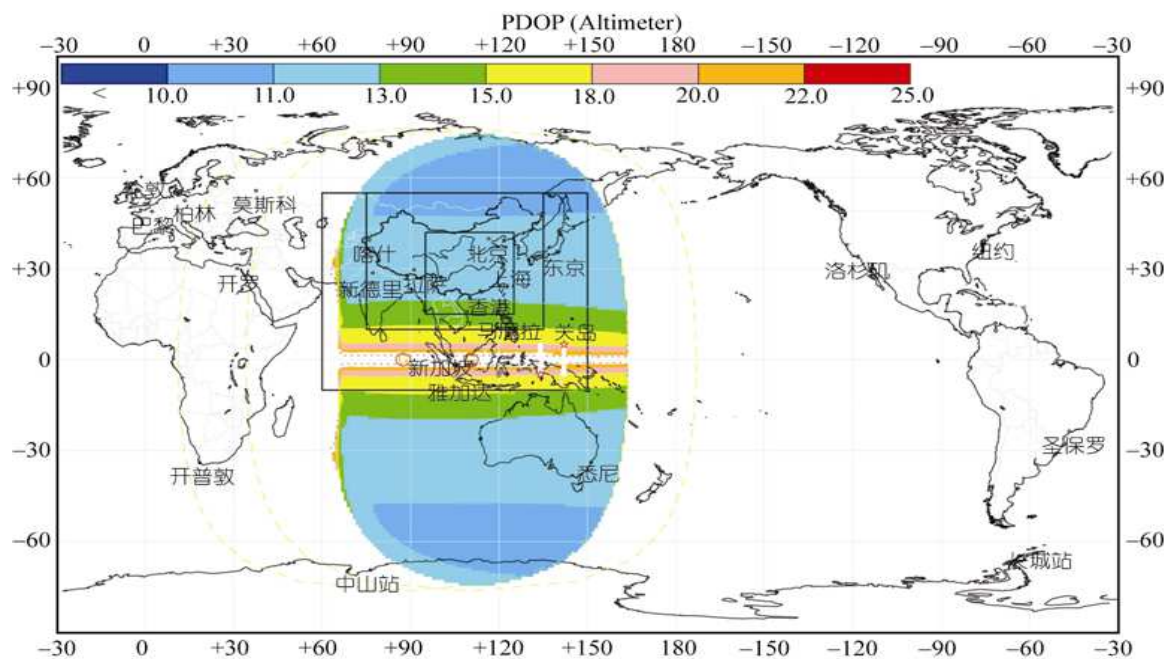


Figure 4.9 Distribution of PDOP equal-value-area of the constellation of CAPS validating system formed by two GEO satellites and two SIGSO satellites with $i=5^\circ$ and atmospheric pressure altimeters are used.

The results show that the retired GEO communication satellite which is controlled to be SIGSO satellite can be used to the transmitting navigation and positioning system, and 3-D navigation and positioning can be actualized. Of course, a certain number of IGSO satellites are necessary to form an ideal constellation for navigation and positioning even if the GEO and SIGSO communication satellites are together used in the constellation or all members of the constellation are SIGSO satellites. The analysis shows that controlled SIGSO satellite from retired GEO satellite can improve PDOP value of the constellation, and its function for improvement of PDOP is better than one of GEO satellite. More SIGSO satellites and greater orbital inclination, the improvement of PDOP is more obvious.

Studies showed that the CAPS needs SIGSO satellites not only lie within the range of 80° E– 140° E, but also lie within the ranges of 50° E– 80° E and 150° E– 180° E, thus navigation accuracy and effective coverage range of the CAPS will be improved significantly. However, Chinese GEO communications satellites launched distributed in 80° E– 140° E generally. Through studies, the research team adopted the way to change the position of retired GEO communication satellites and move the satellites into the ranges of 50° E– 80° E and 150° E– 180° E respectively, in order to form a relatively better navigation constellation. If retired GEO communication satellites do not be used, thus we need launch two GEO communications satellites to the two areas, this must take longer time and spend more fund.

4.3 The capability of anti-jamming

As a lot of C-band transponders in SIGSO satellites with 500/700MHz bandwidth to generate three-frequency, multi-frequency and frequency navigation signals for enhancement of corresponding ground receiving terminals can be used for user's navigation and positioning, it can overcome the limitations of using fixed navigation signal in current navigation system. The implementation procedures are to choice different and contiguous navigation frequencies which can be covered by a ground receiving antenna to convert them down to expected navigation base band signal, and then measure and compensate their converting time delay by software to achieve finally the accuracy navigation and positioning^[52, 2]. As the fixed navigation frequency signals with a low power and easily interfered are used in common satellite navigation systems, frequency-hopping technology^[1, 6, 7] may be applicable to anti-jamming in satellite navigation, therefore, an innovative satellite navigation system can be built up with the functions of multi-frequency and hopping for navigation, they will significantly improve anti-jamming capability and increase more functions in navigation system.

5. A low data rate satellite communications technique

A low data rate satellite communication system is being developed in the navigation and positioning system based GEO communications satellites as SIGSO satellites around end of life span. Such a communication system has its especially technical issues and demands, of course, and its technical difficulties.

5.1 Why developing this type of satellite communication techniques

By means of changing the attitude control mode, GEO communication satellite around the end of life span will drift into a small angle inclined orbit (SIGSO) satellite. Except 2-3 band

transponders for navigation purpose, if remaining 21 to 22 transponders resource can be used well? They are very cheap space resources. In general, human beings demand more increasing communications, so satellite communications techniques tend to improve bandwidth efficiency and data transmission rate with higher cost-effective. Would SIGSO satellite meet these needs?

As SIGSO satellites have "8" shape shift daily movement and continue increasing drift, the communication terminal antenna must point to the satellite. It will be required to be able to control the antenna beam or antenna beam directive should be able to cover a very wide range, in particular, the composition and structure of the terminal installed on the mobile carrier will become more complex.

There are various demands of application, for example, vehicle travel monitoring carrying dangerous goods; the transmission of measured data in meteorological and hydrological monitoring stations in remote mountains, ocean and desert etc.; emergency information reporting in real-time in case of disaster; corrosion monitoring for petroleum pipeline and so on. Particularly, after GPS is being used widely, people needs increasingly location and time information transmission service which needs an innovative medium with capacities of long-distance transmission in real-time, low information transmission under a strict error code rate and stronger anti-interference. There are potentially numerous users who hopefully need cheaper device and lower using cost. Thus, a new classified satellite communications with an extra low-information rate are being developed widely.

5.2 Configuration of navigation and communications system

Navigation and communication system is composed of SIGSO communications satellites, master communication ground station, user terminal, data distribution and network management system. User segment is user receivers that are classified into navigation/communication or combined receivers. User receivers in functions may include Positioning, Timing, Velocity and Communication; carrier feature for user terminals could be classified as static, dynamic and highly dynamic motion. The sorts of device include portable devices, vehicle terminal, mobile terminals and static terminals.

CAPS project now has two SIGSO satellite communications with capability of communications for users, and provide positioning and navigation services with higher positioning accuracy—similar to GPS positioning accuracy, and higher timing precision in all weather and day in service area (longitude $60^{\circ} \sim 160^{\circ}$, latitude $20^{\circ} \sim$ latitude 60°) user terminals are featured by short message and low data rate voice communication and compressed image transmission. CAPS communications hub station locates in Huairou region Beijing with 16 meters aperture antenna operated by automatic tracking. Test system shown in Figure 5.1.

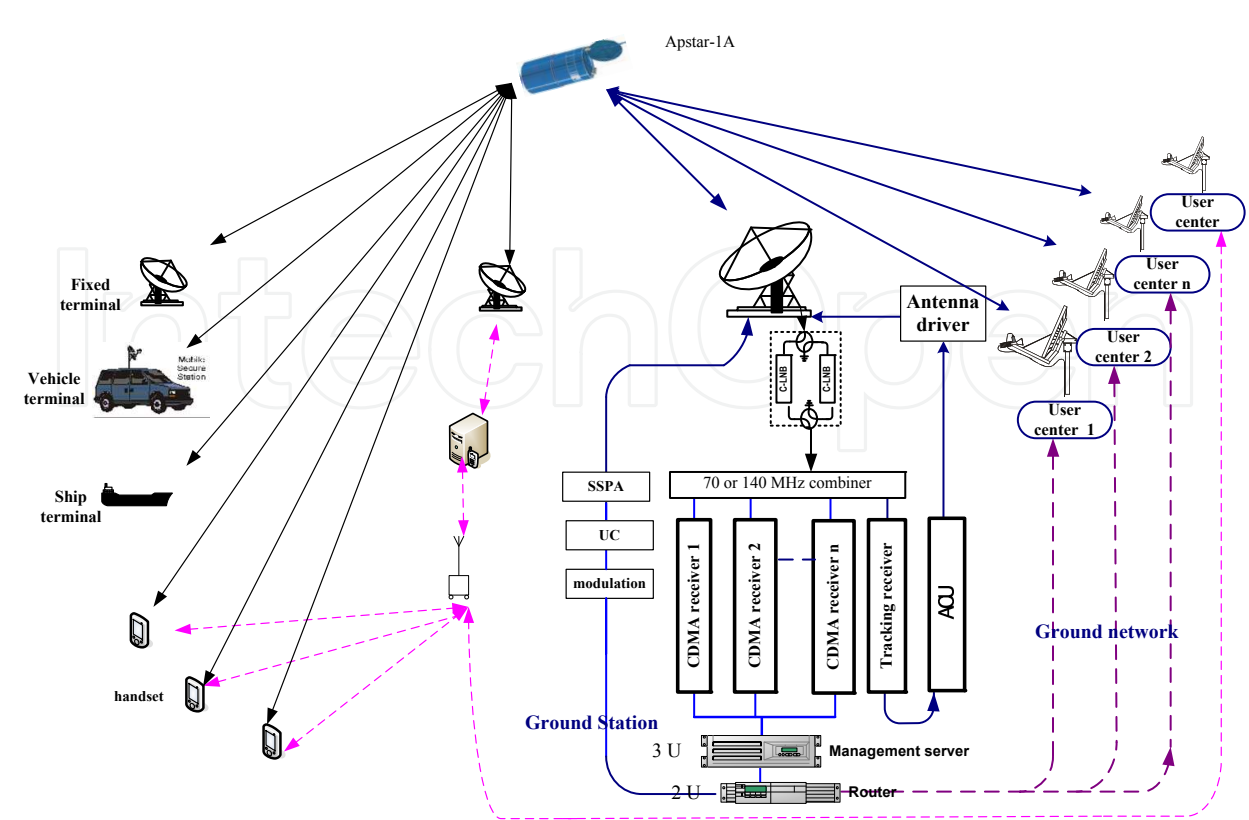


Fig. 5.1 Test principle of CAPS-based integrated communications and navigation in CAPS

5.3 Optimal Design of Link

A portable mobile devices with lighter weight, lower power and lower cost seems to be incompatible in a low data rate satellite communication system, development difficulties focus on user terminal with low power, miniaturized and cost-effective, especially, the design of miniaturized antenna in portable user terminal without tracking systems have to be solved, so, the design of the transmission power link must be optimized. Power link margin is usual expressed by decibel difference between system E_b/N_0 and demodulation threshold (E_b/N_0). E_b/N_0 obtained by the following formula

$$[E_b/N_0] = [C/T]_t - [R_b] - [k], \tag{5.1}$$

where $[C/T]_t$ (C/T)_t is total link carrier power and noise power ratio, shown in (5.2) as follows:

$$\left(\frac{C}{T}\right)_t = \left[\left(\frac{C}{T}\right)_u^{-1} + \left(\frac{C}{T}\right)_d^{-1} + \left(\frac{C}{T}\right)_{co}^{-1} + \left(\frac{C}{T}\right)_{im}^{-1} + \left(\frac{C}{T}\right)_{adj}^{-1} \right]^{-1}, \tag{5.2}$$

where, C/T_u , C/T_{co} , C/T_{im} , C/T_{adj} uplink CNR, co-channel interference CNR, inter-modulation interference CNR and adjacent satellite interference CNR, respectively, their expression are shown as follows:

$$[C/T]_u = [EIRP]_e - [L_u] - [L'] + [G/T]_s,$$

(5.3)

$$[C/T]_{co} = 23 + [k] + [B],$$

(5.4)

$$[C/T]_{im} = 20 + [k] + [B],$$

(5.5)

$$[C/T]_{adj} = [G_r] - 29 + 25 \times \log(2) + [k] + [B],$$

(5.6)

where, L_u is free space path loss in uplink transmission, L' are other losses, including the uplink rain attenuation, antenna pointing error in master control navigation station; $[G/T]_s$ are the gain and noise temperature ratio of satellite receiving antenna.

The three parameters C/T_{co} , C/T_{im} , C/T_{adj} of total Carrier to Noise ratio $[C/T]_t$ in satellite communications system relate with carrier noise bandwidth and temperature parameters, and C/T_{co} relate with the number of CDMA users working in same frequency and cross-correlation of their PN codes. If 20 groups GOLD code are selected as PN codes with 2047 code length, the above three values are generally 130 ~ 150 dBW / K in inbound communication link, the C/T_u at the margin of APstar-1 coverage is about 190 dBW / K, therefore, in equation (5.2), C/T_u and the C/T_d are dominant. $(G/T)_s$ is about 7 dB / K at the margin of APstar coverage, if R_b takes 50 bps, demodulation threshold $(E_b/N_0)_{th}$ is 10.6dB, it will be known by Eq. (5.3), $(C/T)_u$ value is 195.3 dBW / K, the uplink C/N is very low, and the demodulation threshold of signal to satellite is close to system threshold. Similarly, for the outbound link, as receiving antenna gain is lower, downlink or C/N is also limited power system.

In order to achieve miniaturization of user terminal, the terminal's power amplifier configuration should not be too high. Data rate is less to 50-300bps for short message transmission with antenna gain of 5-6dBi. CNR uplink signal to satellite is close to demodulation threshold with very weak signal, so a large size antenna need to be configured to center ground station in this system so that downlink CNR is not dominant to have weak signal receiving and demodulation. The link power budget in the existing APstar communications satellite are shown as follows.

The link power budget results in inbound (terminal transmitting and receiving in central ground station) and outbound (transmitting in central ground station and terminal receiving), respectively are shown in Table 5.1 and Table 5.2.

Table 5.1 Inbound link power budget in C-band mobile communication

APstar-I 2A-50bps--single-carrier transmitting in margin region and received in Beijing	
	Edge coverage - Beijing
A. Satellite Parameters	Parameters
1. Satellite Name	APstar-I
2. Orbital position (deg.E)	142
3. Transponder No.	1A

4. Transponder gain attenuation(dB)	2
5. Satellite saturated effective isotropic radiated power (dBw)	36.00
6. Satellite Saturation Flux Density (dBw/m^2)	-90.82
7. Satellite receiving antenna gain and noise temperature ratio (dB/k)	-2.00
8. Transponder Output backoff (dB)	4.50
9. Transponder input backoff (dB)	10.50
10. Uplink Frequency (MHz)	5965.00
11. Downlink Frequency (MHz)	3740.00
12. Transponder Bandwidth (MHz)	72.00
B. Ground station parameters	
1. Transmission parameters□	
a. Antenna diameter (m)	Monopole Antenna
b. Ground station location	Coverage
c. Feed losses (dB)	1.00
d. Power amplifier to feed insertion loss (dB)	0.50
e. Type of power amplifier (klystron, traveling wave tube, SSPA)	SSPA
f. Power amplifier output (dBw) (10W)	10.00
g. Power amplifier maximum output power (dBw)	10.79
h. Amplifier output margin (dBW)	0.79
i. Antenna efficiency (%)	45.00
l. Antenna gain (dB)	5.70
k. Antenna tracking capability	no
l. Type of antenna	mobile
2. Transmission parameters	
a. Antenna diameter (m)	16.00
b. Ground station position	Beijing
c. Longitude (deg.E)	116.46
d. Latitude (deg.N)	39.92
e. To the satellite distance (km)	38031.35
f. Antenna elevation angle (deg)	36.85
g. Antenna Azimuth (deg)	143.33
h. Antenna efficiency (%)	60
i. Antenna gain (dBi)	53.70

j. Receiving system noise temperature (dBk)	19.54
k.Antenna gain and noise temperature ratio (dB/k)	34.16
l. Antenna tracking capability	Automatic
m. Antenna type	Fixed
C. Space loss	
1. Uplink Rain Attenuation (dB)	0.5
2. Downlink Rain Attenuation (dB)	0.3
3. Uplink free space attenuation (dB)	200.50
4. Downlink free-space attenuation (dB)	195.51
5. Uplink polarization loss	3.00
D. Carrier Parameters	
1. Carrier Type	DSSS
2. Multiplexed mode	CDMA
3. Modulation	BPSK
4. Data Rate (bps)	50
5. Chip rate (kbps)	2047.00
6. Spreading frequency gain	46.12
7. Carrier Noise Bandwidth (khz)	2800.00
8. Carrier allocated bandwidth (khz)	3000.00
9. Threshold E_b/N_0 (dB)	10.00
E. Link Budget	
1. Uplink C/T	
a. Ground station effective isotropic radiated power (dBw)	11.20
b. Uplink free space loss (dB)	200.50
c. Loss of antenna pointing (dB)	2.00
d. Antenna gain per square meter (dB/m^2)	36.96
e. Satellite carrier flux density (dBw/m^2)	-141.55
f. Transponder saturation flux density (dBw/m^2)	-90.82
g. Carrier input backoff (dB)	50.73
h. Satellite antenna gain and noise temperature ratio (dB/k)	-2.00
i. Uplink C/T (dBw/k)	-193.80
2. Downlink C/T	

a. Satellite effective isotropic radiated power saturation (dBw)	36.00
b. Carrier Output backoff (dB)	44.73
c. Carrier Downlink effective isotropic radiated power (dBw)	-8.73
c. Downlink carrier per channel effective isotropic radiated power (dBw)	-19.52
d. Downlink free-space loss (dB)	195.51
e. Receiving antenna pointing error (dB)	-0.30
f. Antenna gain and noise temperature ratio (dB/k)	34.16
g. Downlink C/T (dBw)	-181.47
3. Co-channel interference C/T (dBw/k)	-162.31
4. Inter-modulation interference C/T (dBw/k)	-144.13
5. Satellite interference C/T (dBw/k)	-131.90
6. Total C/T and C/N	
a. Total C/T (dBw/k)	-194.05
b. Boltzmann constant (dBw/k-Hz)	-228.6
c. Receiver Noise Bandwidth (dB-Hz)	64.47
d. Total C/N (dB)	-29.92
e. Threshold E_{bi}/N_0 (dB)	10
f. Threshold C/N (dB)	-37.48
g. Link margin (dB)	7.56

Table 5.2 Outbound link power budget in C-band mobile communication

APstar-I 2A-50bps – Beijing station transmitting and terminal received in margin region	
	Beijing-Edge coverage
A. Satellite Parameters	Parameters
1. Satellite Name	Apstar-1
2. Orbital position (deg.E)	142
3. Transponder No.	5A
4. Transponder gain attenuation(dB)	8
5. Satellite saturated effective isotropic radiated power (dBw)	36.00
6. Satellite Saturation Flux Density (dBw/m^2)	-86.73

7. Satellite receiving antenna gain and noise temperature ratio (dB/k)	-1.12
8. Transponder Output backoff (dB)	4.50
9. Transponder input backoff (dB)	10.50
10. Uplink Frequency (MHz)	6105.00
11. Downlink Frequency (MHz)	3880.00
12. Transponder Bandwidth (MHz)	36.00
B. Ground station parameters	
1. Transmission parameters	
a. Antenna diameter (m)	16.00
b. Ground station location	Beijing
c. Longitude (deg.E)	116.46
d. Latitude (deg.N)	39.92
e. Distance to satellite (km)	38031.4
f. Elevation angle (deg)	36.85
g. Azimuth angle (deg)	143.33
h. Feed losses (dB)	0.30
i. Power amplifier to feed insertion loss (dB)	3.00
j. Type of power amplifier (klystron, traveling wave tube,SSPA)	SSPA
k. Power amplifier output (dBw)	2.21
l. Power amplifier maximum output power (dBw)	20.00
m. Amplifier output margin (dBW)	17.79
n. Antenna efficiency (%)	60.00
o. Antenna gain (dB)	57.98
p. Antenna tracking capability	Automatic
q. Type of antenna	Fixed
2. Transmission parameters	
a. Type of antenna	Double spiral antenna
b. Station position	Edge coverage
c. Antenna gain (dBi)	5.00
d. Receiving system noise temperature (dBk)	24.13
e. Antenna gain and noise temperature ratio (dB/k)	-19.13
f. Antenna tracking capability	None
g. Antenna type	Mobile

C. Space loss	
1. Uplink Rain Attenuation (dB)	0.5
2. Downlink Rain Attenuation (dB)	0.3
3. Uplink free space attenuation (dB)	199.77
4. Downlink free-space attenuation (dB)	196.50
5. Uplink polarization loss	0.00
6. Downlink polarization loss	3.00
D. Carrier Parameters	
1. Carrier Type	DSSS
2. Multiplexed mode	Single carrier
3. Modulation	BPSK
4. Data Rate (bps)	50
5. Chip rate (kbps)	2047.00
6. Spreading frequency gain	49.13
7. Number of path	1
8. Carrier Noise Bandwidth (khz)	2800.00
9. Carrier allocated bandwidth (khz)	3000.00
10. Threshold E_b/N_0 (dB)	10.00
E. Link Budget	
1. Uplink C/T	
a. Ground station effective isotropic radiated power (dBw)	56.89
b. Uplink free space loss (dB)	199.77
c. Loss of antenna pointing (dB)	0.30
d. Antenna gain per square meter (dB/m^2)	37.16
e. Satellite carrier flux density (dBw/m^2)	-105.71
f. Transponder saturation flux density (dBw/m^2)	-86.73
g. Carrier input backoff (dB)	18.98
h. Satellite antenna gain and noise temperature ratio (dB/k)	-1.12
i. Uplink C/T (dBw/k)	-144.80
2. Downlink C/T	
a. Satellite effective isotropic radiated power saturation (dBw)	36.00
b. Carrier Output backoff (dB)	12.98
c. Carrier Downlink effective isotropic radiated power (dBw)	23.02

c. Downlink carrier per channel effective isotropic radiated power (dBw)	23.02
d. Downlink free-space loss (dB)	196.50
e. Receiving antenna pointing error (dB)	2.00
f. Antenna gain and noise temperature ratio (dB/k)	-19.13
g. Downlink C/T (dBw)	-197.92
3. Co-channel interference C/T (dBw/k)	-141.13
4. Inter-modulation interference C/T (dBw/k)	-144.13
5. Satellite interference C/T (dBw/k)	-180.60
6. Total C/T and C/N	
a. Total C/T (dBw/k)	-198.00
b. Boltzmann constant (dBw/k-Hz)	-228.6
c. Receiver Noise Bandwidth (dB-Hz)	64.47
d. Total C/N (dB)	-33.87
e. Threshold E_{bi}/N_0 (dB)	10
f. Threshold C/N (dB)	-40.49
g. Link margin (dB)	6.62

From Table 5.1 and Table 5.2, inbound and outbound margins are about 7dB, and relatively abundant, and can ensure reliable information transmission through satellite.

5.4 The key technologies

The following technologies are adopted to solve limited power and meet special design requirements for small terminal device, as well as SIGSO satellites operational requirements.

1) Broadband spread spectrum technology

As bandwidth resources in the SIGSO satellite are abundant, so it can be used to wideband spread-spectrum communication. The trade off using frequency bands for power solves the limited power and enhancement of C/N. the bandwidths of spread spectrum are optimized in terms of meeting the relevant ITU provisions so that we can solve adjacent satellite interference in using wide beam antenna, reducing the power flux density, and improving the system of anti-jamming capability.

2) Large size receiving antenna in ground station

The small size and wide beam antenna with lower gain and power result in power and CNR limitation in satellite transmission links, it can be solved by adjusting attenuation in the transponder, or adopting FEC technique, besides that, a practical solution is to use large size receiving antenna on ground station. Thus, CNR in the downlink cannot effect on the SNR of the whole link which can be met well.

3) Shaped wide beam antenna
As SIGSO satellite drift all the time, and its daily motion is "8" shape (Figure 5.2). Such as the APstar-1 satellite drifts over $\pm 4^\circ$ /day in north-southern direction, the azimuth and elevation of satellite observing from antenna change larger per day (Figure 5.3).

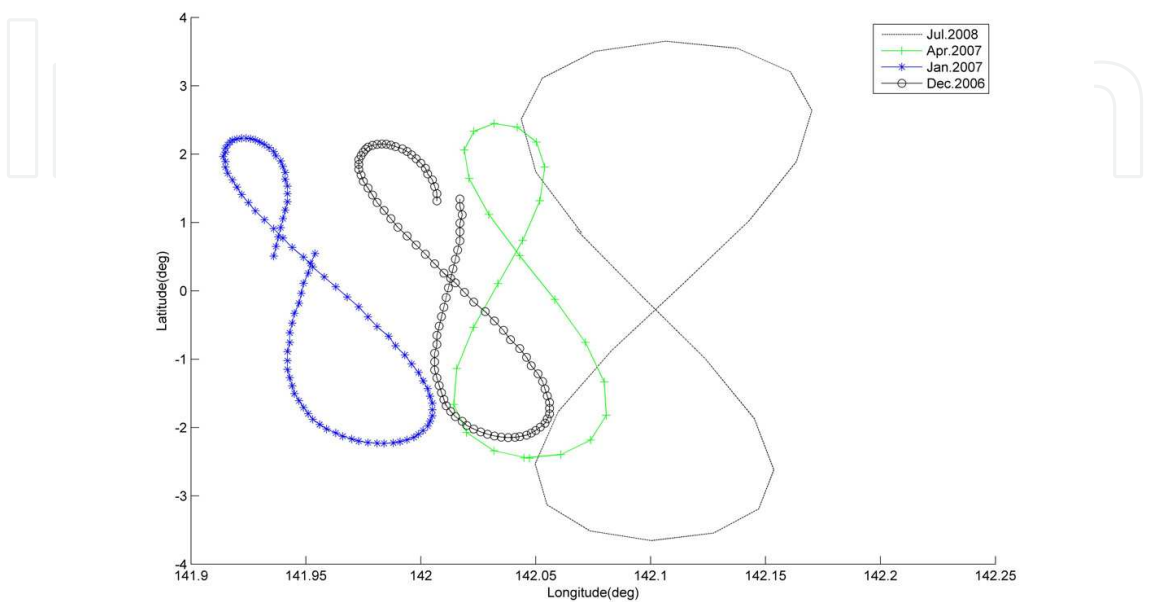


Fig. 5.2 APstar-1 track of subsatellite point

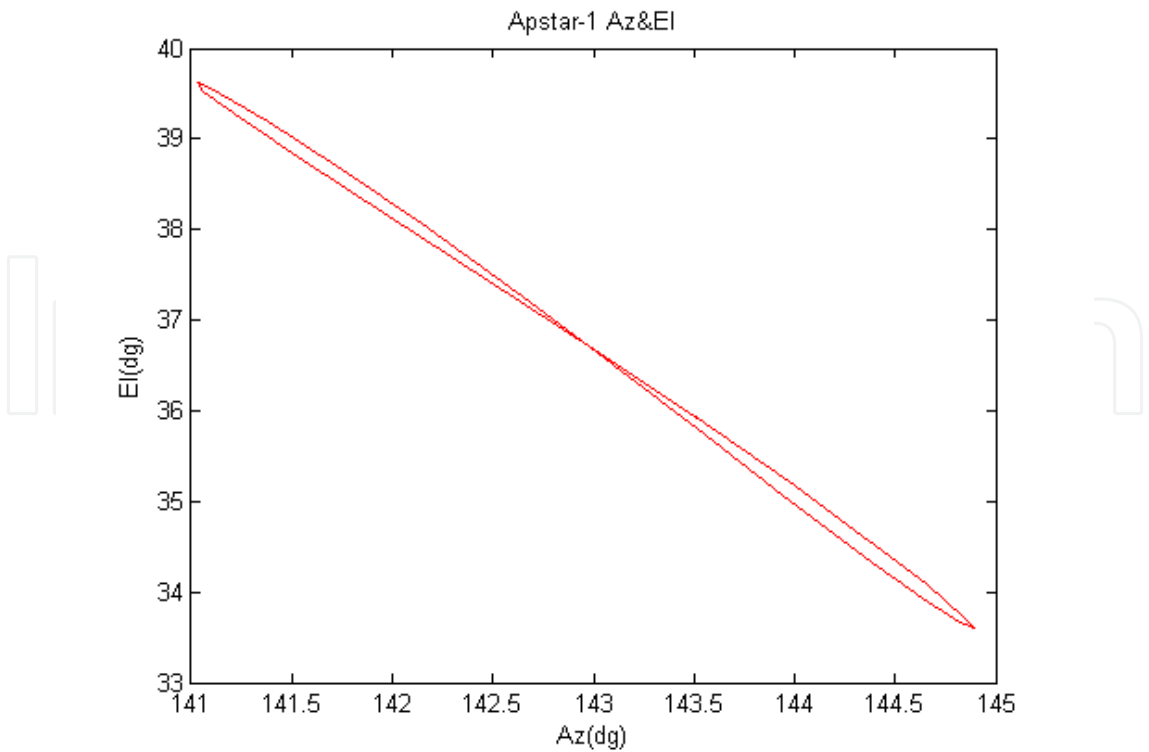


Fig. 5.3 The azimuth and elevation in Beijing earth station

In the mobile satellite communication systems, antenna is a crucial component. Antenna directive, tracking accuracy and its cost restrict the overall system performance and price in certain extent, restricted definitely the availability and promotion of the system. Therefore, we developed a monopole shaped beam antenna. Antenna pattern is shown in Figure 5.4, where it is omnidirectional and wide-beam with about 60° elevation angle, the antenna maximum direction can be designed to required direction. It totally does not need to change the antenna attitude to meet the demand for satellites drift. And even devices would be installed in the mobile vehicle, they can meet the moving dynamic requirements, so it is very simple and cheap.

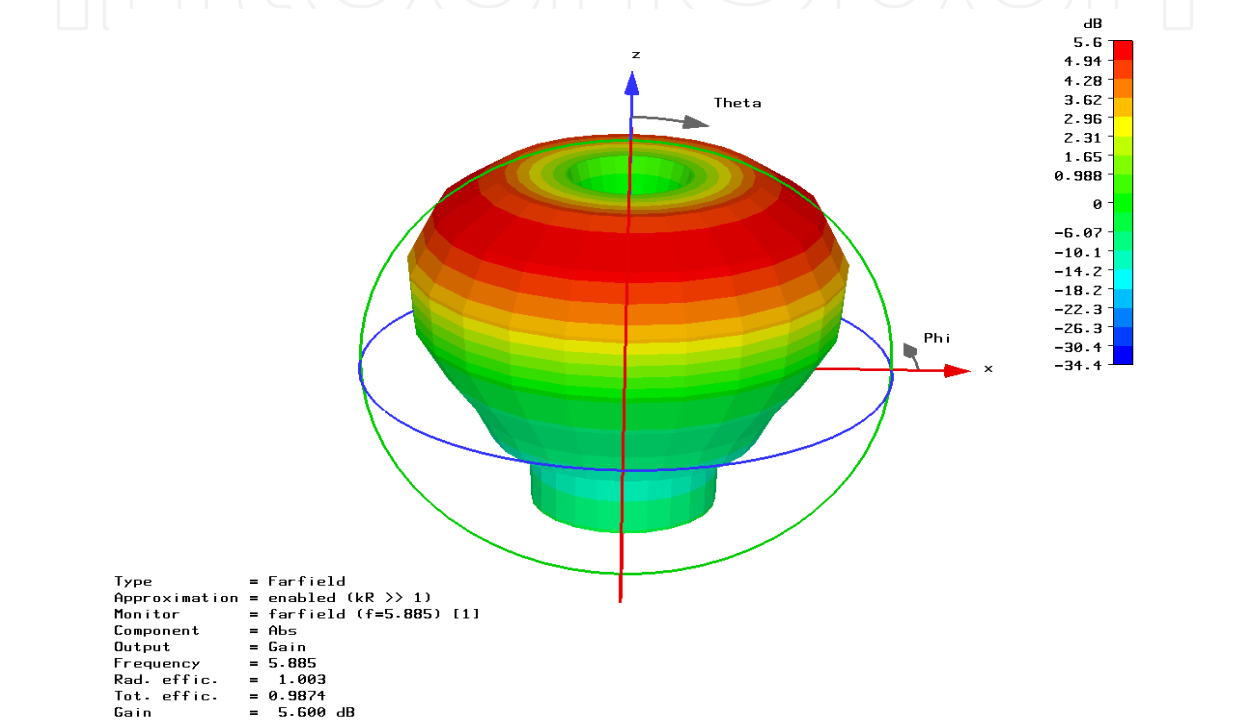


Fig. 5.4 Monopole Antenna 3-D pattern



Fig. 5.5 Monopole Antenna

Terminal antenna is vertical polarization; polarization loss is relatively small between antenna and satellite. Antenna shape is shown in Figure 5.5. The disc of its bottom is reflection plate and its diameter is 6cm.

Other kind receiving antenna is double spiral antenna; its 3-D antenna pattern is shown in Figure 5.6.

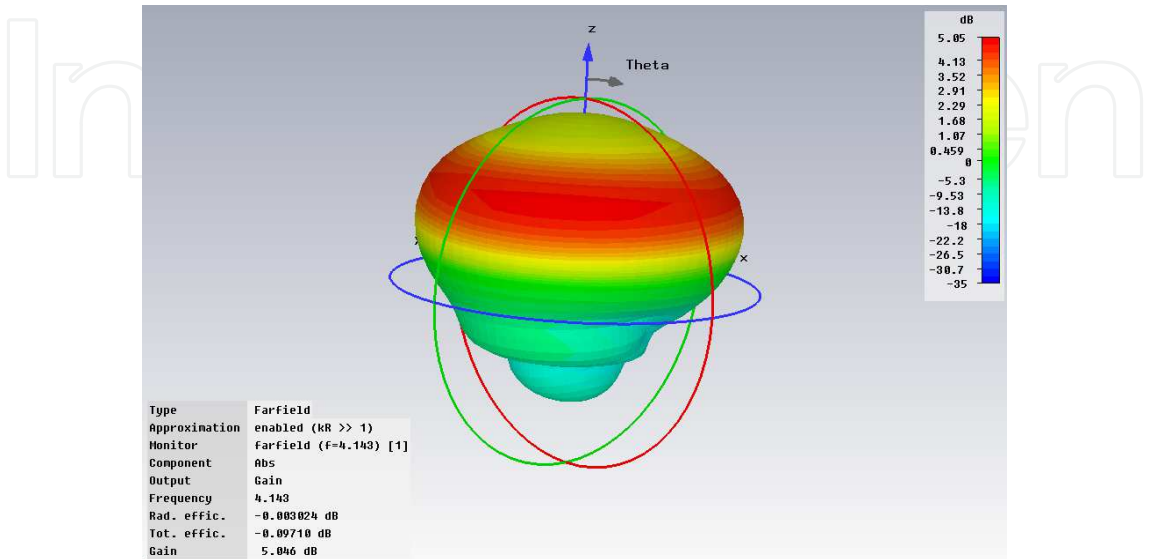


Fig. 5.6 Three-dimensional pattern of double spiral antenna

Double spiral antenna gain is relatively low around 5dBi with whip-like in (as shown in Figure 5.7).



Fig. 5.7 Double spiral antenna

In order to prevent carrier signal interfere from earth stations with neighboring satellites, the International Radio Consultative Committee and the International Telecommunication Union (ITU) on the uplink station carrier axis radiation power density is strictly required; in order to prevent interference to ground microwave communications, ITU regulated

international standards to allow power flux density on the ground transmitted from space communications systems. In addition, the coordination is required about above two issues by satellite operators. From Figure 5.4 and Figure 5.6 it can be seen that such antenna beam is wide, and even adjacent satellite is radiated by antenna main beam, so, the measures must be taken to avoid interference with adjacent satellite.

It is very important to three aspects mentioned above for low data rate satellite communication system design which is typically different from normal satellite communication system, of course, in addition, technologies generally used in satellite communications need to be optimized, such as the use of data compression, optimized multiple access and modulation and so on.

5.5. The system characteristics and advantages

1) Information exchange

As CAPS has successfully developed satellite communications technology with a low data rate, it can exchange and transmit spatial and time information. This system can provide the spatial location and time information.

2) Stronger anti-interference

As the system uses wideband PN spread spectrum system, signal will be buried in the noise below, so the signal will not be easy to be intercepted and deciphered, but also it is difficult to interfere with its transmission and has anti-interference ability.

3) Cost-effectiveness

Constellation adopts GEO communications satellite around late life span; it is prolonged 10 times life expectancy and satellite by changing attitude control with very cheap transponder. System is designed to use small devices and small antenna; equipment development costs are relatively small. Ground station can continue to use the original communication equipments and operate with a little modified equipment. So, the whole system invests less, system cost-effective and easy to build up.

5.6 Typical application

1) Based on the position and time service

The development of a low data rate of satellite communications technology in satellite navigation system based on communication satellite enables to communicate each other to position message and create more applications in combining of satellite navigation and position and timing service, it solve the limitations of individual navigation service in GPS, and to realize the group and center system navigation, and center. Figure 5.8 is shown terminal vehicle positioning information in the electronic map picture.

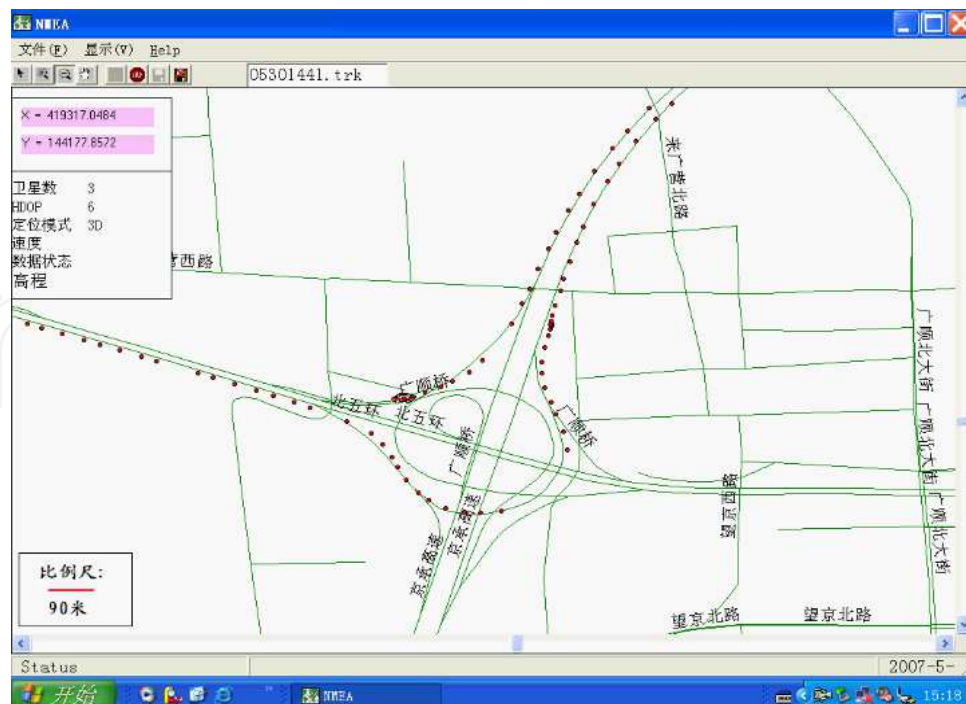


Fig. 5.8 Display on electronic map of vehicle terminal location

2) Applicative for scattered users, rare routing and small traffic communication network, data transmission in automated and unattended station.

3) Applicative for anti-terrorism, disaster relief, emergency communications, When the earthquake disaster and other emergencies happen, it is very important the timely to report the disaster. Disaster relief center also need to control the situation in real-time, directly command and deploy disaster relief teams. People need emergency communication means as facing terrorist activities, also need reliable means of communication, which requires. The project develops a low information rate of satellite communications to meet the emergency communication needs.

4) A new satellite monitoring function

Low information rate satellite communication system can send timely data to control center, for example, operating parameters of large equipments like scraper, oil pipeline corrosion data, measurements data in marine, hydrological and meteorological investigation, logistics management information of ship and vehicle, displacement transfer parameters of reservoirs, rivers, lakes, and dams and so on, contrarily, control center can also transmit instructions to the monitoring terminal in time, to change work parameters and set working status for monitoring.

Totally, the low information rate satellite communications experiments for integration of navigation and communication and multi-satellite communication applications, and to be a practical technology orient to market applications.

6. The application value of GEO communications satellites with extra-live span

We proposed the technological methods to reuse retired communication satellite^[1], it has obtained significant results through the conceptive research, simulation and project validation, as well as practical application.

CAPS system now use Apstar-1 and Apstar-1A satellites, where orbital position of Apstar-1 satellite was adjusted from the 138° E to the current 142° E orbital position, Apstar-1A satellite from the 134° E to current 130° E. Apstar-1 and Apstar-1A satellite began to be adjusted to SIGSO satellite in August 2004 and in May 2005 respectively. They still keep orbital precision to the original $\pm 0.05^\circ$ [19, 20] along latitudinal direction without control in longitudinal direction. Apstar-1 satellite's inclination had reached 4.1°, Apstar-1A satellite's inclination was 3.5° till March 2009. The following detailed description of the project application value:

1) The protection of spatial environmental resources

Research and realization of retired GEO communications satellite remaining payload fuel without abandonment can be used as constellation of satellite navigation and positioning system. they are only be maintained and adjusted along longitude in orbit spaces, the working mode can save 90% fuel keeping the new control method for CAPS and significantly extend the life of satellites, a retired communications satellite achieves to reuse, creating a development and utilization of extra life-cycle of satellite.

A new model of satellite orbit control has been study and proposes new methods and technologies of reuse retired GEO communications satellites. For example, AP-star 1 satellite reuse, the remained using period of fuel in normal control mode was 3 to 6 months while it was replaced by other new satellite in 2004. At this time, the satellite's solar cells and electronic equipment is still intact with 24 transponders still working, even six spare transponders not yet being used. In the new orbit control mode, the retired satellite became the SIGSO satellite, and has worked more than five years, the GEO communications satellite resources are ultimately used and delay the period to become space junk and pollute the space environment, it plays a very important role to protect the space environment resulting in significant social and economic benefits. In contrast, in previous years, without this new technique, the AP-star 1 satellite in end of life span would be replaced by new satellite and retire to be abandoned as space junk.

2) The constellation of satellite navigation and positioning system, improvement of navigation and positioning accuracy

In the new satellite control mode, the retired GEO communications satellite were regulated as SIGSO satellite to improve the geometry of the navigation constellation, reducing constellation DOP, and can further improve the navigation and positioning accuracy, therefore, it is obvious augmentation due to SIGSO satellite.

Chinese satellite navigation and positioning system (CAPS) purchased retired APstar-1 GEO communications satellite at 138° E orbit, and maneuvers to the 142° E orbital position to SIGSO satellite, it realized GEO communications satellites to reuse. A preliminary application system was configured by adding other two transponders in two GEO satellites, and barometer supplement to realize 3-D positioning. In 2005, the system has reached the GPS navigation and positioning accuracy in coarse code level, positioning accuracy of 10 m,

velocity accuracy is 0.2 m / s, timing accuracy of 12 ns [2, 12]. Communication data rate 50bps ~ 1.2kbps; spread spectrum bandwidth of $\pm 1.5\text{M}$; transmitting power 3W ~ 20W; BER $1 \times 10^{-5} \sim 1 \times 10^{-6}$; modulation is BPSK. Reusing retired satellites can extend the life span of the satellite more than 8 to 10 times, and the band-costing decreasing by about 80%. It will save investment and costing less than one-tenth of the new satellite launching to buy this satellite, or lease their transponders, this can generate significant economic benefits in terms of deploying navigation system and investment. The innovative satellite navigation and positioning system is featured lower cost, shorter deployment period and better performance.

Retired satellites often have full-band (C band) transponders, it can be used to navigation frequency change to become a multi-band satellite navigation system and find new way to improve anti-interference capability, lay the foundation for reuse retired GEO satellites. For example, currently, it is a rather large PDOP <10 region. SIGSO satellite orbital inclination increases along with regulation time (for example, when at about 7°), PDOP value is further reduced,

3) Developing a satellite communication system with a low data rate transmission and small satellite user terminals

GPS class satellite navigation system can provide user position, but its positioning message cannot transfer and communicate each other within the system. The satellite navigation system based communications transponders have a strong communication transmission capacity, easily achieved communicating positioning message, and enhance information value. Conventionally, we need to lease other GEO communication satellite transponders, but do need to increase the cost of transponder rental. Fortunately, we bought a retired GEO communications satellite with 24 transponders where two transponders use for navigation, in addition, using three transponders for tri-frequency measurement, so there are 21 transponders can be used for communication. Reuse of retired communications satellite is to turn waste into treasure, and make lower channel cost in this satellite communication system. Mobile Micro-Satellite Terminal (MMSAT) with wide-beam antenna are applicable to mobile communications, especially time, position and state message service in navigation system, the development of the spread spectrum communication system with low data rate and small antenna and user terminal can be used for short messaging, voice communication and transmission of static images in various fields such as traffic safety and vehicle management, calling, emergency rescue, search and rescue, emergency rescue and disaster relief, mobile TV and video broadcast. Satellite MMSAT terminal series can be formed to provide a short message and data communication services, which promote the application of satellite communications. Therefore, it is necessary to use more retired GEO communications satellite which provides a plentiful space transponder resource to give the full enhancement of combined navigation and communication.

NAOC in china has developed a class low data rate satellite communications technology with short text and data messages more than four years in vehicle monitoring and oceanic observation, recently, a class of low data rate voice communication system is developing.

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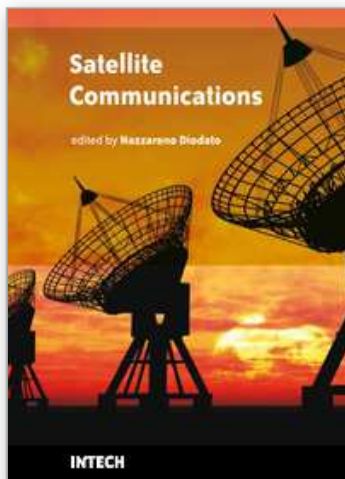
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