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The application of decommissioned GEO satellites to CAPS

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Abstract. To ensure the reliable service of geostationary earth orbiting (GEO) communication satellites during the period of in-orbit, the hardware design life of each system usually has some redundancies in contrast to the limited fuel used to keep the satellite position and attitude. After the brief analysis of the life of the satellite subsystems, the feasibility of turning the decommissioned GEO communication satellites into slightly inclined geosynchronous orbiting (SIGSO) satellites is proved. In addition, the role and the actual usage of SIGSO satellites in Chinese Area Positioning System (CAPS) are analysed and discussed, including the effect on the improvement of Position Dilution of Precision (PDOP) of the navigation constellation and the application to satellite communication system, thus the potential value of satellite material and devices is exploited.

1. Introduction

In recent years, with the development of space technology, more and more satellites have been launched into space and are widely used in communication, navigation, remote sensing, meteorology and space exploration, etc. Among them, GEO have become the preferred orbit of most satellites due to its wide coverage, continuous visibility and it's geosynchronous. Limited orbital space has become a scarce resource. Currently, the life of GEO satellites in orbit is generally 8 to 15 years, and the GEO satellites from some countries even can work in orbit for more than 15 years [1]. When a GEO satellite ends service or enters the end of life, in order to guarantee continual customer service, new satellite will be launched before the satellite decommissions. According to international convention, the original decommissioned satellites must shut down all the power and be pushed to the grave orbit about 300 km above geostationary orbit, become the space debris.

Decommissioning of satellite usually because of the lacking of carried fuel, it's difficult to continue maintain the position and attitude of satellite for a long time, when the structure and electronic equipment such as solar cells, signal transponders of the satellite remained intact, they can still work for a long time. In references [2], a scheme of maneuvering the end-of-life GEO communication satellites to SIGSO (slightly inclined geosynchronous orbiting) satellites was introduced. It has realized the full and reasonable utilization of the residual fuel and the electronic equipment such as transponders on the satellites, and has created the second life cycle of the end-of-life GEO satellites. Meanwhile, we use these SIGSO satellites and GEO communication satellites to constitute the space satellite constellation of CAPS (Chinese Area Positioning System), to transpond the carrier signal modulated ranging code and navigation message launched from the ground station, and to realize satellite positioning [3].

This work briefly introduces the influence factors of satellites life, analyzes and proves the feasibility of using decommissioned satellites as SIGSO satellites, and introduces the technology and application of SIGSO satellites in CAPS.

2. Satellite life and main influencing factors

The working life is one of the most important performance indexes of the satellites. Users tend to prefer the longer working life of the satellites, but the working life is restricted by various factors. The extension of satellite life will generally require higher or additional requirements for the satellite subsystems, which will increase the complexity and mass of the subsystem, resulting in the total mass and total cost of the satellite rising. Therefore, the extension of design life is at the cost of increasing satellite mass and development cost [5].

For the components of the satellites, the probability of failure is a function of time, and the typical failure rate curve is the Bathtub curve, as shown in Figure 1. The shape of the curve is high at both sides and low in the middle, with obvious stages, which can be divided into three phases: early life failures, random failures and wear out failures. The early life failures often occurs in the development stage before the satellites are launched, and the failure rate is high and decrease rapidly with the increase of working time. It is possible to eliminate faults by modifying design, improving production, screening of components and so on, so that the early life failure isn't as part of system failure in normal circumstances. The wear out failures generally occurs at the end of the equipment life and increases with the extension of time. When the device or equipment is developed, the life time can be extended by means of design method and production process, so that the device will not work to the wear out failures period before the satellites decommission. The failure rate in the random failures period is low and stable, which is generally regarded as the effective life of the equipment. The failures of this period is mainly due to working conditions, external environment conditions, error operation and other factors causing the equipment stress to exceed a certain intensity [6].

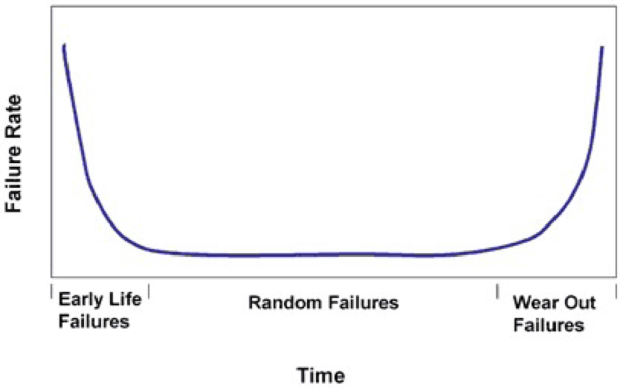

Figure 1. Bathtub curve of satellite equipment.

According to the operating situation of GEO satellites, the factors that affect the life of on-orbit satellites are mainly the space environment, equipment performance, the consumption on satellites and the ground misoperation.

The various perturbing forces of GEO satellites will cause the orbit and attitude disturbance, so it is necessary to constantly consume propellant fuel for attitude control and position maintenance. If satellite with large communication antennas and solar panels is affected by solar radiation pressure and earth's non-spherical gravitation, it will drift on east-west direction. The effect of lunisolar gravitation makes satellites drift on south-north direction, which is the most important factor that causes the change of the orbital inclination angle of the satellites [7]. On the other hand, space radiation will cause the problems such as flexible parts damage, reduced energy supplies, the device performance degradations, and star misoperation and so on. The space geomagnetic storm will affect the performance of the electromagnetic device and the electromagnetic environment of the satellites. In addition, the performance of solar cells and other devices will be reduced by temperature changes, solar radiation, and space electronics, etc. [6].

Due to the components on satellites work in random failure period, the failure rate is low and constant, and in the process of design and development, means of improving the satellite reliability such as the environment protection design, redundancy key components design and derating design are used, so the satellite life will not end except the occasional single point failures. The in-orbit situation of GEO satellite also shows that propellant used for attitude and orbit controlling is often carried according to design life due to restriction of launching mass. It will gradually reduce with use, eventually runs out and the satellites are out of control, so the propellant fuel becomes the main factors restricting the service life of the satellites.

3. Reuse of decommissioned GEO communication satellites

As mentioned above, when GEO communication satellites invalid at the end of life, the remaining fuel on satellites is not enough to maintain orbit position and satellite attitude for a long time. But other components, such as solar power and signal transponders, are still in good condition, even some spare parts are not used which can continue to work for many years. If GEO satellites are decommissioned at this time and pushed into grave orbit, it does waste the equipment and residual fuel on satellites, furthermore, more and more space debris also causes destruction to the valuable space environment around the GEO orbit. Therefore, the reuse of decommissioned GEO satellites has significant social and economic benefits.

The drift of GEO satellite orbit position is divided into two directions: north-south and east-west, usually the fuel consumption of north-south station-keeping maneuvers accounts for about 90%, which is about 10 times of fuel consumption of east-west station-keeping maneuvers. So if only maintaining position of satellites in east-west direction, and leaving uncorrected on north-south direction under the influence of lunisolar gravitation, they will gradually become SIGSO (slightly inclined geosynchronous orbiting) satellites. In this way the use time of the residual fuel of satellites will be extended by 10 times. After stopping control in north-south direction, the north-south drift of satellites leads to orbital inclination angle increasing gradually. The inclination angle increases about 0.75°~0.96° every year [9].

On the other hand, the performance of solar cells will decline gradually about 2% ~ 3% per year due to long-time use and the complex space environment, and the battery will charge and discharge repeatedly because of the satellite eclipse about 90 times every year. These can lead to a decline in the capacity of electric power supply of GEO satellites at the end of life. The normal work of most of the equipment can be guaranteed by turning some transponders off.

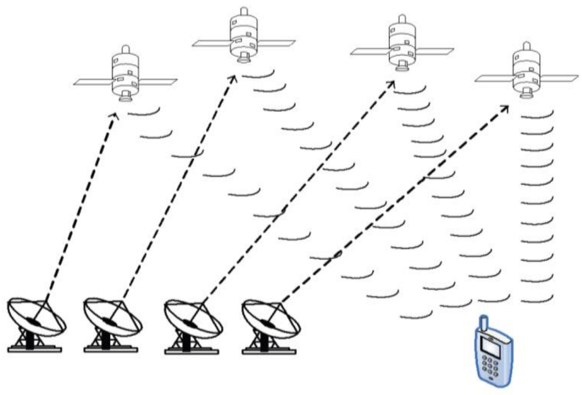

Figure 2. CAPS schematic.

4. Application of SIGSO satellites to CAPS

The CAPS (Chinese Area Positioning System) system is a transponding satellite navigation system based on communication satellites, which uses communication satellites to transpond the navigation signals generated by the ground station for the first time. The system can provide users with position, velocity and time service, and the system configuration is shown in figure 2.

4.1. Improvement of the CAPS navigation constellation by SIGSO satellites

For satellite positioning systems, satellite space geometry has important influence on the positioning accuracy, system availability and continuity, in general, position dilution of precision (PDOP) is used to describe the quality of satellites' spatial layout [9]. The positioning RMS error can be expressed as:

$$\sigma_{(x,y,z)} = \text{PDOP} \cdot \sigma_\rho$$

Where, $\sigma_{(x,y,z)}$ is the positioning error of the user receiver and σ_ρ is the user equivalent range error. It can be seen that PDOP values are amplification of user range error. Therefore, it is necessary to minimize the PDOP value in the navigation system constellation design to improve the positioning precision.

Since 2003, CAPS has leased commercial communication satellite transponders for experiments. But most communication satellites are GEO satellites, the leased satellites are all in the equatorial plane, so it's unable to achieve three-dimensional positioning. However the SIGSO (slightly inclined geosynchronous orbiting) satellites drifted from decommissioned GEO satellites fundamentally solved this problem. The drift quantity in north-south direction of SIGSO satellites greatly improve the constellation space layout, GEO satellites and SIGSO satellites constellation has completely realize three-dimensional positioning. To verify the contribution of the amount and orbit inclination angle of SIGSO satellites to PDOP value, the PDOP values every 10 minutes are calculated by using digital simulation, the tested fields include China and surrounding areas with 1° latitude×1° longitude grid, the results are as follows [11,12].

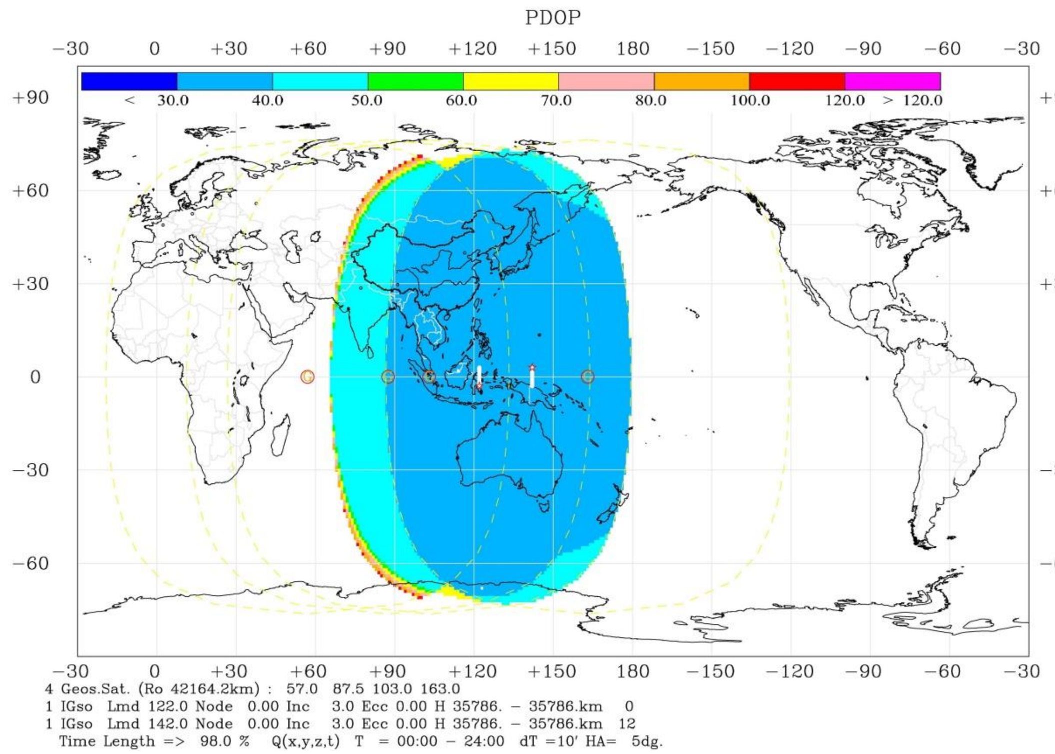

Figure 3. PDOP value of the constellation with 4 GEO and 2 SIGSO (3° inclination angle) satellites.

6 GEO satellites located at 57°E, 87.5°E, 103°E, 122°E, 142°E and 163°E orbits are used. First, we drift 2 of them which located at 122°E and 142°E into SIGSO satellites with 3° inclination angle, the daily mean PDOP values of China and surrounding areas are shown in Figure 3. It can be seen from the figure that the average daily PDOP values in China and surrounding areas are all less than 50. Except for parts of Xinjiang and Tibet, PDOP values of most areas are under 40. Although it is still large, it's possible to realize three-dimensional positioning. Next, we set the GEO satellite at 103°E as SIGSO satellite, constitute 3 GEO + 3 SIGSO constellation, average daily PDOP values are shown in Figure 4, PDOP values of Chinese territory are less than 20, it is obvious that the addition of SIGSO satellites can observably optimize the geometry of constellation. Finally, the orbital angle of 3 SIGSO satellites are increased to 5°, as shown in Figure 5, it can be seen that with the increasing of inclination angle of SIGSO satellites gradually, the geometry of the constellation will be continually optimized, PDOP value reduced to about 10.

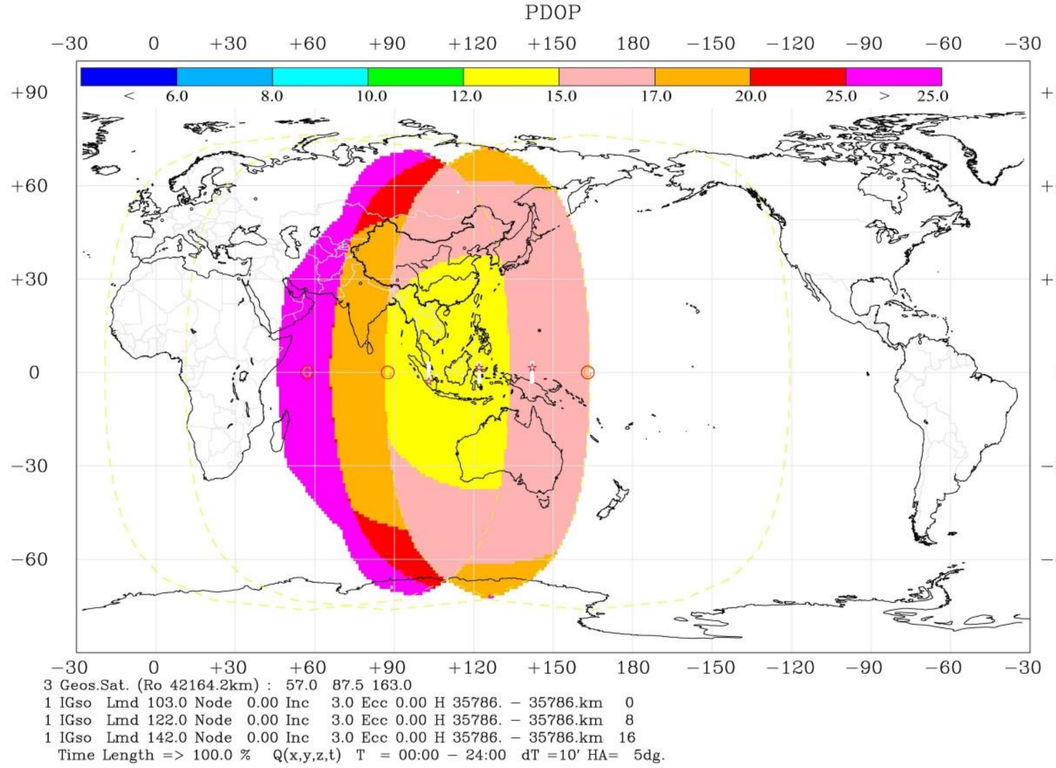

Figure 4. PDOP value of the constellation with 3 GEO and 3 SIGSO (3° inclination angle) satellites.

In CAPS constellation, two decommissioned satellites are controlled to be SIGSO satellites. They are the APSATR-1 satellite located at 138°E and the APSATR-1A satellite located at 134°E, respectively. When these two satellites are decommissioned, they have no any malfunctions, the 24 C-band transponders can still work, and even the six backup transponders are never used. Moreover, the remaining fuel can supply for 1 year, if we adopt the work mode of SIGSO satellites described previously, i.e. only maintain the east-west station-keeping maneuvers and allow to drift freely in north-south direction, then the fuel consumption of two satellites will be reduced 90%, and satellites can continue to be used about 10 years. It can greatly improve the service life and utilization of satellites and the equipment.

In 2004, the APSATR-1 satellite located at 138°E was drifted into the orbit at 142°E, meanwhile, stopped north-south station-keeping maneuvers, and drifted freely to be SIGSO satellite. Until 2014, the orbital inclination angle of APSATR-1 satellite has been drifted to 9°, but the fuel exhausted, the satellite was officially invalid and pushed into the grave orbit, while the equipment such as transponders can still work normally. During the 10 years of reutilization of APSATR-1 satellite, it constituted the space constellation of the CAPS system together with the GEO satellites, and assisted by the pressure measurement technology, the CAPS system successfully realized the three-dimensional positioning. At the same time, a number of experiments and research projects have been completed.

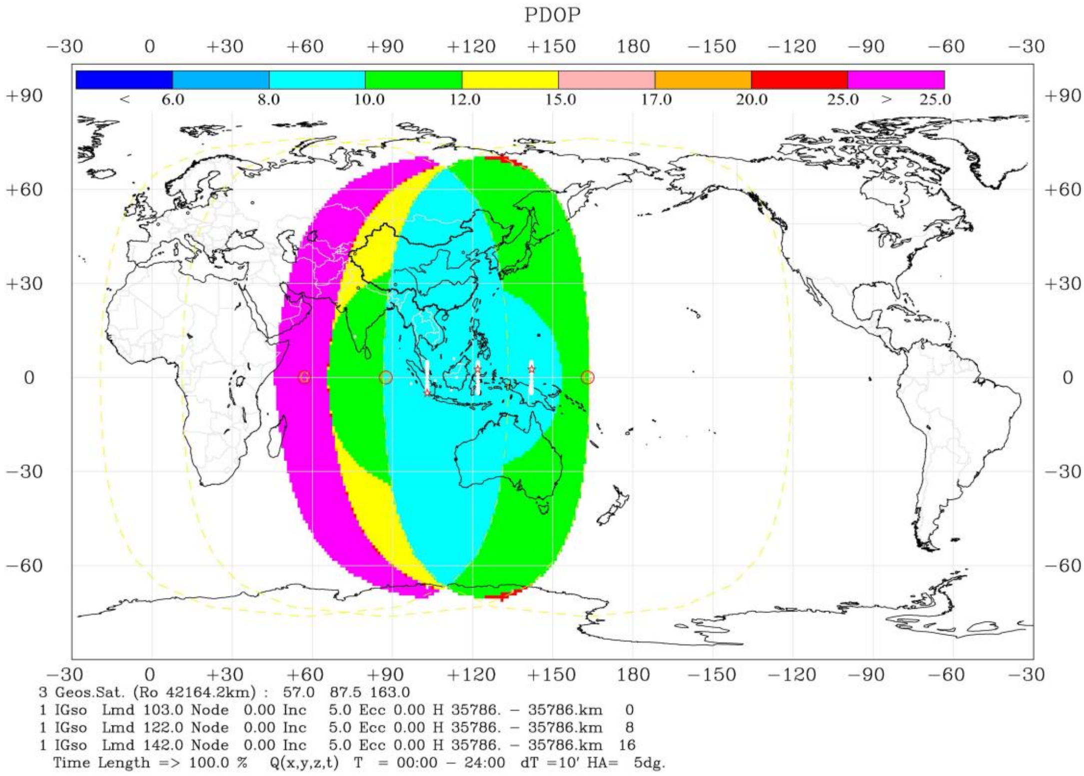

Figure 5. PDOP value of the constellation with 3 GEO and 3 SIGSO (5° inclination angle) satellites.

4.2. Application of SIGSO satellites to CAPS satellite communication

After the decommissioned GEO satellites are re-used as the SIGSO satellites, due to the change of orbit, the original business ceased or is undertaken by other GEO satellites. All 24 signal transponders on the SIGSO satellite are idle. Except two transponders are used for navigation and positioning applications, and some transponders are closed to reduce the power supply load of solar cells and batteries, there are still many transponders can be used continually for satellite communications business. CAPS system is an integration of navigation and communication system based on communication satellites, therefore, SIGSO satellites with abundant frequency bandwidth and transponders can provide a large number of precious resources for communication, and make the CAPS system combine the advantages of navigation system and communication system, so it can provide the location and time information communication when position, velocity and time are determined. The low rate (50 bps~1 kbps) information transmission based on SIGSO satellites can contain a large number of terminals to realize communication, and can make up the covers insufficient defects of the current communication methods in remote areas, mountains and sea areas. Combined with satellite positioning, it is widely used in vehicle management, disaster relief, satellite search and rescue, combat command, etc., with the advantages of fast, cheap and reliable.

The communication with SIGSO satellite also faces some new problems. For example, the information transmission rate of CAPS communication system is less than 1kbps, forming a new low rate satellite communication system. At the same time, the SIGSO satellite is different from the GEO satellite, the earth trace of satellite has "8" shape. In order to track the SIGSO satellites, it needs to increase the antenna beam width. Considering the factors as antenna gain and cost performance, the antenna diameter of communication center station is about 10~15 meters. In addition, to prevent the interference of the wide beam uplink signal to the adjacent satellites, the power limited communication signal needs to adopt the spread spectrum technology, and the amplification gain is about 40 dB [12].

Based on the technology mentioned above, the CAPS satellite communication system has successfully taken several experiments and obtained good results. The testing field of CAPS communication experiment in Tianjin is shown in figure 6. This indicates the feasibility of applying SIGSO satellites to satellite communication. The long-term stable operation of the CAPS system has also verified the reliability of the decommissioned GEO satellites, and the research and experiment of the integrated navigation and communication system have application value and social value.

Figure 6. Testing field of CAPS communication experiment.

4.3. Application of SIGSO satellites to the maintenance of frequency and orbital resources

With the development of space technology around the world, more satellites are competing for limited GEO orbital position, which is a very important space resource. Orbital positions need to be occupied by satellites in order to retain the right to use orbit. As a result, the decommissioned GEO satellite can be used as an effective satellite in orbit with its fewer services and longer running time. These satellites can maintain national satellite frequency and orbital resources while maximizing the use of the equipment. Since 2004, the decommissioned APSATR-1 satellite stayed at 142°E orbit for a long time, serviced for the CAPS navigation and communication experiments. In 2012, when the fuel was running out, APSATR-1 satellite was moved into 163°E orbit, until completely ran out of fuel in 2014. It retained orbit position for the new GEO satellite. Also, the APSATR-1A satellite was moved into 115.5°E, 125°E, 130°E and 51.5°E orbit position for a short time, to protect the orbital and frequency resources. In 2015, CAPS bought decommissioned satellite MEASAT-2 at 148°E position now. It will be able to use until about 2025, servicing for CAPS navigation and communication project.

5. Conclusions

CAPS (Chinese Area Positioning System) is a new navigation and communication system based on communication satellites. The experiment results and project acceptances have proved the feasibility of CAPS navigation and communication technology after years of effort and overcoming difficulties, and have had solid foundation. In CAPS, SIGSO (slightly inclined geosynchronous orbiting) satellites transformed from decommissioned GEO communication satellites are important component. CAPS use SIGSO satellites to achieve positioning and communication functions innovatively, so that greatly improve the service efficiency and life of decommissioned satellites. During the process of using, CAPS develops the unique advantages of SIGSO satellites.

In order to extend the service life of decommissioned GEO satellites, we only maintain the position in east-west direction and make them drift freely in north-south direction at an annual rate of about 0.85° orbital inclination into SIGSO satellites. The SIGSO satellites can provide the navigation constellation of CAPS with the north-south drift distances which can improve the spatial constellation geometry, reduce the PDOP value, and improve the positioning accuracy. At the same time, decommissioned satellites have abundant C-band full frequency transponders. On the one hand, they can provide more options for navigation, for example, three frequency or multiple frequency positioning, changing frequency and hopping frequency navigation, etc., so that improve the anti-interference ability of the satellite navigation system significantly. On the other hand, a large number of redundant transponders can be used in satellite communications, and they can also be used for short message transmission, voice communication and so on at the time of navigation and positioning services. In addition, extending the life of GEO communications satellites can help preserve the valuable GEO orbital position and frequency resources, so as not to lose the use priority because of lacking a satellite in orbit for a long time.

The reuse of decommissioned GEO communication satellites not only reduces the cost of the CAPS system construction, but also maximizes the use of the residual fuel and transponders aboard the satellites. Years of practical use have demonstrated that the SIGSO satellites can do play a unique role in CAPS system.

The research and application of decommissioned GEO satellites proved that the whole service life of the important equipment and devices often is not limited by material strength and service life of most devices, but is only restricted by a few conditions of use. So we can change the restraint condition, it is possible to make the material and most devices to extend the service life and make the material and devices play more role.

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