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Review on strategies of space-based optical space situational awareness

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Abstract: Space-based optical (SBO) space surveillance has attracted widespread interest in the last two decades due to its considerable value in space situation awareness (SSA). SBO observation strategy, which is related to the performance of space surveillance, is the top-level design in SSA missions reviewed. The recognized real programs about SBO SAA proposed by the institutions in the U.S., Canada, Europe, etc., are summarized firstly, from which an insight of the development trend of SBO SAA can be obtained. According to the aim of the SBO SSA, the missions can be divided into general surveillance and space object tracking. Thus, there are two major categories for SBO SSA strategies. Existing general surveillance strategies for observing low earth orbit (LEO) objects and beyond-LEO objects are summarized and compared in terms of coverage rate, revisit time, visibility period, and image processing. Then, the SBO space object tracking strategies, which has experienced from tracking an object with a single satellite to tracking an object with multiple satellites cooperatively, are also summarized. Finally, this paper looks into the development trend in the future and points out several problems that challenges the SBO SSA.

Keywords: space situation awareness (SSA), space-based space surveillance, space-based optical (SBO) observation strategy, general surveillance, space object tracking.

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1. Introduction

With the increase of space activities, the number of space objects grows steadily, then the problem how to manage space objects and prevent the collision events, becomes very important. Especially, a mass of space debris brings a great threat to on-orbit spacecraft and future space activities. According to the information of space objects catalogued by the U.S. Space Surveillance Network (SSN) (released on http://celestrak.com/), there are 45 357 space objects catalogued, and 20 470 of them are still in orbit up until March 15, 2020 (coordinated universal time, UTC). Besides, there are hundreds of thousands of small debris that cannot be catalogued because few effective observations can be obtained.

The number of new catalogued and decayed space objects each year is shown in Fig. 1. According to the statistical history data, the growth of space objects is usually larger than the decay of space objects, indicating that the number of on-orbit space objects will maintain a steady increase. However, the increase may be faster with the coming of the NewSpace (also called Space 2.0) era [1]. The space can be accessed faster and cheaper which triggers a lot of commercial and private space activities. Many companies, such as SpaceX, OneWeb, and Sumsang, have proposed their large constellation plans [2] to meet the requirements of the applications on global communications and internetwork, and some of these plans have already been approved and carried out. In particular, the U.S. federal communications commission has given SpaceX permission to launch 4 425 low earth orbit (LEO) satellites and 7 518 very LEO satellites, forming a mega constellation named Starlink composed by nearly 12 000 satellites [3]. Up until March 18, 2020 (UTC), 360 Starlink satellites have been deployed successfully. These large constellations may change the space environment in LEO and have an impact on future activities [4].

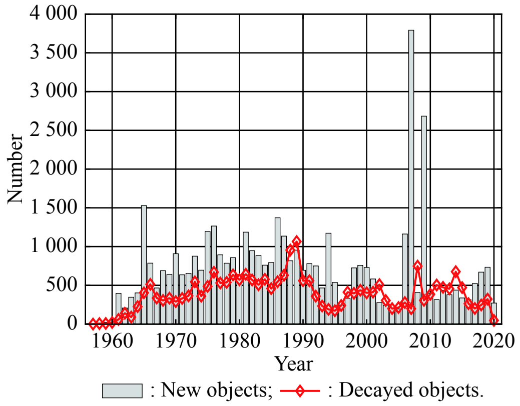

Fig. 1 Number of annually new catalogued and decayed space objects

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In addition, there are another two very important regions, i.e., medium Earth orbit (MEO) and geosynchronous orbit (GEO). To make up for the dead satellites and develop new applications, more and more satellites will be sent to these regions. Fig. 2 shows the total number of catalogued on-orbit objects in MEO and GEO. Due to the very long natural decay period (usually measured in thousands of years for a GEO object [5]), these regions will become more and more crowded. Increasing space objects will bring great pressure to ground stations, and challenge the safety of space activities and the stability of future space environment.

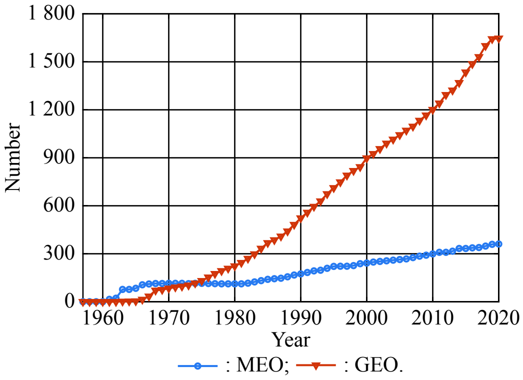


Fig. 2 Number of on-orbit space objects in MEO and GEO

On February 10, 2009, the first collision event in human history between two satellites happened: the Iridium-33 satellite collided with the Cosmos-2251 satellite over the North Pole, creating a large number of debris [6]. After orbital evolution, these debris were widely distributed in a LEO region, causing serious impact on the space environment. Once the number of space objects in a region reaches the threshold, where the environment is unstable, the collisions will occur and make new debris, which in turn, will create new collisions and make the environment worse and worse [7,8] like a “chain reaction”. Finally, it will cause irreversible effects on the Earth’s space resources and thus, it is necessary to take effective measures to protect the space environment. To govern the space environment, the Inter-Agency Space Debris Coordination Committee (IADC) proposed the Space Debris Mitigation Guidelines [9] which was voted through the United Nations in 2007. One of the important mitigation measures is “post mission disposal”. The Guidelines indicates that the LEO satellites should follow the “25-year rule”. That is, an LEO satellite should use the rest energy to deorbit after finishing its missions to guarantee it can re-enter the atmosphere and decay within 25 years. For a GEO object, it is required to maneuver to the graveyard orbit (about 235 km above GEO) at the end of its life to protect the GEO region. To ensure the implementation of the Guidelines, effective supervision is necessary.

Toward the deteriorating space environment and the requirements of space activities, it is necessary to develop space situational awareness (SSA) technologies. With the support of SSA, space objects are catalogued and under surveillance, which guides the optimal design of spacecraft, collision warning of on-orbit spacecraft, etc., is essential for space activities. In addition, SSA is the base of the international governance of the space environment and the supervision of the Guidelines’ implementation.

SSA relies on the SSN. Many countries have established their SSNs, such as the U.S. Air Force SSN [10] and the ground-based electro-optical deep space surveillance system [11], the space debris telescope of the European Space Agency (ESA) on Tenerife [12], the Australian SSN [13], and the international scientific optical network (ISON) [14]. Most of them are mainly composed of ground-based equipment, including radars or photoelectric telescopes. However, ground-based observation methods have many limitations. The ground stations are required to be widely distributed to observe space objects as more as possible. Otherwise, they are easily to be constrained by geographical conditions. The power received by the radar is inversely proportional to the biquadrate of the distance from the observed objects. Thus, it is disadvantageous to observe space objects in high Earth orbit (EO). Ground-based telescopes are susceptible to the environment and the weather, so that they cannot operate continuously. In order to improve the performance of SSA, space-based space situational awareness technologies have been developed.

Space-based radars and laser systems have high energy consumption, which limits their applications. In addition, comparing with ultraviolet and infrared measures, the space-based visible or optical measure is more suitable for observing space objects, especially debris. After a lot of engineering practices, it is demonstrated that space-based optical (SBO) observation is effective for SSA. This method depends on SBO sensors that capture the reflected sunlight of observed space objects, having the following advantages: low energy consumption, light weight, high reliability, long observation distance, and the ability of observing multiple space objects.

The strategy of SBO SSA is the top-level design for SSA related works, as shown in Fig. 3. Under the strategy level, there is the state estimation level to determine the orbits of space objects. Meanwhile, the performance of the application level, such as the optimal protection structure design of spacecraft, collision warning and avoidance, maneuvering detection, and threat detection, is highly dependent on the output of the state estimation. In other words, the strategy of SBO SSA will influence the final applications. Due to the important position in SSA, this paper surveys the existing strategies of SBO SSA. Other parts in Fig. 3 are independent research areas and thus, they are not reviewed in this paper. In Fig. 3, dashed lines means that the item is optional.

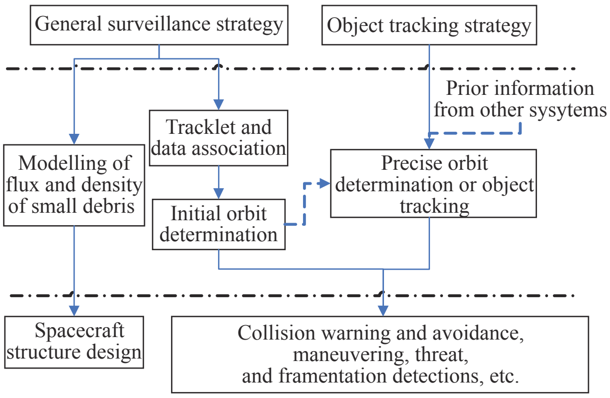


Fig. 3 Relations of strategy of SBO SSA and other related research areas

2. SBO SSA programs

Many countries and organizations have proposed their SBO SSA plans, including the U.S., Canada, ESA, China, and Russia. Some of the plans have been accomplished, and some of them are still under research. Fig. 4 shows a time chart, indicating that when these plans came into effect (U.S. and Canada) or were proposed (ESA). The plans proposed by China and Russia are rarely mentioned in open literature and not shown in Fig. 4. In this section, an overview of these plans will be presented.

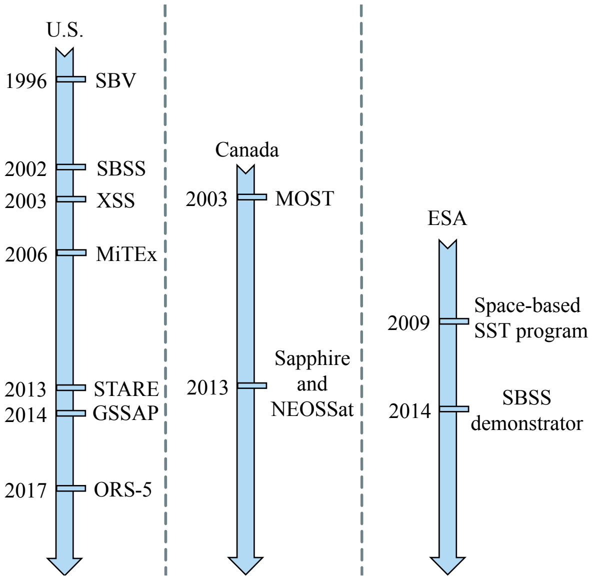


Fig. 4 Time chart of the SBO SSA programs proposed by U.S., Canada, and ESA

2.1 Plans of the U.S.

2.1.1 SSO-based programs

In 1996, the U.S. started to carry out the proposed Space-Based Visible (SBV) program [15]: the Midcourse Space Experiment (MSX) satellite was launched into an 898-km altitude, near sun-synchronous orbit (SSO), and one of the principal sensors on board is the SBV sensor developed by the Massachusetts Institute of Technology Lincoln Laboratory. This was the first demonstration for the space-based space surveillance in the world. The SBV sensor is the focal-plane array with four low-noise charge-coupled-device (CCD), each of them has a field of view (FOV) of 1.4°×1.4°. In the experimental phase, over 10 000 observations of resident space objects (RSOs) were collected, and over 95% of them belonged to deep space objects (more than any other SSN sensors) [16]. In addition, SBV sensor has high observation accuracy, which was possible to reach 2-arc-s metric accuracy according to the measurements obtained by observing the Global Navigation Satellite System (GLONASS) and laser geodynamics satellite (LAGEOS) satellites [17]. The excellent experimental results validated the feasibility of SBV observation. Hence, the SBV program became the pathfinder of the subsequent SBO plans.

In view of the good performance of the SBV program, the U.S. started to develop the state-of-the-art space-based system for the next generation, i.e., the Space Based Space Surveillance (SBSS) system. In 2002, the U.S. Air Force proposed the preliminary scheme for the SBSS system [18], planning to construct a satellite constellation with expected three to eight satellites in SSO, each carries a widefield SBV sensor. In 2010, the first satellite, SBSS Block-10, was launched, and an average of 15 000 observations per day can be obtained, including GEO objects as small as a one-meter cube [19]. The follow-up plans of the SBSS grogram are still in progress.

2.1.2 NEO-based programs

In 2014, the U.S. announced the Geosynchronous Space Situational Awareness Program (GSSAP) aiming at providing significant improvement in space object surveillance in GEO. In 2014 and 2016, four satellites of the GSSAP were successively launched into near-geosynchronous orbits (NEOs), a type of nearly equatorial orbits, each of them had an electrooptical sensor payload to characterize the objects in GEO [23].

In 2017, the ORS-5 satellite was launched for the operational demonstration of SSA. The Lincoln Laboratory was responsible for the design of the SensorSat, which can scan the GEO belt from LEO [24]. The ORS-5 chose a low-altitude NEO, for which the inclination is 0°, to guarantee observing GEO objects rapidly. The goal of the ORS-5 program was to demonstrate the cost-effective

GEO SSA technology. In addition, it was expected to be used cooperatively for SSA with current SBSS satellites.

2.1.3 Proximity observation programs

In 2003, the XSS-10 microsatellite was launched into a circular LEO, with an inclination of 39.8° and an altitude of 800 km. XSS-10 mission was to demonstrate the proximity operations with an RSO. XSS-10 can maneuver to a LEO object 800 m away and photograph with the onboard visible camera [25].

In 2006, the U.S. carried out the Micro-satellite Technology Experiment (MiTEx). Two satellites with the onboard visible cameras payload were launched into the near GEO to perform a series of proximity observation experiments [26]. Besides, the subsequent GSSAP satellites also have the capability to maneuver and perform proximity observations for a GEO object.

2.1.4 Other programs

In 2012 and 2013, to support the Space-based Telescopes for the Actionable Refinement of Ephemeris (STARE) mission, the STARE-A and STARE-B nanosatellites were lunched respectively, a collaboration led by Lawrence Livermore National Laboratory and Texas A&M University, with the aim of observing debris in LEO and improving the accuracy of collision analysis [20]. Each STARE satellite carried an optical telescope which can detect debris at a distance of 100 km, with a relative speed of less than 3 km/s. The first two STARE satellites chose an elliptical LEO (480 km perigee, and 770 km apogee) with the inclination of 60º [21]. It was announced that the STARE has the capability to reduce the collision false-alarm rate by 99% with a constellation composed of 18 nanosatellites [22].

2.2 Canadian plans

In 2003, Canada launched its first space-based surveillance satellite-Microvariability Oscillations of Stars (MOST) microsatellite. It operated in the dawn-dusk SSO (local time of ascending node is 06:00) at the inclination of 98° with an optical telescope payload. During the operation, MOST successfully tracked GPS IIR-11 and GPS IIR-04 satellites [27]. The MOST program is the pioneer of the following Canadian space-based surveillance programs.

Since 2007, Canada focused on developing its new space-based surveillance system, that is, the Sapphire System comprised by the Sapphire Satellite, which is a small satellite with an electro-optical sensor payload, expecting to detect a minimum of 360 objects daily ranging from 6 000 to 40 000 km in altitude [28]. Sapphire was scheduled to operate in a dawn-dusk SSO at an altitude of approximately 750 km (finally 786 km). The design of Sapphire's optical sensor was the heritage from the SBV sensor, aiming to achieve 6-arc-s observation accuracy for objects from the 6th to the 15th magnitude [29]. Sapphire was successfully launched in 2013 and acted as a contributing sensor for the U.S. SSN [30].

As the follow-up of the MOST, the Near Earth Orbit Surveillance Satellite (NEOSSat) project was kicked off in 2005. Different from Sapphire, NEOSSat microsatellite was developed for high earth orbit space surveillance (HEOSS) and near earth space surveillance (NESS), i.e., to detect GEO objects and asteroids, although its orbit was similar to Sapphire because of the shared launch in 2013 [31]. During the operation, NEOSSat microsatellite performed a series of experiments and obtained impressive results [32,33]. On February 11, 2020, Canadian Forces announced that NEOSSat captured imagery of the North Grumman MEV-1 spacecraft approaching Intelsat-901 in GEO; on March 7, 2018, NEOSSat tracked 2017-VR12 asteroid closely at its Earth fly-by. Besides, it also tracked space activities in LEO, for example, Sapphire in conjunction with Iridium-16 was observed on June 29, 2018. NEOSSat's success further proved the important application values of SBO observations on SSA.

2.3 ESA's plans

Since 2009, ESA has been undertaking its SSA program with three segments, including Space Weather (SWE), NEOs and Space Surveillance and Tracking (SST) [34]. The SBO observation was an important measure to perform the missions of SST and observe NEOs.

In 2014, ESA completed the assessment study for space based space surveillance demonstration system. The capability of an SBO sensor orbiting in LEO to observe objects in and beyond LEO, including MEO, GEO, geostationary transfer orbit (GTO), highly-elliptical orbit (HEO), and Molniya, was investigated [35]. The microsatellite platform with an optical telescope payload was proposed and expected to operate in an SSO with an altitude of 700 km to detect small debris and very fast objects [36]. Besides, ESA also did a lot of research on the observation strategy. This program is still under progress.

2.4 Other plans

In July, 2013, China launched three satellites to LEOs and it is reported that one of the satellites will carry out the experiment of space-based optical observation for space debris [37]. According to [38], Russia also proposed some SBSS programs, but most of them mainly focus on the ballistic missile early warning.

2.5 Discussion

Some of the key parameters of the proposed SBO surveillance missions are summarized in Table 1. To cover the shortage of ground-based SSNs, most of the SBO SSA programs were designed for observing the objects beyond LEO, especially in GEO. However, the good performance of SBO sensor also allows it to detect small debris in LEO. Therefore, SBO sensors usually have strong ability to observe objects in different orbits.

Table 1 Parameters of some proposed SBO surveillance missions

Program	Instrument orbit	Mission	Detector	Mass/kg
SBV MSX [15,39]	898-km altitude, near SSO	Observing objects from LEO to beyond GEO	CCD (FOV: 5.6°×1.4°)	2812 for launch
SBSS Block-10 [18,19]	SSO	Observing objects from LEO to beyond GEO	Heritage from SBV	<1100 for launch
STARE A and B [21,22]	Elliptical LEO	Detecting debris in LEO	COMS (FOV: 2.08°×1.67°)	<10 for launch
GSSAP [23]	Around GEO	Observing objects GEO	–	–
ORS-5 [24]	600-km altitude, EO	Scanning GEO belt	CCD	140 for satellite
XSS-10 [25]	800-km altitude, 39.8° inclination	Proximity observation of LEO objects	CCD	31 for satellite
MiTEx [26]	GEO	Proximity observation of GEO objects	–	225 for satellite
MOST [27]	830-km altitude, SSO	Measuring bright star	CCD (FOV: 0.23°×0.8°)	<100 for satellite
Sapphire [28]	786-km altitude, SSO	Observing objects from LEO to GEO	CCD (FOV: 1.4°×1.4°)	150 for satellite
NEOSSat [30]	780-km altitude, SSO	Observing GEO objects and near Earth asteroids	CCD (FOV: 0.85°×0.85°)	73 for satellite
ESA's SBSS Demonstrator [36]	700-km altitude, SSO	Observing objects from LEO to beyond GEO	CMOS (FOV: 3°×3°) CCD (FOV: 2.74°×2.74°)	≤150 for launch

Illumination condition has the most influences on the optical observation. Therefore, most of the observation satellites chose to operate in SSOs, especially dawn-dusk SSO, to obtain the optimal and similar illumination condition during operation. In this case, the SBO sensor always points opposite to the sun, such that it is easier to detect objects. However, due to the limitation of observation strategies or the ability of SBO sensors, SSO-based methods usually cannot access the whole GEO belt in a short period and thus, the NEO-based methods is necessary. For example, the U.S. ORS-5 satellite can scan GEO belt rapidly from LEO, making up the gap of the SBSS system.

In view of the development of the SBO SSA, establishing a comprehensive system is necessary to improve the space-based SSA ability. In addition, due to the advantages of SBO sensors, the observation platforms are progressing to be smaller and cheaper. Therefore, the SBO SSA will become more low-cost and popular in the future.

3. Preliminaries

Some necessary preliminaries are introduced in this section to help understand the SBO SSA strategy design.

3.1 Constraints of SBO observation simulation

The simulation of space-based optical observation mainly includes three types of physical constraints. They are visibility condition, brightness condition, and FOV condition. The process of judging the visibility of an object is shown in Fig. 5. The visibility condition means that the line of sight (LOS) from the sensor to the object cannot be blocked by the Earth body, atmosphere, and other RSOs. The brightness condition is a comprehensive index influenced by the performance of the sensor, the characteristics of the object (shape, cross-sectional area, material, etc.), distance, and illumination condition [40]. In general simulations, it can be assumed that the brightness condition is satisfied if the object is within a certain distance and under certain illumination conditions, including that the object cannot be sheltered by the Earth shadow and the sun angle must be less than a certain value. The FOV condition is related to the adjustment capability of the sensor's pointing and the size of the sensor's FOV. The object can be observed only if it is in the FOV of the sensor.

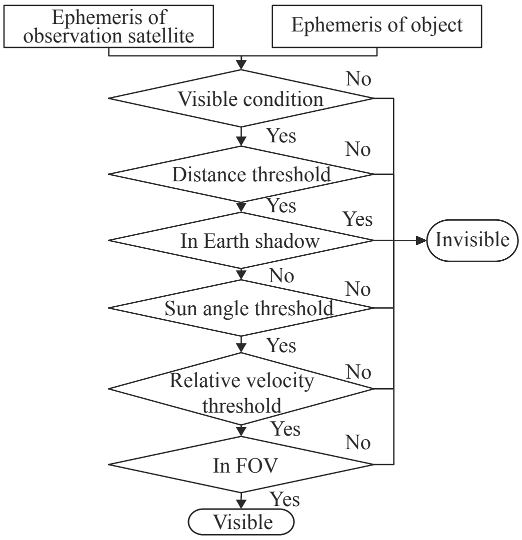


Fig. 5 Process of judging visibility of an object

3.2 Distribution characteristics of space objects

Analyzing the characteristics of space objects is the basis of designing efficient observation strategies.

LEO satellites are widely distributed in the whole sphere. However, many of them will pass through the regions above the North and the South Pole, where there is a high collision risk. In addition, LEO debris mainly operates in orbits of inclinations between 60° and 105° [41]. For MEO, geostationary transfer orbit (GTO), and Molniya objects, certain regions where they pass with high probability or stay for a long time, also can be found (MEO: the regions above the North and the South Pole; GTO: equatorial region; Molniya: the region above the North Pole) [42].

Most of the GEO objects operate within the GEO belt, for which its edges are two curves with equal-widths and sinusoidal shapes, and the declination width of the GEO belt at any right ascension is 15° approximately [43,44], as shown in Fig. 6.

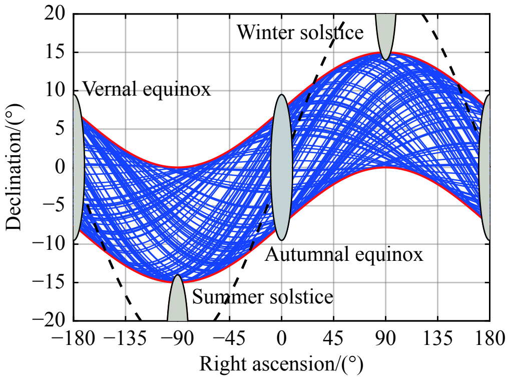


Fig. 6 Variation of Earth shadow on GEO belt during the whole year

3.3 Influence of obliquity of ecliptic

The obliquity of the ecliptic is about 23.5°, and the revolution of the Earth changes the influence region of the Earth shadow in the inertial space. This is very important for the observation of GEO objects because a part of the GEO belt will be sheltered at certain times in the whole year, as shown in Fig. 6.

Due to the existence of the obliquity of the ecliptic, the observation of GEO objects will be influenced by the Earth shadow around the vernal equinox and autumnal equinox, while the Earth shadow has little impact on the observation around the summer solstice and the winter solstice.

3.4 Image processing

SBO sensors utilize photography technologies to observe the space objects [15]. For typical SBO sensors, raw observation data are images, in which there are stars and objects appearing as pixels. With the image processing algorithm, the pixels of preselected stars and observed objects are extracted. The stars are then matched to a catalog of known stars. Using the star-fit residuals, the pointing of the SBO sensor can be determined accurately. Finally, by using this information, the points of the observed object in the image can be transformed to absolute angular positions in the inertial space.

The performance of SBO observation highly depends on the brightness condition. When an object is observed, the worse brightness condition (for example, bigger sun angle) will cause larger observation noise.

4. General surveillance strategy

The mission of general surveillance of space objects is to detect and catalogue new objects, and maintain catalogued space objects by updating their states. Thus, its aim is observing objects in a region, such as in LEO, MEO, or GEO, as much as possible, and guaranteeing that observed objects can be revisited in time. To achieve this goal, most of the surveillance strategies focus on how to observe the most objects in the shortest time with a reasonable visibility period. In this section, different surveillance strategies are summarized and compared.

4.1 General surveillance for beyond-LEO objects

To observe beyond-LEO objects as much as possible, two basic strategies are usually used, as shown in Fig. 7. One is to make the sensor point to a certain region, and the objects can be observed when they pass through it. In this case, observation satellites are usually deployed in SSO. The other is to let the sensor scan a wide region where the objects are. In this case, NEO is the best choice.

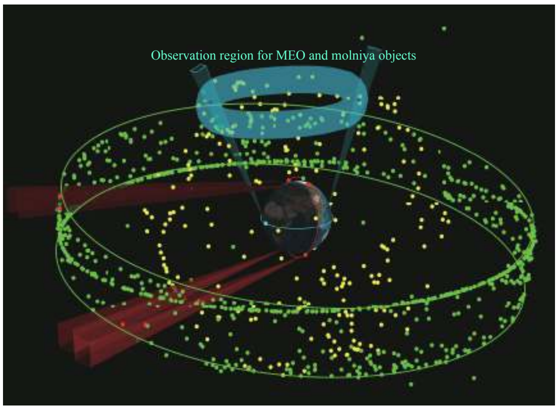


Fig. 7 Scheme of observing MEO, GEO, and Molniya (not shown) objects with SSO and NEO satellites

4.1.1 SSO-based strategy

Most of the SSO-based strategies choose dawn-dusk SSO to deploy observation satellites, because similar illumination conditions can be obtained during the operation. In this case, the sensor usually points orthogonally to the orbital plane to have the best illumination condition. According to whether adjusting the pointing of the sensor when performing the SSA mission, the observation strategies can be divided into three types: passive, active, and semi-active strategies.

(i) Passive observation strategy

The passive observation strategy is the simplest and the least energy-consuming, because the sensor is fix-mounted on the satellite with certain elevation and azimuth angles and the objects will be scanned with the revolution of the observation satellite. In this case, the observation region will be an annulus in the inertial space. In addition, with different elevation angles, the size of the observation region will be larger or smaller if the satellite is earth-oriented, while the position of the observation region in the inertial space will be various if the satellite is inertia-oriented [44].

Focusing on observing geostationary orbit objects, the GEO belt can be simplified as a rectangle shape. To revisit all the objects, the key step of the strategy design includes optimizing the orbital period of the observation satellites to make sure all the GEO belt can be scanned in the shortest time. It can be found that the goal is much easier to be achieved with the increase of the FOV of the sensor. Diao et al. [45] employed a four-satellite constellation to make up the limitation of the FOV (the FOV of each sensor is 3°×3°), and almost all the geostationary orbit objects can be revisited within one day. Flohrer et al. [46] focused on observing the GEO objects and a sensor with larger FOV (6°×6°) orbiting on 800 km altitude SSO was employed. With optimal sensor’s elevation angle, the revisit time of all the GEO objects is on average from every one and a half to three days.

For observing GEO objects, the passive observation strategy is limited by the “seasonal drop” problem [46]. The shape of the GEO belt and the variation of Earth shadow influence the observation efficiency in different months of the year. For SSO-based strategies, the shape of the GEO belt challenges the observation around the summer and winter solstices, while the Earth shadow challenges the observation around the vernal equinox and autumnal equinox. As for observing other beyond-LEO objects, due to their distribution characteristics, the performance of the SSO-based passive observation strategy is usually unsatisfactory.

(ii) Active observation strategy

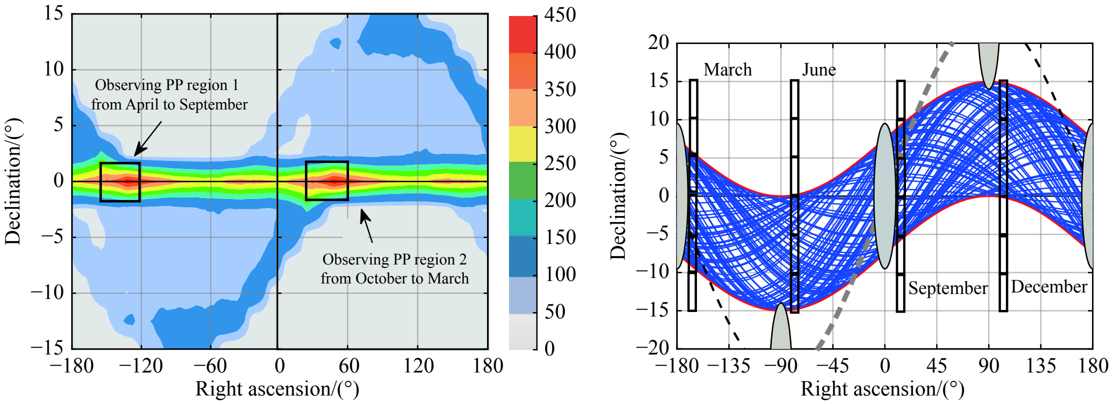
The active observation strategy needs the pointing of the sensor change with the revolution of the satellite, so that a fixed region in the inertial space can always be covered. In this case, the sensor will take the sidereal stare mode (SSM) [28], and stars will appear as point sources and observed objects will appear as streaks in the obtained images.

Many of the active observation strategies are designed based on the pinch point (PP) regions in the GEO belt. Lincoln Laboratory found that most of the GEO objects would pass through two fix regions in the inertial space [18], as shown in Fig. 8(a). According to this property, the efficiency for observing GEO objects can be improved if the sensor always points to the PP regions to establish observation fences on them. Taking this model, the SBV sensor obtained more than 350 tracks per day in October [47].

Wu et al. [48], Wang et al. [49], and Tang et al. [50] proposed their observation strategies for observing GEO objects based on PP regions. The simulation results showed that observation efficiency can be significantly improved by employing satellite constellation to scan the PP regions. However, the observation strategies based on the PP regions have the following defects: (i) due to the limitation of the observation geometry, PP regions are not always visible so that multi-satellites are needed to achieve continue observation; (ii) to observed PP regions, the illumination condition varies during the whole year and thus, it is not the best in most cases; (iii) the PP regions will be sheltered by the Earth shadow around the vernal equinox and autumnal equinox, then the strategy will fail. To overcome these shortages, Diao et al. [51] proposed that the sensor should point to the regions beside the Earth shadow, where the illumination condition is the best, if the illumination condition is unsatisfactory when observing PP regions.

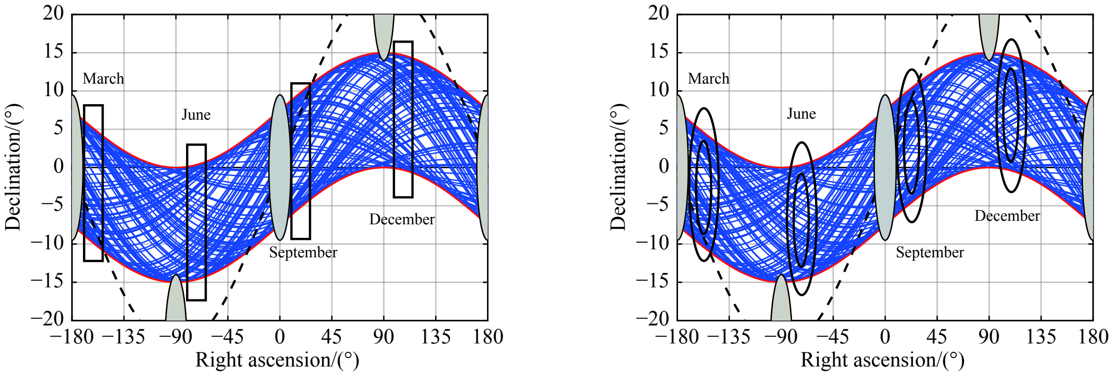
Unfortunately, the PP regions are diffusing and will disappear in the future according to the evolution of GEO objects [52]. Therefore, strategies based on observing PP regions may be inapplicable on the future surveillance for GEO objects.

The ESA’s team, Shilha et al. [35] proposed the leak proof strategy to observe the beyond-LEO objects, especially GEO objects, as shown in Fig. 8(b). That is establishing multiple fences by using the sensor (FOV: 5°×5°) scanning from lower declination to higher declination at specific right ascension to “cut off” the GEO belt. However, some of the objects will escape the fences (about 15% of GEO objects) due to the time gap of “cutting off” the GEO belt once, and some fences are of lower efficiency of observation, such as the bottom fence around the winter solstice (see Fig. 8(b)). Hu et al. [52] proposed the pseudo-fixed latitude observation strategy which relies on a sensor with wide FOV (20° in the delineation) to improve the aforementioned strategy as shown in Fig. 8(c). With proper sensor’s pointing adjustment strategy, the fence can maximize its efficiency for observing GEO objects, and almost all the GEO objects can be observed every day in the whole year.



(a) Typical observation strategy based on PP regions

(b) ESA’s leak proof strategy



(c) Pseudo-fixed latitude observation strategy

(d) Semi-active observation strategy

Fig. 8 Four strategies for observing GEO objects

In addition, the leak proof strategy was also tested to observe MEO, GTO, and Molniya objects [35], but the results were also unsatisfactory (about 7.9% GTO objects, 6.1% MEO objects, and 10.4% Molniya objects cannot be observed in over 25 h in March). The reason is that many of these objects do not pass through the established observation regions. According to the distribution characteristics of these objects, the SSO-based strategy is probably not the best choice for the surveillance of MEO, GTO, and Molniya objects.

(iii) Semi-active observation model

Hu et al. [44] proposed a trade-off strategy for observing GEO objects based on the passive observation model to overcome the “seasonal drop” problem and reduce energy consumption. The sensor on an inertia-oriented satellite only needs to adjust a little once a day to cover the GEO belt, as shown in Fig. 8(d). Almost all the GEO objects can be observed every day in the whole year if a satellite have such three sensors payload (FOV of each sensor: 6°×6°).

4.1.2 NEO-based strategy

The NEO-based strategy means performing SSA missions with the satellites for which their inclinations are about 0°.

Satellites deployed in low-altitude circular EO have a short orbital period, and a fixed declination zone can be rapidly scanned if the sensor is fix-mounted with certain elevation angles. Oswald et al. [53], Olmedo et al. [54], and Sanchez et al. [55] tested this strategy in which the sensor points to the zenith direction, for observing beyond-LEO objects (see Fig. 9 for observing GEO objects). It was observed that with the same sensor, NEO-based strategies usually have a shorter revisit period and a shorter visibility period. In particular, for observing MEO, GTO, and Molniya objects, the efficiency of the NEO-based strategy is significantly higher than the SSO-based strategy. With the increase of the altitude of the observation satellite, the revisit period will increase but the visibility period will be longer.

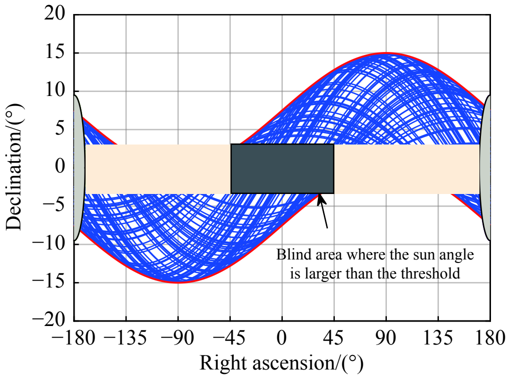


Fig. 9 Observing GEO objects with an EO satellite on March (assumed sun angle threshold =135°)

When the altitude of the observation satellite is close to 35 786 km, then another strategy emerges. With an observation satellite operating in a sub-GEO (1 164 km lower than GEO), the mean visibility revisit period can reach about eight days [55]. Lockheed Martin Space Systems Company proposed to evenly deploy 16 microsatellites on the geostationary orbit to make sure most of the GEO objects can be observed in real time [56].

In addition, Olmedo et al. [54] attempted to use an observation satellite operating in a GTO to observe beyond-LEO objects. Comparing with low-altitude EO, this strategy exhibited higher performance for observing GEO objects, while worse for observing MEO and other objects. Yates et al. [57] designed a satellite constellation operating in eccentric orbit with 0° inclination to observe GEO objects, and its performance can be improved if the satellites are maneuverable.

Although GTO-based strategies combine the merits of using low-altitude circular EO and sub-GEO observation satellites, it cannot overcome the inherent defects of NEO-based strategies, which are as follows: (i) the illumination condition varies fast during operation; (ii) there exist blind areas when satellites operate to the sunny slope and the Earth shadow region (see Fig. 9). In particular, under the influence of precessional motion, the GTO-based strategy may fail for SSA when the apogee of the orbit moves to the sunny slope.

Hu et al. [44] utilized an EO satellite with multi-sensors having different pointing directions to make up the blind areas. In addition, they found an optimal pointing direction to observe MEO and Molniya objects simultaneously with only one sensor based on the characteristics of MEO and Molniya objects, as shown in Fig. 7. Although the coverage rate is increased (over 40% of MEO objects, and over 90% of Molniya objects), the mean visibility period is still short. To offset these defects, another method is to use a sensor with wide FOV. As proposed by Du et al. [58], a 4 163 km-altitude circular EO satellite with a sensor payload (FOV: 20°×20°) can scan the whole GEO belt within two revolutions, and the visibility period of observed objects can be improved as well.

4.1.3 Other strategies

Lupo et al. [59] proposed to utilize an observation satellite operating in a polar orbit (PO) to observe geostationary objects. The sensor only needs to point to the geostationary region where it is opposite to the orbital plane, the geostationary objects can be observed continuously without the influence of the Earth shadow and the shelter of the Earth body. However, because PO has no precessional motion, the illumination condition is various in a year.

4.2 General surveillance for LEO objects

Comparing with general surveillance for beyond-LEO objects, observing and revisiting all LEO objects is much challengeable, because LEO objects are high-speed and distributed in the whole spherical space with different altitudes.

Olmedo et al. [54] and Sanchez et al. [55] attempted to observe LEO objects with SSO and EO satellites. However, the results are unsatisfactory compared with the results of observing beyond-LEO objects. No more than a third of LEO objects can be observed in a day even if the sensor’s FOV is 15°×15°. Moreover, most of the observation arcs are too short for appropriate image acquisition.

One way to solve this problem is to employ a sensor with a very wide FOV. For example, Nallapu et al. [60] proposed the concept of employing a CubeSat in LEO with a 143°-FOV sensor to effectively monitor objects entering the Earth’s atmosphere. However, it is difficult to manufacture a sensor that both has a high performance and a wide FOV. Thus, the problem may find solutions by utilizing satellite constellation. Chen et al. [61] attempted to use three satellites operating in SSOs, each of them has a sensor payload (FOV: 10°×10°). Their results showed that more than 80% of LEO objects can be observed over three days. Snow et al. [62] obtained that an eight-satellite constellation at an altitude of 979 km and an inclination of 68.7° orbits can achieve the best observation performance with 14.23°×11.38° FOV sensor after comprehensive optimization. Du et al. [41] also proposed their constellation design scheme to catalogue cm-size debris based on the characteristics of LEO debris, and most of them can be detected and maintained within two months.

The SBO observation approach was also developed by Gruntman [63] to detect mm-size debris in LEO to improve the model of space environment. Different from detecting larger LEO objects, what needs to know is the flux and density of mm-size debris. Therefore, a photon-counting imaging detector (image processing is different from a typical SBO sensor as illustrated in Section 3.4) carried by an SSO satellite was employed to detect the debris around its orbit. Hopefully, the whole model of mm-size debris in LEO can be established after a year.

4.3 Discussion

According to the performance of the proposed strategies, both the SSO-based and NEO-based strategies are possible to cover the whole GEO belt by using SBO sensor with certain FOV and proper pointing adjustment strategies. Among SSO-based strategies, the passive observation is the easiest for the pointing control of the sensor, while the active model usually has the highest cost performance [64]. On the other hand, for observing MEO, GTO, and Molniya objects, low-altitude EO-based strategies are superior to the SSO-based strategies, because the former has a higher coverage rate in a day.

SSO-based and NEO-based strategies have different characteristics. SSO-based strategies have the advantages in the visibility period while the low-altitude EO-based strategies are good at revisit times. Performance of several typical strategies for observing GEO objects in a day on December are summarized in Table 2.

Table 2 Performance of several typical strategies for observing GEO objects in a day on December

Strategy	Size of FOV	Mean visibility period/s	Mean visibility times
Passive	2°×6°	100−200	1−2
	6°×2°	200−400	1−2
Leak proof (one fence)	2°×2°	400−500	1
	6°×2°	1 400−1 500	1
EO-based (7 r /d)	6°×2°	174	2−3
EO-based (10 r /d)	6°×2°	125	3−4

For SSO-based strategies, the observation satellite operates in a dawn-dusk SSO with a 98° inclination. The visibility period of the passive observation model is related on the size of FOV, especially the size along the direction of right ascension. This is much easier to be understood in the active observation strategies, which usually scan a fixed region in inertial space. The size of FOV along the direction of right ascension is wider, GEO objects need more time to pass, and longer observations can be obtained. However, most of the active observation strategies can only visit an object once a day. Table 2 also shows the performances of observing GEO objects by using a circular EO satellite with the orbital period of seven revolutions per day and ten revolutions per day, respectively (sun angle threshold is assumed as 135°). It is observed that the lower the orbital altitude (shorter orbital period), the more revisit times in a day can be obtained, but with a shorter visibility period. In addition, the size of the FOV along the direction of right ascension also influence the visibility period. For observing other objects, similar conclusions can be obtained.

From the perspective of image processing, the active observation model is the best because it is easy to distinguish the points and streaks in obtained images. However, stars and objects may all be streaks in the images obtained from a passive observation model and NEO-based strategies. In particular, the high scan speed (for low-altitude EO satellite) and various illumination condition will seriously influence the image processing for the NEO-based strategies [55].

As observed in those general surveillance strategies, many short-arc, and even very short-arc data will be obtained during operation. Some of the observation data may originate from a same object. Thus, the next step is to associate data [65−68], which is not only for finding new objects, but also for accumulating more data for an observed objects. Reihs et al. [69] analyzed the performance of data association of the measurements obtained by ESA's fence strategy for observing the GEO object in two days. The success rate of data association can only achieve 46% but it can be improved to 76% after post-processing. They also suggested that if an object is always observed at a similar position, the success rate of data association will reduce due to the measurement noise. At this point, the NEO-based strategies may be superior to the SSO-based strategies, because the former can detect objects at various positions.

To support the following applications, the orbit of the observed objects should be determined with the obtained data. Although there are many algorithms to deal with the initial orbit determination problem with short-arc and too short-arc measurements [70−72], it is better to use longer data to improve the estimation accuracy, and both SSO-based and NEO-based strategies can make some improvements on this point.

5. Space object tracking strategy

Space object tracking usually refers to sustained observation for an object of interest, the prior information of which is known. The aim of space object tracking is to measure an object of interest as long as it is possible, so that more detail information can be obtained. In this case, the sensor will take the track rate mode (TRM) [28,73] to keep up with the movement of the object. Different from the SSM, stars will appear as streaks and the object will appear as point sources in the obtained images. In this section, the development of the SBO tracking strategy is reviewed. Because the tracking algorithm highly depends on the tracking strategy, the development of the SBO tracking algorithm will also be introduced briefly, although it is beyond the scope of this paper.

5.1 Tracking an object with a single satellite

The space object tracking strategy is simpler than general surveillance, because space object tracking only focuses on the object of interest. With the dynamics model and the prior information of the object, the pointing of the sensor can be adjusted to point to the object in time. Combined with the real-time tracking algorithm, initial ephemeris of the object can be updated to reinforce the tracking. The process in Fig. 5 can be sued to judge whether a space object can be tracked, and the angular velocity threshold of the pointing of the sensor should be added to guarantee the sensor can catch up the object.

Most of the space object tracking missions are carried out by the observation satellite operating in the SSO to obtain high-quality tracking data. For example, a geostationary object can be tracked by an 800 km-altitude dawn-dusk SSO satellite uninterruptedly over three hours a day on December ideally. Similar to the general surveillance, tracking LEO object is the most challengeable because of the high relative speed. Therefore, an observation satellite only can track an object around its orbit for a long time.

The first generation SBO object tracking is performed by a single satellite. The related works mainly focused on developing real-time tracking algorithms to support the tracking mission. Many of the linear and nonlinear algorithms, such as Kalman filter (KF), extended Kalman filter (EKF), and unscented Kalman filter (UKF), also can be used in the space object tracking. Recently, some of the researchers focused on developing a more roust filter to deal with the measurement malfunctions and sparse measuring problems which usually occur in real-world applications [74–76], as well as tracking the object which can maneuver [77].

5.2 Cooperative space object tracking

SBO observation has its inborn defects, that is, the SBO sensor can only obtain the direction information for an observed space object. Thus, there always exists the biggest estimation uncertainty along the LOS direction [78]. Moreover, the continuity of tracking is usually unsatisfactory due to the constraints of SBO observation as illustrated in Fig. 5, especially for tracking LEO objects. To improve the tracking performance, it is necessary to employ multiple satellites to carry out the mission.

Inspired by the multi-agent system, the new tracking strategy —cooperative SBO space object tracking, attracts widespread attention recently. Li et al. [79] employed two-satellite formation to differentiate the debris of interest from other clutters. Felicetti and Emami [80] proposed a concept of tracking LEO debris with a 12-satellite formation where there are leaders to organize the cooperative tracking mission, including forming team, involving new member, and leaving member. Jia et al. [81] established a distributed system to tracking beyond-LEO objects cooperatively. Their idea was based on the well-known consensus theory in multi-agent system. By sharing the information with the neighbours, the tracking performance can be improved significantly.

Based on the cooperative tracking strategy, many cooperative tracking algorithms are developed recently [82–84]. Most of them are based on the well-known Kalman consensus filter (KCF) [85,86], and some of the algorithms are improved to deal with the problem of asynchronous measurements [83].

6. Summary and prospects

In the last two decades, space-based optical (SBO) observation, which exhibited excellent performance in SSA, has become a good assistant for ground-based space surveillance network. SBO observation is a cost-effective approach because the SBO sensor is light, with low-consumption, and high-efficiency, so that it is suitable to be carried by microsatellites, and even nanosatellites.

In general, SBO SSA includes general surveillance and space object tracking defined by the aim of the mission. The SBO strategy is the top-level design for SSA missions, because it decides the performance of SSA, including coverage rate, revisit time, visibility period, and tracking accuracy.

General surveillance focuses on visiting space objects as much as possible in a short time. To achieve this goal, the understanding of the distribution characteristics of space objects is necessary. For observing GEO objects, most of the observation satellites are deployed in SSOs or NEOs. Strategies using both two kinds of orbits can achieve a high coverage rate in a day with the proper pointing adjustment strategy and a certain FOV of the sensor. SSO-based strategies are usually good at obtaining a longer visibility period, while low-altitude EO-based strategies can visit objects multiple times a day. For the surveillance of MEO, GTO, and Molniya objects, NEO-based strategies are superior to SSO-based strategies, because a higher coverage rate can be obtained. However, for observing LEO objects, the performance of all the strategies is usually unsatisfactory compared with observing beyond-LEO objects. The way to improve the SBO surveillance performance includes utilizing the SBO sensor with a wider FOV, employing an observation satellite with multiple sensors payload, or using a satellite constellation.

Space object tracking aims at measuring an object of interest as long as possible. To offset the constraints of SBO observation and achieve better tracking performance, employing multiple observation satellites to track the object cooperatively is the best choice.

In view of the limitation of a single observation satellite, employing multiple satellites operating in different kinds of orbits to provide observation information from various perspectives is the development trend in the future, as shown in Fig. 7. By this stage, swarm intelligence theory may be helpful for the design of real observation strategies. Moreover, combining with the scheduling of ground-based sensors, the SSA strategy uniting both space-based and ground-based sensors may also be the future development direction to achieve "the right modes of the right sensors are directed at the right places at the right time [87]".

The realization of SBO strategies also relies on the development of SBO sensors and corresponding information processing system. With using a high-performance wide-FOV sensor, the design of the SBO observation strategy will be easier. In addition, the raw data of SBO observation are images which take up a lot of space to store and time to transmit after a period of surveillance or tracking. Meanwhile, the typical image processing algorithm, such as the moving target indicator detecting algorithm, usually consumes long time [88–90]. To support future SBO SSA, in which a mass of data may be obtained in a shorter period, developing fast and reliable image processing algorithms is also necessary.

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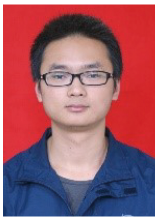

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