Chapter 2
Special Space Orbit: Concept and Application

Since the beginning of the 21st century, mankind has been carrying out various space activities, especially new types of space missions such as space-based space target surveillance, on-orbit service, and so on. These activities have brought about increasingly higher requirements for orbits with special space motion characteristics. However, traditional orbit theories and design methods can no longer satisfy these special application demands. Therefore, in this chapter, the concepts and characteristics of a special space orbit will be introduced and analyzed, with six typical special space orbits elaborated in accordance with their specific application requirements.

2.1 Special Space Orbit: Concept

A spacecraft orbit refers to the motion trajectory of the centroid of an operating spacecraft. In the light of different flight missions, orbits can be generally classified into three categories, i.e., the artificial earth satellite trajectory, the Earth-to-Moon flight trajectory and the interplanetary flight trajectory. Typical orbits are usually Keplerian ones, which satisfy the fundamental motion equations of the restricted two body problem. Taking advantage of the typical orbit equations, such as the above fundamental motion equations and the Kepler Equation, these orbits can be precisely predicted.

$$r = \frac{a(1 - e^2)}{1 + e\cos f} \tag{2.1}$$

Here, a, e, r and f refer to the semi-major axis, the eccentricity, the geocentric distance and the true anomaly of an orbit, respectively.

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The concept of special space orbit was put forward relative to the currently widely applied typical space orbit. Compared to typical orbits, special space orbits have the following unique features.

2.1.1 Differences in Orbit Design Concepts

With the successful launch of the first artificial earth satellite in the 1950s, design theories and methods of spacecraft orbit have been developing rapidly. The primary missions of a spacecraft at that time were to conduct reconnaissance and surveillance of hotspot areas, and to provide communications and navigation support for the army, the navy and the air force. Hence, the design of a spacecraft orbit at that time focused mainly on the relative motion between the spacecraft and the ground area, and the absolute orbit design methods, which take the Earth as the reference, were adopted, e.g., the sun-synchronous orbit, the recursive orbit, the stay orbit, and so on.

In addition, mankind has spared no efforts in exploring untapped areas in space. In the 1960s, there were many lunar exploration projects with burgeoning interplanetary explorations to Venus, Mercury, Mars, and other planets. Meanwhile, theories and design methods in interplanetary exploration orbits have become increasingly mature. The mid and late 1990s witnessed another round of upsurge in lunar exploration and interplanetary exploration with well-established theories and design methods.

With the continuous development of astronautical technology and the heightened military status of space, the functions of spacecraft, such as providing on-orbit service, conducting space-based space target surveillance and so on, have become the focus of all countries. To support these missions, the concept of relative orbit, which takes spacecraft as the reference point, started to emerge. In the 1990s, the idea of distributed satellites led to the explicit proposal of theories and design methods of a spacecraft relative motion orbit, which have matured in the last 20 years.

To sum up, the well-developed spacecraft orbit theories and the corresponding typical orbits today are shown in Table 2.1.

Nevertheless, there are major distinctions in the theories and design methods between special space orbits and the above typical orbits. Moreover, completely different space orbits are required by different missions, resulting in the discrepancy in the theories, principles and methods when designing these special space orbits. For instance, the hovering orbit is a type of relative orbit that regards the target spacecraft as a reference; the spiral cruising orbit is a kind of relative orbit that takes the target orbit as a reference; and the non-coplanar multi-target rendezvous orbit is a fitting orbit based on several traversing points in the rendezvous orbit plane. Hence, it is necessary to introduce the theories and design methods of special space orbits in combination with the specific mission requirements and orbit types.

Table 2.1 Well-developed spacecraft orbit theories and design methods at present

Initial time	Orbit theory	Type of typical orbit
1950s	Theory and design method of absolute orbit	Recursive orbit Sun-synchronous orbit Frozen orbit Stay orbit…
1960s	Theory and design method of interplanetary orbit	Lunar probe orbit (Chang'e Lunar probe satellite, China) Mars probe orbit (Curiosity Mars Rover, U.S.) …
Mid-and-late 1990s	Relative orbit design method that takes spacecraft as the reference point	Formation flight (Cluster II, European space agency, ESA) (TanDEM-X/TerraSAR-X formation flying satellite of synthetic aperture radar, Germany)

2.1.2 *Coupling of Orbit Control and Orbit Design*

At the early stages of astronautical technological development, restricted by immature technologies in space marching, fueling, and others, spacecraft orbit control was cautiously applied in the following four areas:

(1) Launching GEO satellites

Restricted by the geographic latitudes of spacecraft launching spots, GEO satellites are unlikely to be launched directly into their orbits. Generally speaking, a GEO satellite is usually firstly sent up into the parking orbit with an altitude of 200–400 km. As the satellite approaches the space above the equator, the upper stage rocket is ignited, and the satellite breaks away from the tail stage rocket after the brennschluss. The satellite enters the highly elliptical transfer orbit there, with both the perigee and the apogee of the orbit above the equator. Usually, the altitudes of the perigee and the apogee equal those of the orbit-insertion point and the GEO respectively. At the apogee of the highly elliptical transfer orbit, the apogee engine on the satellite is ignited, driving the satellite into the GEO ultimately (Fig. 2.1).

(2) Orbit maintenance

Affected by a variety of perturbations including the Earth's non-spherical perturbation, atmospheric drag, lunisolar attraction, solar radiation pressure, and other factors, the spacecraft eventually deviate from their originally designed orbits after long-term operation. As shown in Fig. 2.2, a GEO satellite with a fixed point longitude of 100° east at a certain Epoch time experiences a longitude drift under the influence of perturbation. For satellites deviated from their preset orbits, it is necessary to conduct orbit maintenance to ensure that they remain in the correct orbits. As only a limited amount of fuel can be carried by the satellites, the service

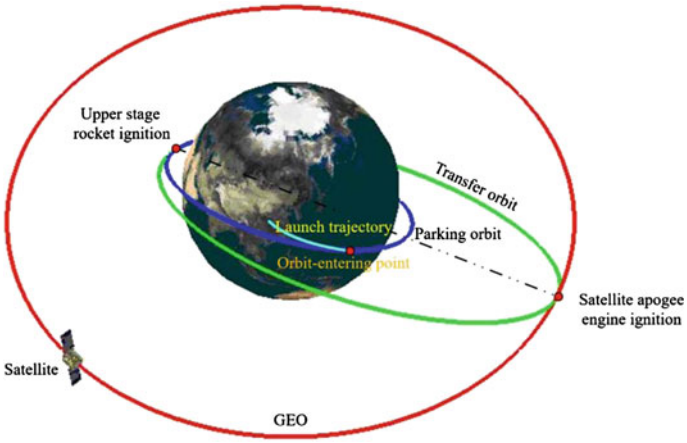

Fig. 2.1 Schematic figure of the launching process of GEO satellites

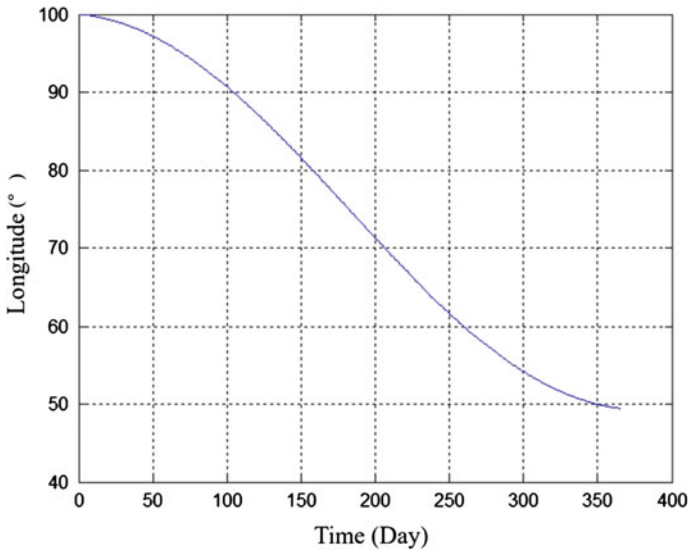

Fig. 2.2 Longitude drift of GEO satellite within a year

of many spacecraft has to be terminated because of fuel exhaustion. Hence, a rigorous plan of satellite orbit control has to be made.

(3) Earth-to-Moon flight and interplanetary exploration

We can take Earth-to-Moon flight as an example. Firstly, the lunar probe is launched into the Earth-Moon transfer orbit (or into the parking orbit first, and then the orbit is maneuvered into the Earth-Moon transfer orbit). During this process, orbit adjustments may be required. Then, after the lunar probe enters the lunar sphere of influence, orbit control should be conducted to transfer the lunar probe from an Earth satellite into a lunar satellite that circles the Moon. If the lunar probe is designed to be recalled, then orbit control is conducted again to transfer it from the lunar orbit back into the Moon-Earth transfer orbit finally bringing it back to Earth.

(4) Space rendezvous and docking

During the process of space rendezvous and docking, the tracking spacecraft experiences a series of orbit control and also attitude control, consistently bringing down the relative position and relative velocity between the tracking spacecraft and its target spacecraft, and meeting the initial conditions of docking in a relative attitude angle and angular rate. Space rendezvous and docking requires a high precision in both orbit control and attitude control.

In these applications, orbit control is primarily used in the transfer between the initial orbit and the target orbit. It is in essence an intermediate state, rather than the final state of an orbit. Some special space orbits, however, regard orbit control as an integral part of their orbit design, i.e., the special space orbit itself is possibly a type of controlled orbit. For instance, the hovering orbits must be subject to the successive monitoring of an orbit control system, thus maintaining the relative position between the spacecraft and its target unchanged or just making relative movements in a minimal range during a certain period.

Thanks to the development of modern space marching technology, long-term, highly-precise and low-thrust orbit control has become a reality. Special space orbits are thus free from the conventional restrictions of Keplerian orbits, and are enabled to provide on-orbit service and meet the application requirements of new space missions.

2.1.3 Requirements for Special Space Application

During the past decade or so, a large number of new-concept space application experiments have been conducted at home and abroad, including the already completed Orbital Express (OE) Program, the Micro-Satellite Technology Experiment (MiTEx) Program, the Deep Impact Program, the X-37B space maneuvering vehicle program in the United States, the still on-going Phoenix Program, and other typical ones. The major details of these experiments are shown in Table 2.2.

In the above space experiments, the main purpose of a spacecraft is no longer to provide reconnaissance, communications, navigation and other information support for the ground, rather, it is to provide flexible and various services in space, including on-orbit supply, close inspection, space interception, rapid maneuver, component replacement in space, and so on. Apparently, these space service missions can hardly, or never, be accomplished on the basis of the current typical

Table 2.2 New-concept space application experiments conducted in the U.S

Space experiments	Details
Orbital express (OE) program	A space service operation experiment conducted by the U.S. Defense Advanced Research Projects Agency (DARPA) in 2007, including four major parts: (1) Testing small space robot orbiters which can provide services for satellites (2) Testing target satellites that can be upgraded and repaired (3) Testing interfaces between the two satellites during the process of docking (4) Operating the on-orbit satellites
Micro-satellite technology experiment (MiTEx) program	In December 2008, the U.S. Department of Defense utilized two MiTEx satellites to examine the on-orbit malfunctioning missile early-warning satellite of the defense support program (DSP-23)
Deep impact program	At Beijing time 13:2:4 on July 4, 2005, the impactor of the deep impact program conducted by the U.S. National Aeronautics and Space Administration (NASA) accurately hit the core of Comet Temple 1, with a diameter of less than 6 km, more than 100 million kilometers away from the Earth at a relative velocity of 10.2 km/s
XX-37B space maneuvering vehicle program	From 2010 to 2013, flight experiments of the space maneuvering vehicles (SMV) were carried out by the U.S. Air Force, aiming at developing the fuselage structure, the on-orbit maneuver, the advanced thermal protection system, the autonomous approach and landing, and other key technologies for reusable SMVs. It was also aimed at exploring combat concepts and the capabilities of unmanned spacecraft that have the capability of operating in space for a long period
Phoenix program	In October 2011, the U.S. DARPA proposed the phoenix program, hoping to disassemble the communications antennas from abandoned GEOs and reuse them to provide more economical and sustainable space-based communications services for the U.S. Air Force. The program is predicted to conduct on-orbit demonstration during the 2015–2016 period

orbits. By contrast, special space orbits are exactly designed for these special space missions. For example,

(1) Hovering orbit: proposed for space missions in which the servicing spacecraft should be kept stationary relative to the target spacecraft;
(2) Cruising orbit: proposed for the space-based space target surveillance missions;
(3) Multi-target rendezvous orbit: proposed for space missions in which the servicing spacecraft should conduct orbital rendezvous with several non-coplanar space targets simultaneously;

(4) Initiative approaching orbit: proposed for missions that require a rapid approach towards a space target;
(5) Responsive orbit: proposed for missions in which the global coverage period is longer and the access frequency of the spacecraft is higher than those of the typical orbits;
(6) Earth pole-sitter orbit: proposed for the continuous exploration missions of the Earth's North and South Poles.

2.2 Types of Special Orbit

In accordance with the specific space application needs, six special space orbits will be introduced in this section.

2.2.1 *Hovering Orbit*

In the 21st century, thanks to the continuous development of space technology, a lot of spacecraft enter into space each year. However, under the influence of the complexity and unpredictability of the space environment, requirements for on-orbit service have been brought forward by an ever increasing number of spacecraft. Generally speaking, it is a necessity that a spacecraft travelling in an orbit should satisfy Kepler's Three Laws, resulting in many problems for on-orbit service. One of the problems is how to keep the servicing spacecraft stationary, relative to the target spacecraft in any orientation.

Hovering orbits refer to the orbits on which the servicing spacecraft is kept stationary, or moves within a minimal range, relative to the target satellite during a certain period under the control force, as shown in Fig. 2.3.

The key to the hovering orbits is to realize the hovering of the servicing spacecraft at a certain point or in a certain area in the target orbital coordinate system by adopting orbit control. In this way, the station-keeping of the relative location and orientation between the servicing and the target spacecraft can be achieved when both spacecraft are travelling at high velocities in space, thus laying the foundation for accomplishing space missions such as space maintenance, on-orbit refueling, space-based space target surveillance, and so on.

2.2.2 *Cruising Orbit*

Space target surveillance and space environment surveillance are the basis for all space activities. However, due to the geographic restrictions and the limited

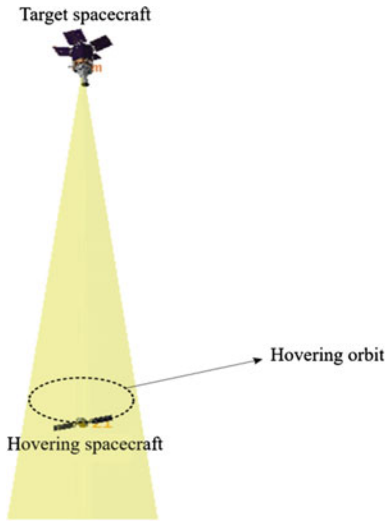

Fig. 2.3 Schematic figure of hovering orbit

detection range of the ground-based space detection system, it is difficult to realize high-precision detection of a high-orbit spacecraft and certain space environmental elements.

Since the GEO satellites are stationary relative to the Earth's surface, the observation stations deployed on the ground can only observe the GEO satellites above them which are within their visual range all the time. They can never observe the GEO satellites stationed above the other half of the Earth. Moreover, due to the long distances, it is very difficult for the ground stations to identify the high-orbit targets, especially the GEO ones, even if they are detected.

Currently, it is still challenging to image space targets tens of thousands of kilometers away by adopting the ground-based large-scale self-adaptive optical system. In addition, the possible slow tumbling of high-orbit targets makes it even more difficult to achieve fine imaging results. In fact, the current ability to identify high-orbit targets is still immature. Correspondingly, space-based and ground-based research have been simultaneously conducted abroad to tackle the problem. Aiming to enhance its space target surveillance capability, the U.S. has carried out a series of research programs on space-based space target surveillance. On September 25, 2010, the first Space-Based Space Surveillance (SBSS) satellite, i.e., the Pathfinder, was successfully launched at the Vandenberg Air Force Base. As the first SBSS satellite, it is capable of providing preliminary space surveillance service for monitoring space objects in low-Earth orbits. It is projected that a satellite constellation consisting of four SBSS satellites which is equipped with more advanced global space surveillance technology will be deployed in the next phase.

According to the U.S. Air Force's plan, the SBSS system is a LEO (Low Earth Orbit) optical remote sensing satellite constellation, characterized by its strong orbit observation capability, short repeated observation period, and all-weather observation capability. It is expected that the System will substantially enhance the

U.S.'s ability for exploring deep space objects. Allegedly, it will enhance the U.S.'s GEO satellite's tracking ability by 50 %, and shorten the update period of the U.S.'s space targets catalogue information from five days to two days, therefore enormously boosting its Air Force's space situational awareness. The System can detect and track space targets such as satellites and orbital debris, detect in time the tiny targets in deep space, and distinguish whether it is human factors or non-human factors such as the space environment that are damaging the space system. This system prominently outperforms the ground-based space surveillance system which cannot monitor deep-space small objects.

The U.S. Air Force has also planned to develop a space target surveillance satellite that travels in an even higher orbit, i.e., the Orbit Deep Space Imager (ODSI). The envisaged ODSI system is a satellite constellation consisting of optical imaging satellites that travel in the GEO, the major function of which is to provide the images of three-axis stabilized GEO satellites. The ODSI satellites will travel continuously along the GEO and take pictures of the GEO satellites, capturing their high-resolution images. The system can improve not only the ability of U.S.'s space target surveillance system in monitoring high-orbit targets, but also help to acquire the feature information of GEO targets and enhance its capability in identifying these targets.

In addition, the various types of micro-satellites being developed by the U.S. can also be used for space surveillance. The proposed schemes for the application of micro-satellites in space surveillance by the U.S. military forces include:

① For emergent space targets with potential hostility, other space surveillance detectors are firstly used to discover, track and identify the targets. When other space- and ground-based space surveillance detectors fail to obtain more detailed information about the targets, micro-satellites used for space surveillance (including on-orbit stay micro-satellites and promptly responsive and launched micro-satellites) can be sent to approach the targets, conducting close observations and taking pictures at short range for more detailed feature data of the targets.

② As for its space assets that require special protection, the U.S. armed forces can deploy micro-satellites in the neighborhood, monitoring the surrounding environment, providing early warning and distinguishing between natural destruction and man-made sabotage. A typical application of the micro-satellites is the U.S. MiTEx test.

To sum up, two patterns can be used by the space-based space target surveillance system to monitor the GEOs:

(1) Monitoring the targets in the GEO by using spacecraft deployed in the medium and low orbits;
(2) Deploying the surveillance satellites around the GEO orbits and monitoring the targets like a *drifter*.

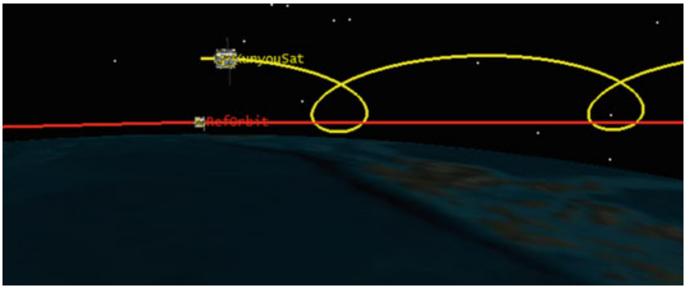

Fig. 2.4 Spiral flying-around orbit

In the above two patterns, the first one is more suitable for general surveys of the GEO targets, allowing the cataloguing of the targets within a short time. However, as a result of the long distance and the large relative velocity between the surveillance satellite and the target spacecraft, it is difficult to acquire abundant detailed information about the targets and meet the demands for target identification, on-orbit service, and others. In the second pattern, however, because of the short distance and the small relative velocity between the surveillance satellite and the target spacecraft, close observation and picture-taking of the targets are feasible. In this way, geometrical morphology, signal features and other detailed information can be obtained.

A cruising orbit is a type of relative orbit, in which the cruising spacecraft cruises around the target orbit in a certain pattern, conducting close observation, providing on-orbit service, monitoring nearby space debris and the nearby space environment, and so on, for multiple spacecraft in the target orbit. The spiral flying-around orbit is shown in Fig. 2.4.

Compared to ordinary satellite formation flying such as flying-behind and flying-around, a cruising orbit has obvious advantages in the following aspects: Firstly, the detection target of a cruising orbit is not limited to a single satellite. Given enough time, the orbit can accomplish the detection of all the on-orbit spacecraft in this specific orbit. Secondly, the configuration design of the cruising orbit enables a multi-perspective detection of the target, thus obtaining the detailed description of a specific object. Thirdly, the detectors will not stay around the same object for a long time. Finally, the energy consumption required for multi-target detection is low. If there is no demand for cruising velocity, then the cruising spacecraft can conduct a cruising and detection flight along a free trajectory, which consumes almost no energy theoretically.

2.2.3 Multi-Target Rendezvous Orbit

In April 2007, the space refueling experiment of the U.S. Orbital Express (OE) Project was successfully accomplished. Successively, the Phoenix Program

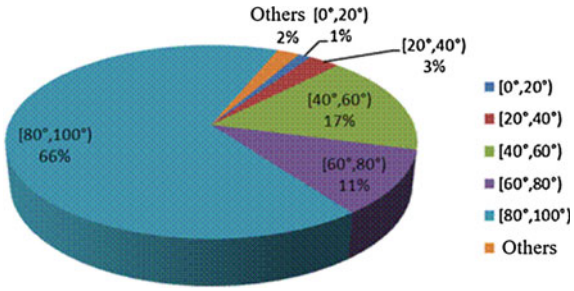

Fig. 2.5 Distribution of orbit inclinations of LEO satellites

proposed in 2011 put on-orbit maintenance on the agenda. In accordance with the demands of different space missions, spacecraft are usually deployed in different orbit planes in space. According to the statistics of the satellite database of the Union of Concerned Scientists (UCS), there were 521 LEO spacecraft as of June 1, 2013. The distribution of the orbit inclinations of these spacecraft is shown in Fig. 2.5.

Different orbit inclinations inevitably result in differing orbit planes. Changing orbit plane consumes a lot more energy than in-plane maneuvering does. Therefore, it is difficult for a single servicing spacecraft to provide services for multiple target spacecraft travelling in different orbit planes. Taking advantage of the feature that any spacecraft orbit inevitably crosses a random orbit plane in space, scientists have proposed a coplanar multi-target orbital rendezvous method based on traversing point. In this method, the traversing point of the target orbit is considered as the orbit rendezvous point and the traversing time of the target spacecraft as the orbit rendezvous time. In this way, the non-coplanar orbit rendezvous problem is turned into a coplanar orbit rendezvous issue. Moreover, without a restriction on the amount of target spacecraft and orbit distribution, this method realizes, in essence, the one-to-many orbit rendezvous pattern.

2.2.4 Initiative Approaching Orbit

An initiative approaching orbit refers to an orbit in which a spacecraft rapidly or slowly approaches a cooperative or a non-cooperative target through orbit control, thus accomplishing rendezvous and docking, rapid detection, on-orbit service and other space missions. A typical initiative approaching orbit is the orbit in which the U.S. MiTEx (Micro-Satellite Technology Experiment) satellite initiatively approaches and detects the DSP-23 missile early-warning satellite.

According to the U.S. *Aerospace News* on January 14, 2009, the U.S. Department of Defense was inspecting the on-orbit malfunctioning Defense Support Program (DSP)-23 missile early-warning satellite utilizing two Micro-satellites (MiTEx).

This was the first on-orbit inspection mission conducted in a geosynchronous orbit after the U.S. on-orbit maintenance demonstration of the OE satellite in 2007.

The MiTEx Project is a part of the Microsatellite Demonstration Science and Technology Experiment Program (MiDSTEP) jointly implemented by the Defense Advanced Research Projects Agency (DARPA) and the U.S. Air Force. The project, including MiTEx-A, MiTEx-B and three upper stage vehicles that push them into a geostationary orbit, aims to determine, integrate, demonstrate and evaluate micro-satellite technology relevant to GEO maneuvering. Because of the strong propulsion capability and long service life of the upper stage vehicles of the MiTEx Project, the satellites can travel to any location in the geostationary orbit, conduct close-range operations, take pictures, receive all radio communications sent and received by the target satellite. They can even conduct counter operations such as disabling communication networks, discharging propellant in the fuel tank of the target spacecraft, and others.

The DSP-23 satellite was launched on November 10, 2007, but lost touch with the ground control station around October 8, 2008. At that time, the DSP-23 satellite was travelling above the equator in southern Nigeria at longitude 8.5º east. Then the satellite drifted eastwards along the geosynchronous orbit, in accordance with the orbital mechanics law, for around a year and a half, before it reached the space above Australia and then returned to the west. It did this repeatedly. From December 8 to 13, 2008, the MiTEx-A satellite approached DSP-23 from the west towards the east; on December 23, 2008, the MiTEx satellite reached the DSP-23 satellite and established images; on January 1, 2009, the MiTEx-B satellite also approached the DSP-23 satellite.

This experiment demonstrated that the U.S. was already equipped with key capacities in rapid orbital maneuver, space-based object measurement, on-orbit operation service, system comprehensive integration, and so on. The orbit in which the MiTEx satellite operated during its missions is a typical initiative approaching orbit (Fig. 2.6).

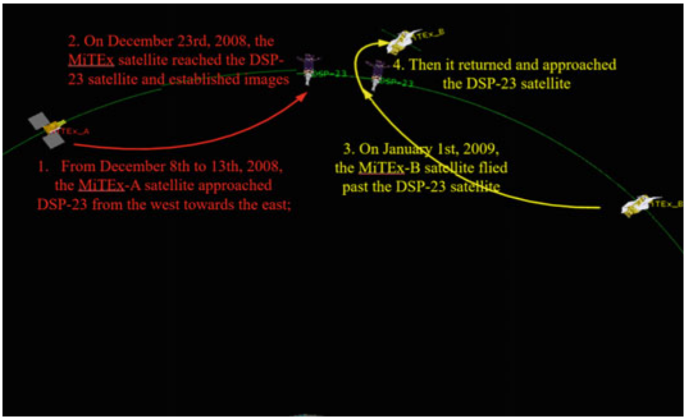

Fig. 2.6 Process of MiTEx satellite initiatively approaching and detecting DSP-23 satellite

2.2.5 Fast Responsive Orbit

To meet the demands of emergent space missions, the U.S. Department of Defense and The Institute for Defense and Disarmament Studies jointly released a research report entitled *Military Space Systems: the Road Ahead* in October 2005. The report put forward the development strategies for Operationally Responsive Space (ORS), which included responsive satellite, responsive carrier and other technologies.

The TacSat Program being conducted by the Office of Force Transformation (OFT), U.S. Department of Defense, is a typical responsive satellite project. The program involves four experimental tactical satellites, which are jointly developed by the U.S. Air Force Research Laboratory, the Naval Research Laboratory, and other collaborative laboratories. It aims to lay the technical foundation for the development of responsive mini-satellites, and demonstrate the affordability of a battlefield that integrates responsive launching, test and systems to support and satisfy the tactical requirements from field commanders by providing them direct access to space assets. The TacSat-3 launched in June 2009 is a mini-satellite developed by the U.S. Air Force Research Laboratory, which is the first responsive satellite that carries a mini-satellite public spacecraft and an optical payload.

A responsive orbit refers to an orbit that can carry out responsive missions. Here, 'responsive time' usually means the period from the time when a mission is proposed to the time when the mission is accomplished. Giving up a number of important indicators such as global coverage, a necessary feature for common spacecraft orbits, and even orbit lifetime, a responsive orbit focuses on its ability to make fast responses to certain space missions.

The most important characteristics of a responsive orbit are:

- Fast response: The responsive time of a responsive orbit is far shorter than that of an ordinary orbit. For example, it takes only a couple of hours for a responsive orbit to send back valid data after being launched into space;
- Low cost: This orbit can be used by small vehicles;
- Tactical application ability: It is specifically used for certain operational missions.

2.2.6 Earth Pole-Sitter Orbit

An earth pole-sitter orbit refers to an orbit that can realize long-term stay above the Earth's poles through orbit control. These types of orbits have two major properties. Firstly, an earth pole-sitter orbit can realize long-term stay above the Earth's poles. By adopting the earth pole-sitter orbit, a single satellite is allowed to cover the high latitude regions in the northern or southern hemisphere (including the North or the South Pole). Apparently, the cost-benefit ratio of an earth pole-sitter orbit is rather high though its security is guaranteed because of the high locations of deployment.

Secondly, the deployment location of the earth pole-sitter orbit is high. The distance from the earth pole-sitter orbit to the Earth's surface is about 0.01 astronomical unit (1 astronomical unit = 1.49597870 × 10^8 km). Though this may result in a relatively low resolution in ground detection, the orbit can be used for communications and navigation under proper conditions.

2.3 Description of Special Space Orbit

2.3.1 Orbit Element

Generally speaking, a spacecraft orbit can be described with six orbit elements, i.e.,

- Semi-major axis a: Half of the distance between the apogee and the perigee of an elliptical orbit, usually used to describe the size of an elliptical orbit.
- Eccentricity e: The ratio between the focal length and the semi-major axis of an elliptical orbit, usually used to describe the shape of an elliptical orbit, i.e., its non-circular extent;
- Perigee argument ω: The angle measured from the orbital ascending node to the perigee in the motion direction of the satellite in the orbit plane, usually used to describe the orientation of the apsidal line of an elliptical orbit in the orbit plane, i.e., the orientation of the perigee;
- Right ascension of ascending node (RAAN) Ω: The angle measured anti-clockwise from the orientation of the vernal equinox to the orbital ascending node in the equatorial plane, usually used together with the orbit inclination to describe the orientation of an elliptical orbit in space;
- Orbit inclination i: The included angle between an orbit plane and the equatorial plane, or that between the positive normal of an orbit plane and the Earth's North Pole, usually used to describe the inclining degree of the orbit plane relative to the equatorial plane;
- Time of perigee passage τ: The time when a spacecraft passes the perigee while travelling along an elliptical orbit.

Under the postulated conditions of two-body motion, the above six orbit elements are generally constants. Nevertheless, in actual space missions, spacecraft are subject to the influences of the Earth's non-spherical perturbation, atmosphere perturbation, solar radiation pressure perturbation, lunisolar attraction perturbation, and so on. These influences may result in changes to a spacecraft's orbit, i.e., the orbit elements are no longer constants. In order to study the disturbed motion of a spacecraft, concepts such as the osculating orbit and the osculating orbit element will be introduced.

Considering any point in the actual orbit of a spacecraft as a point in a corresponding elliptical orbit (an ideal orbit), then the elliptical orbit would be called an osculating orbit. The osculating orbit is tangent to the actual orbit. On the point of tangency, the actual velocity of spacecraft equals that of the corresponding point in the osculating orbit. If all the perturbations vanish from this point onwards, then the spacecraft will travel along the osculating orbit.

Osculating orbit elements describe the corresponding orbit elements of the osculating orbit at a certain instant (e.g., time t). Regarding the osculating orbit element of a certain time as the starting point, the precise subsequent orbit motion state can be obtained through numerical integration.

In order to describe more precisely the motion of a spacecraft from a macroscopic view, mean orbit elements can be adopted. The so-called mean orbit elements refer to the orbit elements without the short-period changing term.

The conversion formula between the mean orbit elements and the osculating orbit elements is:

$$E_i = E_i' + \delta E_i(E_i'),\ i = 1,\ldots,6 \tag{2.2}$$

Here, E_i stands for the i-th osculating orbit element, E_i' refers to the i-th mean orbit element, and δE_i refers to the i-th short-period changing term of the osculating orbit element.

2.3.2 Non Singularity Orbit Elements

In many applications, the spacecraft's orbit is a nearly round one, such as those of the LEO reconnaissance satellite, the GEO satellite (the orbit inclination approximates 0), and so on. Since the orbit inclination $i \approx 0°$, the right ascension of ascending node (RAAN) shows some singularity; and since the eccentricity $e \approx 0$, the argument of perigee also shows some singularity. The concept of non singularity orbit elements is thus put forward to solve these singularity problems.

For orbits with orbit inclination $i \approx 0°$ and eccentricity $e \approx 0$, there are a number of definitions for non singularity orbit elements, two of which will be introduced in this book. The first definition is:

$$\begin{array}{lll} a, & h = e\sin(\Omega+\omega), & p = \sin(i/2)\sin\Omega \\ l = \Omega+\omega+M, & k = e\cos(\Omega+\omega), & q = \sin(i/2)\cos\Omega \end{array} \tag{2.3}$$

Here, a and l refer to the semi-major axis and the mean longitude respectively; h and k refer to the projections of the eccentricity vectors (whose numerical value equals the orbit eccentricity and the orientation is directed towards the perigee of the orbit) in the XY planes of the Earth centered inertial coordinate system respectively. When we ignore the factor $1/2$, then p and q can be approximately regarded as the projections of the normal vector of the orbit plane into the XY planes of the Earth centered inertial coordinate system. If we take the factor $1/2$ into account, then the above non singularity orbit element is allowed to be used for an orbit with a large inclination and, in the meantime, avoids singularity when the orbit inclination is 90°.

The second definition of non singularity orbit element is:

$$\begin{array}{lll} a, & h = e\ \sin(\Omega + \omega), & p = tg(i/2)\ \sin\Omega \\ l = \Omega + \omega + M, & k = e\ \cos(\Omega + \omega), & q = tg(i/2)\ \cos\Omega \end{array} \quad (2.4)$$

The second definition is more suitable for perturbation calculations.

2.3.3 Rectangular Coordinate Component

Orbit control is regularly adopted in the design of a special space orbit. The equation of spacecraft motion under orbit control is usually described as:

$$\ddot{\vec{r}} = -\frac{\mu}{r^3}\vec{r} + \vec{a} + \vec{a}_T \quad (2.5)$$

Here, $\vec{r}$, μ, $\vec{a}$ and $\vec{a}_T$ refer to the geocentric distance vector, the Earth's gravitational constant ($\mu = 3.986005 \times 10^{14}\,\mathrm{m}^3/\mathrm{s}^2$), the perturbation acceleration, and the controlling acceleration, respectively.

Under orbit control, the motion of a spacecraft can be generally described with rectangular components, which are either components in the Earth centered inertial coordinate system or components in the relative coordinate system.

In space applications, the Earth centered inertial coordinate system usually adopts the Mean Equinox and Equator of J2000.0 Coordinate System, or the J2000.0 Coordinate System for short. The J2000.0 Coordinate System $OX_IY_IZ_I$ is defined as a coordinate system with the geocentric as its origin O, the OX_I axis pointing towards the J2000.0 mean equinox (at bar centric dynamical time 12:00:00.000 on January 1, 2000, corresponding to the Julian Day 2451545.0), the OZ_I axis pointing towards the J2000.0 mean equator normal, and the OY_I located within the mean equator plane of the J2000.0 and determined by using the right hand rule (Fig. 2.7).

The relative coordinate system refers to the relative motion coordinate system with reference to a certain spacecraft. Here, the origin of the relative motion system s-xyz is fixedly connected with the centroid of the reference spacecraft and moves with it; the direction of axis x overlaps with that of the geocentric vector of the reference spacecraft, pointing from the geocentric to s; axis y is perpendicular to axis x within the orbit plane of the reference spacecraft and directs towards the motion direction; axis z is determined by using the right hand rule (Fig. 2.8).

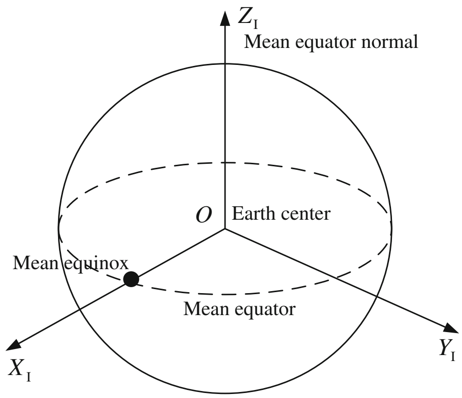

Fig. 2.7 J2000.0 Earth centered inertial coordinate system

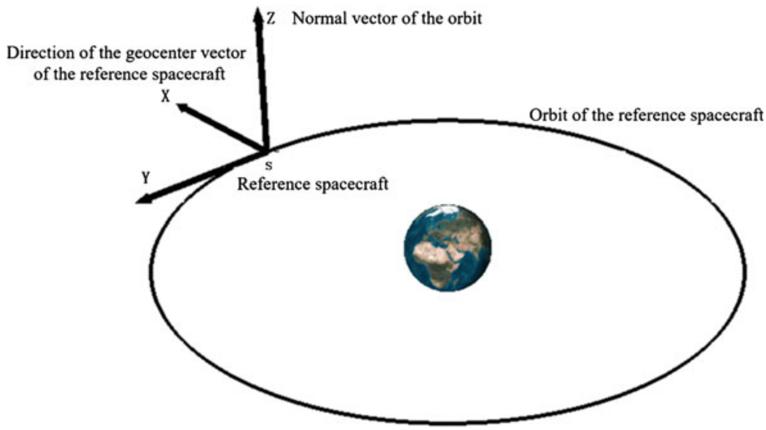

Fig. 2.8 Relative motion coordinate system

2.4 Summary

Special space orbits are proposed amid the development of space technology and the expansion of fields involving space missions. Compared to the more familiar typical orbits, special space orbits mainly demonstrate their distinctive features in orbit design concepts, orbit control application, special space application demands, and so on.

In this chapter, the concept of a special space orbit is introduced, and then the characteristics and applications of six special space orbits, i.e., hovering orbit, spiral cruising orbit, multi-target rendezvous orbit, initiative approaching orbit, responsive orbit, and earth pole-sitter orbit, are briefly illustrated. Finally, three descriptive approaches of special space orbits including orbit element, non singularity orbit element and rectangular coordinate component are discussed. In the following chapters, we will elaborate on the design concepts and methods of the above six special space orbits.

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