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Introduction

1.1 Connotation of Inter-Satellite Link

With the rapid development of aerospace technology, national interests are gradually expanding beyond the traditional territory, territorial waters, and airspace, expanding and extending to the ocean, space, and electromagnetic space. With the rapid development of space technology, space has increasingly become a new source of international strategic competition commanding heights. Space technology embodies the political strength, economic strength, and scientific and technological strength of a country, and has become a strategic means for countries to demonstrate the progress of their national strength and defend their international status. In order to safeguard our maritime rights and interests, defend our space rights and interests, and ensure the expansion of national interests, China must focus on a global perspective and develop satellite navigation, communication, and other systems on a global scale. To this end, it is necessary to use space-based networking methods to break through the limitations of land and solve problems such as satellite full-orbit operation management, constellation autonomous operation, and rapid response to complex tasks, in order to ensure the development of space systems [1].

Satellite technology is the primary breakthrough for occupying space resources. After going through two stages of single-satellite application and constellation application, the satellite field has gradually moved toward networking. The networking between satellites must first require that the information and data between satellites can be interconnected. Considering factors such as security and national strategy, the number of satellite ground stations that can be established is very limited, and most of them are limited to the country. When the ground station is strictly limited, the establishment of an inter-satellite link has become one of the most important necessary conditions for inter-satellite networking [2, 3].

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Once a communication network is established between satellites through inter-satellite links, the satellites are no longer isolated individuals, but a whole with a considerable scale, and satellites can only complete a small number of tasks to complete a general a lot of work. Under a good inter-satellite link network, the satellite not only has more powerful functions, but also its robustness and anti-interference have also been greatly enhanced.

The constellation network is a very complex space network. This is because in the inter-satellite link network, there are not only a large number of space nodes, but also many ground nodes are also part of the network, the composition is complex and changeable, the access is flexible and irregular, with typical flat and centerless features. These features require a high degree of flexibility and adaptability to build inter-satellite networks. In addition, the inter-satellite link is not a single, pure communication link. While carrying a certain rate of communication tasks, it may also need to complete high-precision inter-satellite measurement functions at the same time. In the navigation system, the inter-satellite link needs to meet the core requirements of precise orbit determination and time synchronization of the system, autonomous navigation applications, etc., and support the use of satellite–ground joint orbit determination and the transmission capability of measurement data for autonomous navigation. The construction put forward higher requirements.

Inter-satellite link (or crosslink) refers to the link between satellites and can also be extended to the link between spacecraft. The inter-satellite link can perform functions such as inter-satellite communication, data transmission, inter-satellite ranging, and inter-satellite measurement and control. Different space systems have different functions of inter-satellite links. The inter-satellite link of the communication satellite constellation can reduce the number of satellite–ground hops and communication delay; the inter-satellite link of the reconnaissance formation system can increase the aperture of the virtual camera and improve the resolution; the inter-satellite link of the navigation satellite constellation can support autonomous operation and improve the resolution. Positioning accuracy, the inter-satellite link of the relay satellite system can increase the measurement and control arc of the user satellite. In addition, there are some inter-satellite links used in scientific research, such as gravity detection satellite systems. The inter-satellite link makes multiple satellites form an organic whole to form a constellation system and expand the ability of a single satellite to work [4].

At present, distributed satellite systems mainly include two types: formation satellite constellation and formation satellite. A typical constellation includes the sharing of scientific data through inter-satellite links between satellites in orbits of planets or the sun. They do not rely on each other to complete autonomous onboard navigation corrections, which are transmitted through ground stations.

The formation satellites need to rely on inter-satellite links to transmit navigation data to achieve fully autonomous navigation. At the same time, formation satellites also need to ensure strict positioning accuracy to meet the scientific goals of formation missions. One or several spacecraft in the formation have the function of navigation and processing, and maintain the formation or ensure a certain topology structure through the transmission of data and instructions. At the same time, the state information of the spacecraft also needs to be transmitted by inter-satellite links.

Figure 1.1 divides formation satellite systems into different classes from an inter-satellite link perspective. There are two kinds of communication links between formation satellites: satellite–ground link and inter-satellite link. If satellites transmit information through satellite–ground links, direct communication between spacecraft is generally not required, but data are collected and processed on the ground, and then integrated into scientific or navigational information to be transmitted back to the spacecraft. Usually, this method is very dependent on the ground and can be regarded as centralized control, that is, a star-shaped distributed system. Some constellations exchange and process data entirely through satellite–ground communication. Unlike constellations, formation satellites use inter-satellite communications to exchange navigation data and commands. In addition, the topological structure of the communication network of formation satellites is mainly divided into two types: star type and point-to-point type (Figure 1.1).

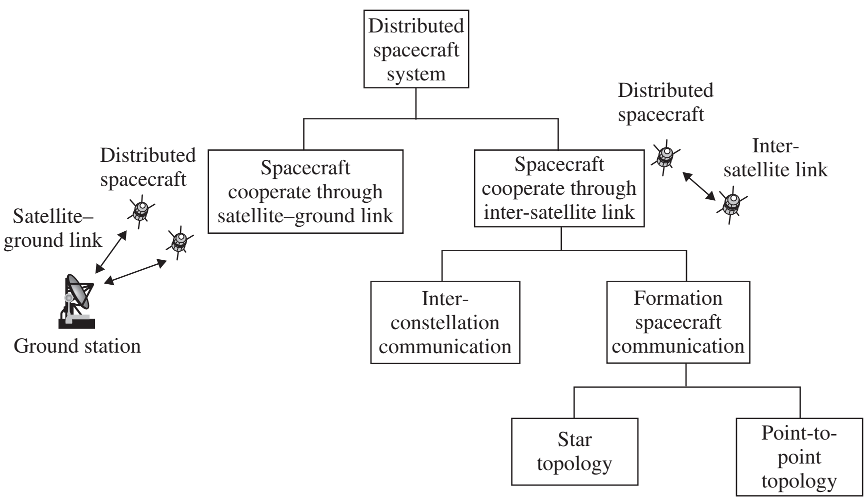


Figure 1.1 Distributed spacecraft communication structure division.

The use of inter-satellite links has many advantages, mainly including:

1) For communication satellites, when users who are not within the coverage area of the same satellite need to communicate, the use of inter-satellite links can eliminate satellite double hops and reduce the propagation delay. At the same time, a relay earth station dedicated to relaying signals between users in different satellite coverage areas is omitted [2, 5].
2) When the system is a constellation composed of many satellites, the use of inter-satellite links to form a complete communication network for all satellites is not only independent of the ground, but also greatly improves the system's anti-interference and anti-destroy capabilities.
3) It can be used to expand the coverage of the system. Multiple satellites are linked together through inter-satellite links, and users within the coverage area of any satellite can communicate directly with users within the coverage area of other satellites through the inter-satellite link.
4) Facilitate network management and form a global seamless network. For some low-orbit satellites, there may be no fixed earth station visibility at all in some cases (e.g. in the middle of the Pacific Ocean) due to their small coverage. At this time, it is almost the only solution to use the inter-satellite link to realize the control of the satellite on the ground and the mobile user to access the ground communication network through the inter-satellite link.
5) It is convenient to form a satellite group at the same orbital position, which is very useful for high-orbit satellites. Due to the increasing traffic volume of communications and the limited orbital positions of high-orbit satellites, it is bound to hope to make more effective use of each orbital position, and to place multiple satellites spaced about 100 km away from each other in one orbital position, so that they are interconnected by inter-satellite links to form a satellite constellation. This not only avoids the problem that a single satellite is too large to be loaded into orbit with existing launch tools, but also greatly reduces the risk of launch failure and satellite failure, and the capacity of the satellite can be adjusted according to actual needs. Incrementally, by increasing the number of satellites.
6) The space segment part of a system may be a constellation consisting of many satellites. For political and economic reasons, it is impossible to build a large terrestrial network that would allow any one of the satellites in the system to be able to see one of the ground control earth stations at any time. At this time, an inter-satellite link can be used to interconnect a satellite in the system that cannot be seen by the ground control earth station to another satellite (such as a high-orbit satellite) that can simultaneously see the ground control earth station and the satellite [6, 9].

On the other hand, the use of inter-satellite links also increases some design difficulties, including the need to increase the transceiver equipment necessary to maintain one or more inter-satellite links, including transceiver antennas, transceiver, radio frequency equipment, modulation and demodulation equipment, and the necessary baseband processing equipment. The satellite is required to have onboard processing function to distinguish whether the signal is sent to the inter-satellite link or the downlink. At the same time, it needs to have the necessary switching equipment to realize the onboard routing and exchange of the signal. Furthermore, the communication over the inter-satellite link should be transparent and the signal quality should not be degraded. All of these will inevitably increase the complexity of the satellite, and may increase the power burden of the satellite [7].

1.2 Types of Inter-Satellite Links

The type of inter-satellite link depends on the user with different usage requirements. However, its basic division includes two kinds: one is division by space domain and the other is division by frequency domain. Inter-satellite links are divided by frequency domain: ITU has allocated 14 frequency bands for inter-satellite links, ranging from UHF to EHF (190 GHz), including unallocated laser bands. That is, it can be summarized as microwave, millimeter wave, and laser links in three frequency bands. The inter-satellite link can be divided into the following two situations according to the airspace, that is, according to the satellite orbit [8–10]:

1) Inter-satellite links between satellites of the same orbit type, such as: GEO/GEO, LEO/LEO, etc.

   The inter-satellite links between satellites of the same orbit type are further divided into interstellar links in the same orbital plane and interstellar links in different orbital planes. Since the relative positions of the interstellar link satellites in the same orbital plane are fixed, we generally only analyze the different interplanetary link within the orbital plane. The interstellar links of the same orbit type mentioned in the subsequent chapters refer to the interstellar links in different orbital planes.

   Under the same coverage as shown in Figure 1.2, the GEO/GEO or MEO/MEO inter-satellite link can greatly improve the communication capacity of the system; when covering different areas, it can greatly increase the area of communication coverage; at the same time, it can improve the ground station. The minimum elevation angle can improve the quality of communication; it

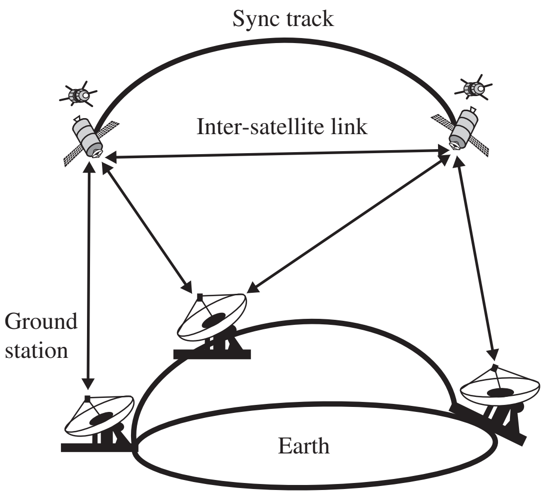


Figure 1.2 Schematic diagram of GEO/GEO inter-satellite link.

can also reduce the restrictions on satellite orbital positions and establish a global satellite communication network.

The LEO satellite inter-satellite link can make up for the two shortcomings of LEO satellite communication: one is that the coverage of a single satellite is very small, and the other is that the continuous communication time of a single satellite is very short, such as for Motoroh's iridium system, the maximum sustainable communication time of a single satellite is only 16 minutes. If the ground gateway station is used as a bridge for information communication between satellites, dozens or hundreds of ground stations may be required. Therefore, for the LEO system, it is unrealistic to rely on the ground station alone to communicate information between the satellites of the system. The inter-satellite link can realize the aerial networking of the satellite mobile communication system. In some cases, the satellite communication signal can reach the ground station only once or not at all before reaching the final communication user, thereby greatly saving the satellite mobile communication system. Invest in the ground segment and enable rapid transfer of information.

2) Interplanetary links between satellites of different orbit types, such as GEO/LEO, MEO/LEO inter-satellite links, also known as inter-orbital links (IOL).

Because the LEO satellite communication system requires a large-scale constellation (tens to hundreds) to form an effective global or regional coverage, the system investment is large, using one or more GEO or MEO satellites and LEO satellites to form a double layer. The satellite network can effectively overcome this disadvantage and maintain the advantages of the LEO system. In addition, the use of the GEO–LEO inter-satellite link can also form a tracking and communication support network for the spacecraft, with the ability to

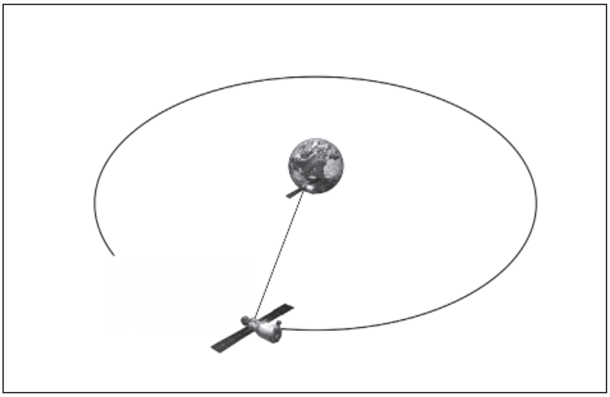


Figure 1.3 Schematic diagram of GEO–LEO interplanetary link.

provide services for multiple spacecraft at the same time; it can provide all-weather, full-orbit continuous tracking, orbit measurement and attitude measurement as shown in Figure 1.3.

1.3 Band Selection of Inter-Satellite Link

Inter-satellite links refer to satellite-to-satellite cross-links that can be used to replace the work done by terrestrial relay stations. The satellite link directly transmits information and data between satellites, avoiding the tedious work and frequent selection of routes such as sending the information back to the ground for processing and then back to the satellite, and also reduces the communication delay compared with the satellite–ground link. The purpose of the inter-satellite link is not only to achieve inter-satellite ranging, but also the high-speed, stable, and low-bit error rate transmission of inter-satellite data is one of its main purposes. For inter-satellite microwave communication, different data transmission rates need to select different inter-satellite link frequency bands, and high-speed data transmission must use high-frequency bands as carriers. Therefore, the selection of the inter-satellite link frequency band requires a compromise between hardware complexity and high-speed data transmission [11, 12].

1.3.1 Selection of Link Band

The inter-satellite link is a wireless link, and the communication and ranging of the inter-satellite link can use a microwave link or an optical link. When using a laser link (mainly a laser link), it has the characteristics of high measurement accuracy (can reach the sub-millimeter level), large communication capacity, good concealment and strong anti-interference ability, etc. However, the laser link device has a complex composition, the cost is high, the volume is large, the power consumption is high, the ranging distance is short, and scanning and alignment are required, which is not conducive to multi-link communication. These shortcomings limit the application of laser links to high ranging accuracy. When a microwave link is used, the bandwidth and antenna beam of the entire inter-satellite link are generally narrow, the frequency of the carrier itself is relatively low, and a large-sized antenna needs to be equipped on the satellite. The transmit power of the antenna is also high, the ranging accuracy is about from centimeters to decimeters, the link acquisition time is short, and multi-link communication is supported, which can be used for satellite constellations with a small amount of information transmission. At present, VHF and UHF frequency bands are mainly used. In recent years, SHF and EHF frequency bands have shown good application prospects due to their large transmission capacity, good spatial propagation characteristics, and no power density limitation. Moreover, since pseudo-code ranging can realize multiple measurements and spread spectrum communication, the pseudo-code ranging system is currently used in major long-distance space ranging at home and abroad, so microwave high-frequency bands have been paid more and more attention. In the GPSIII plan of the United States, Ka and V frequency bands will be used to meet the requirements of precise inter-satellite ranging and high-speed information transmission [13–15].

The commonly used microwave frequency bands are listed in Table 1.1. The frequency and band ranges in the table are both open on the left and closed on the right, that is, they contain an upper limit and do not include a lower limit.

1.3.2 Selection of Working Frequency

The frequency of the inter-satellite link of the satellite navigation constellation system is mainly divided into two major components: radio frequency and optical

Table 1.1 Composition of microwave frequency bands.

Band name	Frequency range	Band name	Wavelength range
UHF	300–3000 MHz	Decimeter wave	100–10 cm
SHF	3–30 GHz	Centimeter wave	10–1 cm
SHF	30–300 GHz	mmWave	10–1 mm
VHF	300–3000 GHz	smeepo	1–0.1 mm

Table 1.2 Frequency allocation of inter-satellite links.

Radio communications regulations	0.3–3 GHz 22.55–23.55 GHz 32–33 GHz 54.25–58.2 GHz 59–64 GHz 116–134 GHz 170–182 GHz 185–190 GHz
Optical frequency	0.8–0.9 micron 1.06 micron 0.532 micron 10.6 micron

frequency. Table 1.2 lists the main frequency ranges used by the inter-satellite link in detail.

The selection of the working frequency of the inter-satellite link can be considered from the following aspects [17]:

1) It must meet the planning requirements of the International Radio Consultative Committee (CCIR-International Radio Consultative Committee) for the frequency of satellite inter-satellite links. UHF, VHF, Ka, S, and L frequency bands can be used for inter-satellite link communication.

   In the navigation satellite system, since the satellite–ground link has already used the S and L frequency bands, considering the electromagnetic compatibility of the satellite system, these two frequency bands are preferably no longer used by the satellite inter-satellite link, but mainly from the UHF frequency band, VHF band, and Ka band.
2) Refer to the inter-satellite link frequency bands selected and used by the US GPS BLOCK IIR and GPS BLOCK IIF. One of the major improvements of the third-generation GPS satellite BLOCK IIR in the United States is the addition of inter-satellite links to provide communication and ranging between satellites, and to provide precise ranging data to GPS satellites for autonomous navigation. The data exchange of the navigation data generation system and the exchange of the autonomous navigation state vector data are carried out among the satellites in the system. All GPS BLOCK IIR satellites are equipped with transponder data units working in the UHF frequency band for inter-satellite link communication and ranging functions. This frequency-hopping spread spectrum communication system belongs to the time division multiple access (TDMA) method. There is also the inter-satellite link of the fourth-generation satellite GPS BLOCK IIF of the United States working in the UHF frequency

band, which is very important for the selection of the frequency of the inter-satellite link.

3) Consider from the perspective of reducing the influence of inter-satellite Doppler frequency shift. Because the relative motion speed between satellites is very large, in general, satellite communication signals will have a certain Doppler frequency shift, and the difficulty of link acquisition will increase correspondingly with the increase of Doppler frequency shift. For radial velocity v_0, the Doppler shift between two satellites at the operating frequency f_0 of the inter-satellite link is $f = 2v_0 f_0/C$. Considering the characteristics of the satellite constellation studied in this paper, the relative motion speed between satellites is very large, and the relative position relationship is always changing to choose from.
4) From the perspective of satellite inter-satellite communication and ranging antenna. For communication and ranging between multiple satellites in the navigation satellite constellation system, shaped wide beam antennas and multi-beam phased array antennas can be used. If a shaped wide beam antenna is used, the antenna beam should be able to cover the azimuth angle of 0°–360°, and the elevation angle of 45°–21° or 68°–44°. Due to the limitation of the transmit power on the satellite and the installation space of the antenna, the gain of the antenna is generally relatively high. Although the size of the antenna can be reduced by increasing the operating frequency of the system, the propagation path loss will increase accordingly. When the distance between the inter-satellite links reaches 60,000 km, the accuracy of the inter-satellite ranging will be reduced. However, if a multi-beam phased array antenna is used, due to the complexity of the relative position and distance relationship between satellites, each beam of the antenna is required to have the ability to automatically capture and track, and the direction of the antenna beam should be controlled according to the orbit. The necessary periodic transfer and switching are carried out according to the law, so the system design is quite complicated.

1.4 Microwave Inter-Satellite Link

1.4.1 Frequency Selection

Looking at the development of inter-satellite links in major navigation constellations in the world today, it is not difficult to find that microwave inter-satellite links are the most important and most widely used space communication system in current navigation systems. The frequency band selection of the inter-satellite link affects the communication capacity and communication quality in the satellite navigation system. At present, the inter-satellite microwave communication technology is developing toward the high-frequency band. According to the frequency allocation table of the Radio Regulations published in 2008, the frequency bands allocated by the International Telecommunication Union (ITU) to inter-satellite research and operation signals are shown in Table 1.3.

Summarizing the signal frequency bands in Table 1.3, it is not difficult to find that more microwave frequency bands are allocated to inter-satellite link services, and the bandwidth of microwave frequency bands is also increasing [7, 9].

Table 1.4 lists the frequency band division of the inter-satellite links of domestic and foreign satellite systems in turn. Combining Tables 1.3 and 1.4, it can be seen that the main frequency bands currently used for inter-satellite links are UHF, S, Ka, Ku, and V.

In addition, it can be seen from the development trend of microwave inter-satellite links that the main development direction of inter-satellite links is high-frequency band, large channel capacity, and wide bandwidth. The advantages of using high-frequency band for inter-satellite communication in the microwave inter-satellite link of the global satellite navigation system are as follows:

1) Comply with the ITU space operation frequency usage specification, allow application, and be protected.

Table 1.3 Inter-satellite link frequency bands allocated by ITU.

Band name	Frequency range	Business scope
UHF band	400.15–401 MHz, 410–420 MHz	Limited to space operations, satellite earth exploration, space research
S-band	2.025–2.11 GHz, 2.20–2.29 GHz	Aviation radio frequency band, satellite downlink navigation frequency band
C-band	5.01–5.03 GHz	Inter-satellite use
Ka-band	22.55–23.55 GHz, 24.45–24.75 GHz, 25.25–27.5 GHz, 32.3–33 GHz	Inter-satellite link services in geostationary orbit only
V band	54.25–58.2 GHz, 59–71 GHz	Inter-satellite only, geostationary applications only
mm band	116–123 GHz, 130–134 GHz, 167–182 GHz, 185–190 GHz, 191.8–200 GHz	Inter-satellite use
Laser	0.8–0.9 μm, 1.06 μm, 0.532 μm, 9.6 μm	Limited to space research, not considered a protected security business

Table 1.4 Frequency bands of inter-satellite links between domestic and foreign satellite systems.

Satellite system	Frequency	Construction practice
The first and second generation of TDRS system	S / Ku sum S / Ku / Ka	1983–2002
Military star second generation	V	1994–2003
Iridium system	Ka	1997–2003
GPSIIR and GPSIIF	UHF	1999–2012
Advanced very high-frequency satellite system	V	After 2010
TDRS third generation	S / Ku / Ka	After 2012
Next generation iridium system	Ka	After 2014
GPSIII	Ka	After 2015
GLONASS-M	S	Under construction
GLONASS-K and GLONASS_KM/NG	Gekikou	Under development
GALILEO satellite GIOVE_A	Gekikou	In-orbit test
“Beidou” second-generation navigation satellite	Microwave	On-orbit test

2) The available bandwidth of the high-frequency band is wider, the bandwidth of the high-frequency band is about 100 times that of the low-frequency band, and the communication capacity is larger.
3) The antenna beam is narrow and the anti-interference is strong.
4) The wavelength of high-frequency radio is small, the size of the signal transmitting equipment is small, and it is easy to be equipped with satellites.
5) It is less affected by the plasma in space, and the data obtained by inter-satellite measurement are more accurate.
6) Radio signals in high-frequency bands are not easily interfered by the ground electromagnetic environment.

1.4.2 Microwave Inter-Satellite Link Data Transmission System

For the global satellite navigation system, the satellites in the navigation constellation are medium and high orbit satellites, the number of satellites is high, and the complexity and precision are high, which makes the inter-satellite link networking of the navigation system a complex network, which is generally low. Orbital communication satellite system networking cannot be compared. In the navigation system, the work done by each satellite is the same, so the satellites in the constellation differ in space except for their spatial positions, which are essentially equal.

Therefore, the inter-satellite communication network formed by the navigation satellites is a centerless satellite inter-network, which has a large number of peer nodes.

The characteristics of the inter-satellite link networking make the inter-satellite link have strong topology adaptability and flexible and convenient network access. In addition, different from the inter-satellite link of the low-orbit communication satellite system, the main task of the inter-satellite link of the navigation satellite system is the communication and measurement between satellites, enabling information exchange between satellites and between satellites and ground stations.

In a satellite network, how to allocate links between satellite nodes to achieve maximum inter-satellite resource sharing is a key issue in the study of the working system of inter-satellite links. The multiple access methods currently existing in the satellite system include code division multiple access (CDMA), frequency division multiple access (FDMA), TDMA, space division multiple access (SDMA), and so on. The characteristics of various multiple access modes are shown in Table 1.5.

Comparing the advantages and disadvantages of various multiple access modes in Table 1.5, referring to the successful inter-satellite networking methods of the GPS system and the iridium system, it can be found that compared with CDMA and FDMA, TDMA and SDMA are more suitable for satellite networking of

Table 1.5 Comparison of multiple access modes.

Multiple access mode	Main allocation of resources	Advantage	Disadvantage
Code division multiple access (CDMA)	Numbers	Easy to accept, good anti-interference performance, good privacy	Complex acquisition and large inter-symbol interference
Frequency division multiple access (FDMA)	Frequency band	Simple equipment, mature technology, flexible receiving and sending	Easy to produce intermodulation interference, not suitable for large-scale networking
Time division multiple access (TDMA)	Time slot	Single carrier operation, mature technology	The time synchronization mechanism is complex
Space division multiple access (SDMA)	Space	Improve frequency band utilization and increase system capacity	High requirements for antennas and complex system control technology

navigation systems. The TDMA mode works on a single frequency point, which makes the onboard frequency point matching process simple, the hardware design is simple, and the maintainability and interchangeability between onboard devices are good. TDMA technology has great advantages in inter-satellite link networking. The characteristics of the SDMA mode determine that it is more suitable for microwave inter-satellites with high frequency and spot beam antennas.

This is an important development trend of inter-satellite link technology in future satellite navigation systems.

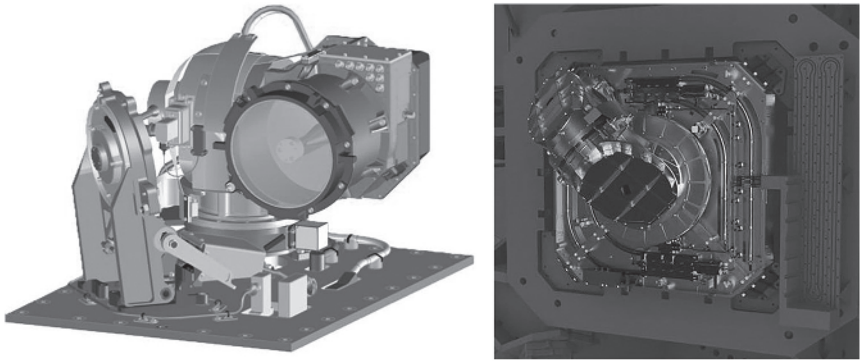
1.5 Laser Inter-Satellite Link

1.5.1 Technical Characteristics of Laser Inter-Satellite Link

The laser inter-satellite link is a new method for realizing high-speed data exchange between aircraft by utilizing the laser wavelength, high brightness, and high collimation characteristics. It is a new method different from the current, widely used inter-satellite radio frequency communication that has several features.

1) High communication rate (from 100 Mbit/s to more than 10 Gbit/s) → fast transmission speed: a single channel can provide a data transmission rate of more than 10 Gbps, which is far greater than the current data transmission of hundreds of Mbps in microwave communication rate. It can reach hundreds of Gbps or more through wavelength division multiplexing.
2) The beam divergence angle is very small → strong anti-interception ability. Different from radio frequency communication, laser communication adopts point-to-point communication mode, so it has the characteristics of high confidentiality, strong anti-interference, and strong interception ability.
3) Small size, light weight, low power consumption → flexible. The beam divergence angle is much smaller than that of microwave communication, and the antenna gain of space optical communication is much larger than that of microwave communication.
4) Away from the electromagnetic spectrum → strong anti-interference ability.
5) Easy to encode (load quantum key) → good security performance.
6) Large information capacity (three to five orders of magnitude wider than the RF bandwidth) → convenient band selection.
7) Communication requirements → The channel is unobstructed and can be seen.

The laser inter-satellite link is the detection of extremely long distance and extremely weak signals. It uses an optical telescope as an antenna for signal transmission and reception, which puts forward high requirements for a number of



(a) (b)

Figure 1.4 Typical advanced space laser communication device. (a) US moon–Earth laser communication device; (b) German LCT laser communication device. *Source:* Deutsches Zentrum für Luft- und Raumfahrt.

optical performance and rotational characteristics of the device. The difficulty in development comes from the ultra-long distance, dynamic changes of links, and complex spatial environments. Establishing an inter-satellite communication link and keeping the link stable is the most critical technology. Satellites are always in high-speed motion, and several major steps are required to successfully establish a link and maintain stability, namely targeting, acquisition, and tracking. To realize the inter-satellite laser communication, the high sensitivity and high precision of the hardware are the foundation, while the speed and accuracy of the algorithm are guaranteed. For inter-satellite laser networking, issues such as multiple access, routing switching, and space network switching also need to be considered. For commercial laser communication constellations, it is also necessary to consider the coordinated development of performance and cost. It will not only be scientific issues, but also issues such as matching and compatibility with different industries as shown in Figure 1.4.

1.5.2 Future Requirements for Laser Inter-Satellite Links

The future demand for laser inter-satellite links may mainly focus on:

1) National deep space exploration and other major scientific projects

   The United States has achieved ultra-long-distance interstellar data transmission through the laser inter-satellite link, and the laser inter-satellite link can serve Chinese major scientific projects such as lunar exploration and fire detection.

2) Inter-satellite and satellite–Earth data interconnection

   Build a laser inter-satellite link constellation to achieve inter-satellite interconnection. It can be realized by deploying static orbit relay satellites, etc. In the occasions where satellite data needs to be quickly returned, such as disaster situation collection, emergency communication, enemy situation reconnaissance, satellite navigation, etc., the inter-satellite laser link can provide good real-time performance. For occasions that need to transmit large-capacity data, such as global mapping, weather detection, etc., the laser link can provide good stability.

3) A new generation of integrated laser payload

   The integrated payload that can realize various functions such as space target ranging, imaging, and communication may become the mainstream in the future.

4) Low-orbit Internet project

   The application of laser communication in Chinese low-orbit Internet project can improve the characteristics of inter-satellite interconnection, and is expected to improve the overall bandwidth and terminal performance.

1.5.3 Development Trend of Laser Inter-Satellite Links

1.5.3.1 The Development of Laser Communication Technology from Technical Verification to Engineering Application Stage

Laser communication technology is developing from the technology verification stage and the technology finalization stage to the engineering application stage. Many technical difficulties were gradually overcome. For example, fast and high-precision pointing, acquisition, tracking (PAT) technology, atmospheric turbulence effect suppression and compensation technology, narrow linewidth high-power laser emission technology, low-noise optical amplification technology, high-sensitivity DPSK/BPSK/QPSK optical receiving technology, etc. The overcoming of these technical difficulties has laid the foundation for the realization of interstellar laser communication.

1.5.3.2 The Communication Rate Develops from Low Code Rate to High Code Rate

The communication rate has been continuously improved, from the initial 2 Mbps to the current Gbps level, and the future planning has reached the order of tens of Gbps, gradually giving full play to the technical advantages of laser inter-satellite links. Early laser communication was mainly concentrated in the 800 nm light wave band. Various technologies in this band are relatively mature, the device performance is reliable, and the cost is low. However, its main disadvantage is the limited bandwidth of lasers and Si-APD detectors applied in this band. Therefore,

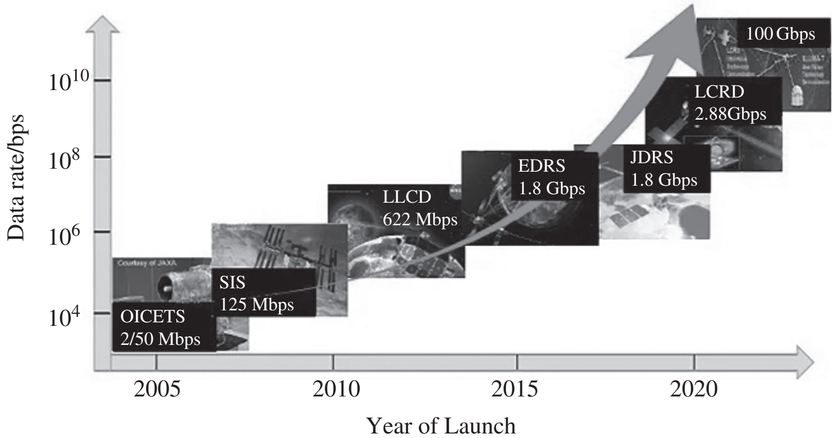


Figure 1.5 Schematic diagram of high-speed laser inter-satellite link.
Source: lilac 的老父亲.

the communication code rate is relatively low, generally less than 1 Gbps. At present, using the 1550 nm band for laser communication can make full use of the high bandwidth of the 1550 nm band laser transmitting and receiving components, and directly apply the mature technology of ground optical fiber to communication to improve the communication code rate as shown in Figure 1.5.

The main difficulties of high-speed laser inter-satellite links are key technologies such as high-speed optical transmission and high-sensitivity reception. The main technical approaches include high-order modulation technology (QPSK/DQPSK/M-QAM, etc.), optical multiplexing technology (wavelength division/time division/polarization/orbital angular momentum, etc.), high-sensitivity coherent receiving technology, etc.

1.5.3.3 Deep Space Will Become an Important Place for Laser Communication Applications

The main advantage of deep space laser communication is that it can realize the return of information from ultra-long-distance deep space exploration missions such as the moon, Mars, and Jupiter. The main difficulty is key technologies such as high-power optical emission and high-sensitivity reception. The main technical approaches include ultra-high-power optical emission technology, large-diameter optical antenna technology, and high-sensitivity single-photon detection technology.

With the continuous improvement of the return rate requirements of scientific missions, free-space optical communication has great potential to meet the high data rate links from deep space, and optical communication will be gradually applied in the deep space field in the future. Optical communications will enable the transmission speeds required for future scientific instruments. For example, the maximum transmission rate of the Mars Reconnaissance Orbiter (MRO) is 6 Mbps (the highest transmission rate for the current Mars exploration mission), which takes about 7.5 hours to empty the orbital recorder and 1.5 hours to transmit a high-resolution photo to Earth. The transmission rate of optical communication will be increased to 100 Mbps, and it only takes 26 minutes to clear the recorder, and the transmission speed of the same photo is only five minutes. Therefore, for future deep space scientific missions, the need to develop new high-speed transmission terminals is self-evident [16].

1.5.3.4 Combined Use of Laser Communication and Laser Ranging

Since laser ranging and laser communication have certain similarities in system composition, signal acquisition, and processing methods, they can be combined together to realize a functional whole to complete ranging and communication functions. The transformation plan of the SLR2000 satellite laser ranging station is proposed to combine laser ranging and laser communication, which is the original concept of the composite system. Since then, the European LISA has inverted the Earth's gravitational wave field through precise distance measurement, and achieved precise distance measurement at ultra-long distances with coherent laser heterodyne, which also has communication functions.

The main advantage is that the combination of communication and ranging enables a device to have multitasking capabilities, thereby reducing the requirements for volume and power consumption, and improving the cost-effectiveness of the system. The main difficulties are poor anti-interference ability and weak light energy for ranging. The main technical approach is to use common wavelength for ranging and communication, modulation dual system, pseudo-code and communication signal conversion technology.

1.5.3.5 Integration and Miniaturization of Laser Communication Terminals

In recent years, the United States, Europe, and Japan have been developing integrated, lightweight, and miniaturized laser communication terminals, which are mounted on small LEO satellites. The main advantages of integrated laser communication terminals are small size, light weight, low power consumption, good stability and low cost, and are usually carried on low-orbit small satellites. The main technical approaches are the lightweight and miniaturization of optical antennas and turntables, and the integration of communication transceivers.

In addition, for the commercial application of laser inter-satellite links, explore low-cost solutions to find a balance between ensuring product performance and reducing costs.

1.5.3.6 Networking of Laser Inter-Satellite Links

At present, the laser inter-satellite links in the world are all point-to-point, which seriously affects the communication relay, networking, and applications. Laser communication networking is an inevitable trend of future development. The main advantages of laser communication network are that the communication network is fast, real time, and wide area. The main difficulties are small beam divergence angle networking, dynamic topology access, and long delay. The main technical approaches are to break through the “one-to-many” laser communication technology, break through the “multi-standard compatible” laser communication technology, break through the all-optical relay technology, study dynamic routing to solve access problems, and seek a joint laser-microwave communication system.

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