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Overview of Research on Space Laser Communication Tracking and Pointing Technology

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Laser communication system is built to satisfy the urgent need of information transmission of the earth observation system and space-based information in high resolution and the need of high-speed transmission rate of distribution system. Laser communication system makes use of laser frequency band, takes laser as information carrier and transmits information by the modulation of laser pulse and thus achieves information exchange. And to achieve information exchange, we must solve the tracking and pointing technical problem because this is the guarantee condition of successful laser communication and key technology to improving communication performance. This article firstly introduces the development of space laser communication technique at home and abroad in recent years and the introduces the research situation of several key technology in space laser communication tracking and pointing system to provide guidance to the research on space laser communication system and tracking and pointing technology.

1. Introduction

With the development of informatization construction of military system, demands have increased for high-speed and high bandwidth satellite communication services, especially that the earth observation system and space-based information transmission and distribution system have very urgent demand for Gbps high-speed data transmission. At present, most communication satellites apply microwave frequency band of 300MHz to 30GHz. However, with the development of on-orbit business applications of communication satellites in various countries, the microwave frequency band available has been very crowded and there is less and less bandwidth available. Therefore, communication satellites have developed to higher frequency and have extended from the microwave frequency band to the laser frequency band. Laser communication system is built to satisfy the urgent need of information transmission of the earth observation system and space-based information in high resolution and the need of high-speed transmission rate of distribution system. Laser communication system makes use of laser frequency band, takes laser as information carrier and transmits information by the modulation of laser pulse and thus achieves information exchange.
Laser has high temporal and spatial correlation, whose oscillation frequency is high. Laser frequency band (typical wavelength of 1 μm) is four orders of magnitude higher than microwave frequency band (typical 10 GHz), so the space laser communication of satellites have the following advantages compared with microwave communication.

1.1 Large Message Capacity

The frequency band of laser is three or four orders of magnitude higher than microwave frequency band (the corresponding frequency band is between 1013 to 1017Hz). Laser, as the carrier wave of communication, has more available frequency band. Optical fiber communication technique can be transplanted into space communication. At present, the data rate of every wave beam of optical fiber communication can be 20Gb/s or higher and we can even make use of the wavelength-division multiplexing technology to increase the message capacity by dozens of times. Therefore, the laser communication possesses great advantage in terms of message capacity than microwave communication.

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1.2 Low Power Dissipation

The divergence angle of laser is very small and the energy of laser highly centered, and thus the power density on the receiver telescope antenna is high. More than that, the transmitting power of transmitters can be reduced and the power dissipation is relatively low. This is very appropriate for space communication that has very high energy cost.

1.3 Small Volume and Light Weight

The weight of the transmitter and its power supply system can be reduced because the high energy utilization rate of space laser communication; the wave length of laser is short, so the caliber of the transmitting and receiving telescope can be decreased under the same requirement of divergence angle and receiving FOV. Space laser communication has get rid of the huge bow-tie antenna of microwave system and is light in weight and small in volume.

1.4 High Security

Laser has high directionality, whose transmitting beam is slim and the divergence angle is usually milli-radian, which gives laser communication high security and improves its anti-jamming and anti-eavesdrop capability effectively.

1.5 Low Cost

The construction and maintenance expense of laser space communication is relatively low.

2. The Development of Space Laser communication technique

Considering so many advantages of the space laser communication, America, countries in Europe, Japan and other developed countries have launched research on this one after another.

The development of space laser communication in Europe is based on the cooperation between different countries. The ESA has invested a large amount of money into the research on satellite laser communication and has developed a series of satellite laser communication terminals under the background of different inter-satellite links, like SILEX and SOUT. One of the terminals of SILEX is installed on the relay satellite of ESA and the other is installed on the French earth observation satellite SPOT-4. On Nov 21st, 2001, Europe successfully built the laser communication link and realized the laser communication experiment at 50Mbps speed ratio. This is the first inter-satellite laser link experiment and stands as a milestone in the field of satellite laser communication.

Although Japan has late start in the research on satellite laser communication but has made rapid development. In 1995, Japan has successfully conducted the laser communication experiment using the terminal installed on the satellite ETS-VI to communicate with the ground station. Although the digit rate of this experiment was only 1.04Mbps, still this was the first successful satellite-ground laser communication experiment. In 1996, the LCE laser communication experiment system developed by NASDA has conducted both-way laser communication experiment with the JPL ground station in America. The NASDA in Japan has also developed special laser communication experiment satellite OICETS and plans to conduct laser communication experiment with ESA and ARTEMIS.

America is one the earliest country in the world to carry out research on space laser communication. The research work has gone through the process of ground demonstration and verification, key technology research and inter-satellite and satellite-ground space laser communication experiment. America has launched many research plans on satellite laser communication and invested a large amount of money into developing many satellite laser communication experiment terminals, like LCDS supported by NASA, LITE system of MIT Lincoln Laboratory. NASA’s JPL has developed 2×600Mbps satellite laser communication terminals and the America military BMDO has established the laser link terminal of low earth orbit satellite to ground station and the data rate is 1Gbps. America has also actively engaged in the development of laser inter-satellite link terminal in small satellite constellation.

Russia has made great achievements in inter-satellite laser communication and the ILDTS has been applied in space station and aircraft.

At present, the international community has completed the conception research on space laser communication link and has solved the problem of key technology and core component. The laser communication experiment of low earth orbit satellite at low and medium speed ratio has been achieved and the laser communication experiment of low earth orbit satellite to ground station has been launched. These communication experiment systems have reached high acquisition probability, short acquisition time, dynamic tracking and pointing with high sensitivity under a variety of interference and relatively high data transmission rate. Meanwhile, assessment and testing platform of laser link system and other analysis and simulation software has been developed.

China has a late start in the research of laser communication technique. China has started its research on wireless optical communication technique and system since 1970s, and achieved some results. At the moment, the units which launched the research on satellite optical communication related technique in China include Harbin Institute of Technology, Changchun University of Science and Technology, Peking University, University of Electronic Science and Technology of China, Shanghai Institute of Optics and Fine Mechanics and No.504 Research Institute of Space Technology in Wuhan University. Besides, the Institute of Optics and Electronics of Chinese Academy of Sciences, No.34 institute of China Electronic Technology Corporation, No.717 Research Institute of China State Shipbuilding Corporation and other units have started the research on space laser communication technique and system. Among all these units, Harbin Institute of Technology has started its research work on satellite optical communication since 1992, which is the earliest unit to start this research. University of Electronic Science and Technology of China has developed the optical transmitter and receiver that has the function of acquisition, positioning and tracking and has conducted the demonstration experiment of space laser communication with real success. Wuhan University has developed the laser communication demonstration experiment at the speed ratio of 42.24Mbits/s. Changchun University of Science and Technology has a history of more than 20 years in launching the space laser communication research and has carried out the theory, simulation, key technology demonstration and validation research of space laser communication. It now has space-ground laser communication technique key discipline laboratory for national defense and attaches great emphasis on the research of airborne platform, ground platform and atmospheric channel of laser communication technique and system.

3. Introduction to Space Laser Communication Tracking and Pointing Process

The main function of laser communication tracking and pointing system is pointing, acquisition and tracking, which is PAT. Another important function is to overcome the disturbance of satellite platform, to maintain tracking state so as to ensure the laser link will not be interfered by external environment. The introduction to the process is as follow:

1) Pointing process: two satellites communication terminals point to each other according to the prediction of satellite orbit; 2) Acquisition process: the error in the posture and positioning of satellite leads to the error whether the laser communication terminal is accurately pointed to the other terminal, so we must search and acquire the other terminal within certain field range after the pointing; 3) Tracking process: when one laser communication terminal discovers and acquires the beacon laser of the other terminal within the acquisition field range, it needs to switch to tracking state and maintain the unimpeded state of laser communication link.

Internationally, the JPL of NASA has done a lot of research and experiments about ATP technology. For example, in Dec 1992, it successfully achieved the laser communication link connection between Table Mountain Observatory in California and Galileo Satellite using the PAT technology; in 1995, it completed two laser communication experiments, one of which verified that the code rate of laser communication reached 750Mbit/s and the other successfully established the both-way laser communication link between Table Mountain Observatory in California and the satellite ETS-VI in Japan and the data rate reached 1024Mbps. Since 2001, America has always been researching the laser communication technique using PAT technology to restrain the atmospheric influence, and carrying out a series of laser communication experiments between aircraft and ground, mainly aiming at low earth orbit satellites. As early as 1980s, the McDonnell Douglas in America conducted the aircraft to ground laser communication voice frequency demonstration experiment, reaching the order of magnitude of 1Gb/s. In 1998, the Lincoln JPL in America also conducted the laser communication between the ground and space shuttle with real success.

In 1998, the NEC in Japan started the research work on laser communication and conducted many applications using PAT technology. They adopted the compound mode of WFPM with CPM in large scale, enabling the ATP system in laser communication field to be lighter, quicker and more effective. In 1992, the AOD developed by Lincoln Laboratory made it possible for people to control and intervene the PAT precise pointing system with non-mechanical device light beam and achieved continuous development.

Considering the present state of research at home and abroad comprehensively, we can see that the research on space PAT technology is still developing and integration space PAT system that is smaller and lighter is been designed and produced and perfected. This has provided more effective technical support for the realization of laser communication in inter-satellite and deep space.

4. Introduction to Space Communication Tracking and Pointing Mechanism

The tracking and pointing system is usually made up of two opto-electro-mechanical systems, one is the rough tracking and pointing opto-electro-mechanical system and the other is precise tracking and pointing opto-electro-mechanical system. The main function of rough tracking and pointing system is to complete the big angle scope motion of terminals and the acquisition and rough tracking and pointing of incident signal beam. This system adopts closed-loop control. The main function of precise tracking and pointing system is to precisely track the incident beam and this system also adopts closed-loop control. Rough and precise tracking and pointing adopt the combination of compound axis mechanism to achieve high-precision tracking in the wide scanning range. Actually, the PAT process is the common process shared by terminals of both sides.

4.1 Rough Tracking and Pointing Mechanism

Rough tracking and pointing mechanism generally adopts the form of two-dimension servo turntable. The two-dimension servo turntable is composed by azimuth axis and pitch axis and the two axes are orthogonality. The optical load is located at the center of turntable. The optical load is driven by azimuth axis and pitch axis to achieve the azimuth and pitching motion. Internationally, we have many successful cases employing two-dimension servo turntable in space-based imaging and tracking and pointing system. Among these cases, the SBSS launched on Sep 25th 2010 by America adopted basic azimuth-type 2-axis rotation system. The positional accuracy of this two-dimension rotation system is less than 5μrad, the payload can reach 2000lb, the structural stiffness is 100Hz and the lifespan is five and half years. The structure is shown in Figure 1.

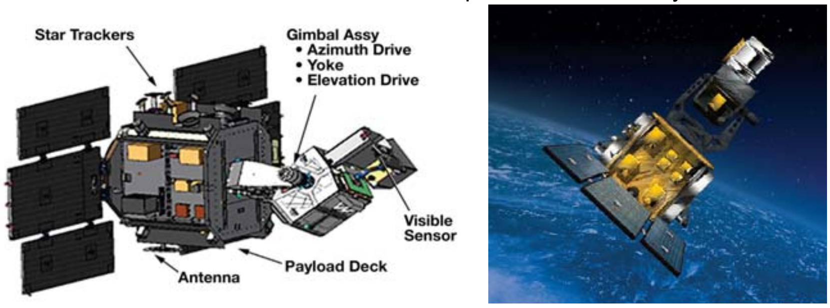

Figure 1: SBSS 2-axis Turntable and Remote Sensor

The research on the turntable of space laser communication system has always been an important index in evaluating laser communication performance. The laser communication platform needs to be carried on aircraft, airship, satellite, observation and control ship, ground and other platforms, so they have different tracking link. Various countries have designed turntables of different structures based on the requirements of their angle servo scope, tracking speed and tracking precision. The structure of turntables can be summarized as follow:

1) Cross-shaped tracking rack structure is composed by azimuth axis and pitch axis and the two axes are orthogonality; the optical load is located at the center of turntable. The optical load is driven by azimuth axis and pitch axis to achieve the azimuth and pitching motion; the main optical antenna of the integrated optical transmitter and receiver on optical load and most of the optical system and part of the electronic system are shown is Figure 2. The main defects are the heavy weight of moving components, high requirements for the moment of driving devices and huge size of the mechanism; the big inertia brought by the rotation of the system leads to the huge ratio of rotational inertia brought by the system and the stars. Therefore, the rotation of the system will exert huge influence on the posture of satellites and severely impact the precision of the system. The laser communication launching servo turntable LCT of Goddard Space Flight Center in NASA adopted this laser communication system.

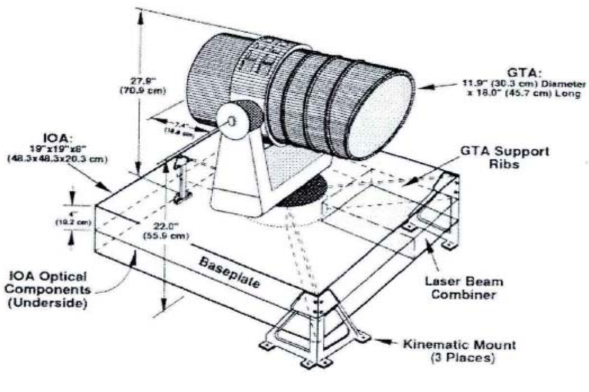

Figure 2: Structure of the LCT

2) Periscope-type structure PAT device adopts two 45° reflectors to respectively achieve azimuth and pitch scanning. Main optical system is located on the carrying platform; the main defects are the huge turning radius at work, that it calls for enough space when it is installed on the satellite, and that azimuth and pitch motion has some effects on the satellite posture, especially when the azimuth and pitch angle is (±71,0). Besides, after reflected twice, the controlling error of reflector angle will be amplified four times to the light path, making it more and more difficult to control the direction of optical axis. The servo turntable SOUT developed by ESA in the early stage adopted this structure. This structure resembles the periscope used in diving because its small volume and caliber. However, the precision is not high and field of view is small so it will be very difficult to establish the link when used in receiving beacon beam. The structure of the system is shown in Figure 3.

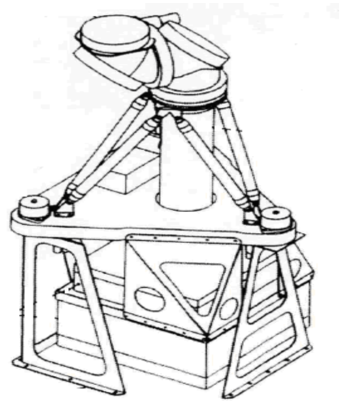

Figure 3: SCOT Turntable with Periscope-type Developed by ESA

3) Plane reflector servo structure. The main optical device of this structure is the reflector. The reflector receives the communication beam sent from outside and reflects the beam to the optical system by specular reflection. Different from the communication system of previous servo turntables, the optical system is not on the turntables. Only reflectors are on the turntables. This structure reduces the weight of optical transmitter and receiver and the structure is simple, so it is appropriate for inter-satellite laser communication. However, the problems are very evident. This system makes use of the light reflex and many problems brought by the light reflex have appeared when we are doing the laser communication. Limited by the plane reflector, clear aperture has increased. Besides, limited by its structure, this system is not that flexible in tracking the target and the tracking scope is very narrow. The LCDS developed by NASA adopted this structure. The specific structure is shown in Figure 4.

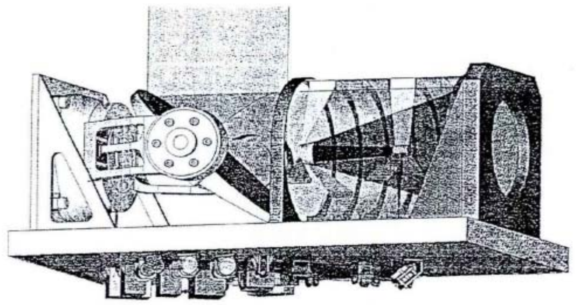

Figure 4: Structure of LCDS Laser Communication Turntable Developed by NASA

4.2 Precise Tracking and Pointing Mechanism

To achieve stable and effective wireless laser communication, the laser signal sent not only need to overcome the attenuation on its transmission path, but need to be accurately pointed to the detector of the receiver; at the same time, the detector of the receiver must determine the arriving direction of the launching site in order to modulate direction automatically. In space laser communication, the diameter of the facula formed from a great distance is small because of the small divergence angle of the laser beam. (if the divergence angle of the laser beam is 10μrad, the diameter of the facula formed by geosynchronous satellite on earth is only 360m). We need to be very precise and the field power of the transmitter must reach the photodetector of the receiver. Therefore, we need to introduce the precise mechanism-fast-steering reflector in space laser communication.

The most outstanding features of the precise mechanism-fast-steering reflector are relatively small dynamic range, relatively high servo bandwidth and high tracking precision. It can further effectively restrains the residual error of rough tracking. Besides, it has strong restraining capability for wide spectrum vibration so as to ensure the speed and precision of pointing and tracking. The final tracking precision of composite axis PAT subsystem is determined by the tracking precision of servo unit in the precise tracking, so precise tracking unit is the core component in the whole composite axis PAT system. The execution mechanism and execution precision of fast-steering reflectors and its own characteristics will undoubtedly pose great influence on precise tracking or even the precision of the whole system.

The execution mechanism of fast-steering reflectors generally adopts piezoelectric ceramic actuators or voice coil motor actuators. The piezoelectric ceramic actuators have incomparable advantages in ultraprecision positioning and micro displacement control than other actuators, like small volume (only several cubic millimeters to dozens of cubic millimeters), high displacement resolution ratio, quick response time (dozens of microseconds), high output, high energy conversion efficiency, athermic, good displacement repeatability. The piezoelectric ceramic actuators are ideal actuators; besides, the response frequency of voice coil motor is very high. Then after the optimizing by system mechanical structure and the compensation by servo control system, the response speed of system can reach Hundreds of Hertz. Therefore, voice coil motor has gradually become one of the recommended actuators in rapid reaction system.

5. Conclusions

At present, the research and development of space laser communication technique is developing rapidly. Many communication experiments in international society have proven the feasibility of space laser communication and we can employ low-weight and low power dissipation terminals to provide higher data transmission rate and at the meantime, the communication has high security and privacy and strong antijamming capability. The development of tracking and pointing technique is an effective technological way to improve the tracking precision for the space laser communication system, enabling the narrow laser beam to track with high precision between two terminals. With the further development of space laser communication tracking and pointing technique, space laser communication will possess great development potential and prospect for a broader and broader application.

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