Abstract:
The increasing demand for high-speed, large capacity data transmission between the earth and satellites may be solved by optical communications today. Otherwise, the satellite-to-earth communication will be constrained by the transmission "bottleneck". Relevant researches have been done with promising achievements, such as the Optical Communication Demonstration System, Optical Demonstration and High-speed Link Devices, STRV-2 Experiment, Geosynchronous Lightweight Technology Experiment (GeoLITE), the Mars Laser Communication Demonstration System (MLCD) developed by the US, and the laser communication experimental devices developed by Japan. Researches have also been conducted in China in the areas of Acquisition, Pointing and Tracking (APT), optical phased array and new types of satellite-to-earth communications. There are numerous problems which are expected to be solved in the future, including improvements of APT technology, solutions of the effect of space atmosphere, high data rate with low bit error rate, and the linking between the satellite and optical network on ground.

Status and Trends of Satellite-to-earth Optical Communications

Zhang Cheng, Hu Weiwei, Xu Anshi
(National Lab on Local Fiber-Optic Communication Networks and Advanced Optical Communication Systems, Peking University, Beijing 100871, China)

The development of information society needs a communications system with high data transmission rate, large storage capacity, and wide coverage as support. Facing the increasing demands on the satellite communications capacity and the data transmissions rate, communication technologies based on microwave cannot yet meet the demands. Therefore, new communications media and technologies need to be urgently found. With the breakthough of key technologies in satellite laser communications and the gradual incarnation of laser's predominace, experts around the world have come to the accordant conclusion that, optical communications must be used to implement satellite communications facing with the increasingly growing demands for a high data rate and a large communications capacity [1]. Communications architecture for the future world will be a space-ground laser communications system with satellite optical networks and ground optical fiber networks interconnected with each other as shown in Figure 1.

Among the various satellite optical communications links, the implementation of satellite-to-earth optical communications links is the most difficult, because the main transmissions media for satellite-to-earth optical communications is the atmosphere, while the complex properties of the atmosphere will have great influences on the laser communications signals transmitted in it. Without the optical communications links between satellites and ground, a "bottleneck" will form between satellite optical networks and ground optical fiber networks, which will restrict the development of communications. Therefore, it is necessary to make detailed research on the satellite-to-earth optical communications.

1 Status Quo for International Satellite-to-earth Optical Communications Development

At global scale, a large amount of human and material resources has been devoted to research on space optical communications since 1970s[2]. Great progress has been attained during the past decades, and it has developed from theoretical solution argumentation and experimental sample system research to engineering testing stage[3]. Currently countries with better-developed satellite optical communications technologies worldwide include USA, Europe,

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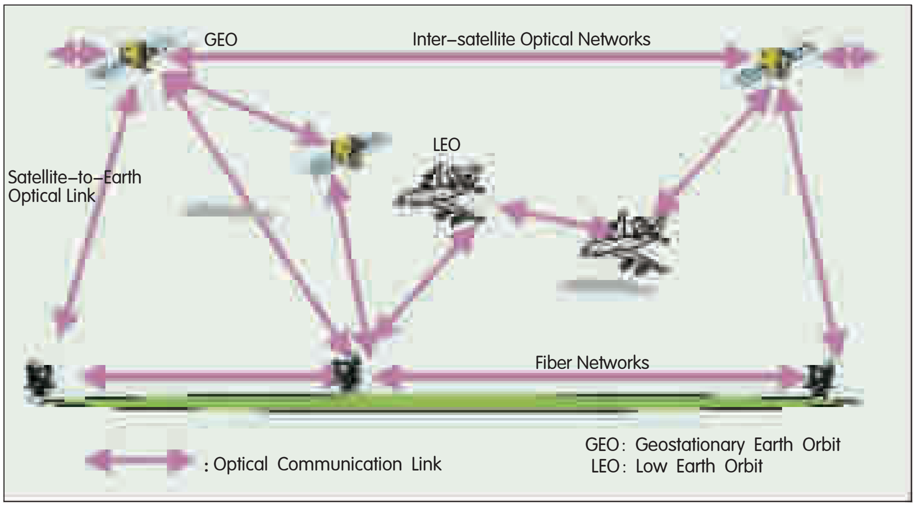


▲Figure 1. Space-ground laser communications system.

and Japan.

1.1 Development of Satellite-to-earth Optical Communications in USA

The United States has a long history in space-based optical communications development since 1970s. Unlike the European and Japanese programs, much of the information about these systems has been classified or at least dated if available. Recently, with the realization that optical Inter-satellite Links (ISLs) are an excellent business line, the US companies involved have begun marketing their products more openly and aggressively, and in fact reworking them to fit the more aggressive cost targets of the commercial world.

Leader organizations for satellite optical communications in USA are National Aeronautics and Space Administration (NASA) and the US Air Force. The main research participants include Jet Propulsion Laboratory of California Institute of Technology, and Lincoln Laboratory of Massachusetts Institute of Technology. Many large companies including Thermo Trex Corp along with Ball Aerospace and Technologies Corp have also done numerous research works. Some representational research results are introduced below.

(1) Research Results from Thermo Trex Corp

Thermo Trex Corp worked on optical communications for US military. Their reason for establishing space-to-earch laser links is that the atmosphere conditions in the troposphere is quite complex, while in the stratosphere the atmosphere condition is relatively simple. They use planes in stratosphere to establish laser links with satellites. Data from the satellites' downlink are compressed and re-sent via microwave or laser to the ground stations to reduce the influence of troposphere on the laser links. The most peculiar point in Thermo Trex Corp's research results is the first application of Faraday Anomalous Dispersion Optical Filter (FADOF) into Acquisition, Pointing and Tracking (APT) systems. The bandwidth of FADOF might be as narrow as 0.01 nm, and has a strong restrain effect on background optical noise. It is shown from experiments that relatively high Signal-to-noise Ratio (SNR) could be achieved under big Field of View (FOV) as to quickly capture and lock targets.

(2) Demo System for Laser Communication

Optical Communication Demo (OCD) system is developed by Jet Propulsion Laboratory supported by NASA. The goal of the research is to implement an optical communication experiment apparatus that is applicable to the satellite-to-earth communication engineering model. It is a laboratory based demo system. The design of OCD incorporated a number of advanced technologies at that time, such as beam obtaining, high bandwidth tracking, precise beam tracking, and feed forward compensation. The apparatus structure contains a 10 cm diameter optical antenna, a Charge Coupled Device (CCD) array used for space capture, high bandwidth tracking devices and the optical fiber coupled generation device[4]. The designed communication data rate is 250 Mb/s-1 Gb/s, when experimenting at Low Earth Orbit (LEO). The communication wavelength of 844 nm and On-off Keying (OOK) mode are used for rapid data modulation.

(3) Optical Communication Research on International Orbital Space Station

Jet Propulsion Laboratory utilized mature research techniques of OCD system and developed Optical Communication Demo and High Rate Link Facility (OCDHRLF)[5]. The objective of this system is to implement laser communication link between International Space Station (ISS) and ground optical telescope at LEO. The designed communication rate is 2.5 Gb/s. The diameter of ISS and ground optical terminals is 10 cm and 100 cm respectively. Here, the communication wavelength used on ISS is 1 550 nm. The beacon signal uses a wavelength of 980 nm.

(4) Space Technology Research Vehicle-II (STRV-II) Experiment

During late 1980s and early 1990s, the American Ballistic Missile Defense Organization (BMDO) started to support the research on STRV-II. The objective of this research is to validate the capability of communication at the data rates up to 1 Gb/s. The STRV-II design adopted direct modulation semiconductor laser transmitter and avalanche photodiode receiver. The APT adopted diode laser (852 nm wavelength) as the beacon light, CCD imager as receiver, and cesium-atom linear filter as background light suppression. The whole terminal contains electronic devices weighted 14.5 kg, and the designed maximum communication length is 2 000 km.

STRV-II experimental system adopts polarization multiplex communication technology to increase communication rate. The designed communication rates are 500 Mb/s×2 from satellite to ground, and 155 Mb/s×2 from ground to satellite. In antenna design, the transmitter and receiver are mutually separated with the terminal antenna diameter of 1.6 cm (transmitter)/

13.7 cm (receiver) on TSX-V satellite, and 30.5 cm (transmitter)/40.6 cm (receiver) at ground station. At the same time, to ease the effect caused by atmospheric flicker, STRV-II system adopts multiple transmission apertures, with 4 at terminal on satellite and 12 at ground terminal[6].

The satellite TSX-V was launched on June 7, 2000. Since its ATP system adopted open-loop capture, i.e. tracking and targeting according to known parameters like ephemeris, and this ephemeris system differed from the actual case, the optical communication terminal was not able to capture ground signals sent from ground optical communication terminals. Therefore the STRV-II satellite-to-earth laser link experiment failed[7].

(5) Lightweight Technology Experiment for Geostationary Orbit

On May 18, 2001, the Geosynchronous Lightweight Technology Experiment (GeoLITE) satellite from National Reconnaissance Office (NRO) was launched successfully into its orbit. GeoLITE brought an experimental laser communication terminal and an engineering Ultra High Frequency (UHF) communication device, in order to carry out laser and wideband communication experiments. Lincoln Laboratory of Massachusetts Institute of Technology was responsible for the design of laser communication terminal[8]. NRO formally announced the extraordinary success of this satellite experiment to implement laser communication links, but no further reports were available[9].

(6) Mars Laser Communication Demo System

NASA further carried out research on Mars Laser Communication Demonstration (MLCD) system. The system was developed through joint effort from NASA, Jet Propulsion Laboratory, and Lincoln Laboratory, with the objective to establish laser communication of inter-planet distance between Mars and the Earth. The designed communication data rate was 1 Mb/s -100 Mb/s. The terminal on satellite adopted 30.5 cm diameter antenna, and the CCD imager as receiver. As for transmitting, Master Oscillator Power Amplifier (MOPA) structure composed of semiconductor laser oscillator and Erbium-doped Fiber Amplifier (EDFA) is used to increase the transmission power. Besieds, Pulse Position Modulation (PPM) is adopted. The ground terminal adopted 1 m optical antenna, 4-beamed transmitter (another scheme with 6-beamed transmitter of 30 cm diameter optical antenna). The whole link adopted 1 060 nm communication wavelength which is compatible to optical fiber technologies[10].

1.2 Satellite-to-earth Communication Development in Japan

Japan started the research on satellite-to-earth optical communication comparatively later than USA, but with a more rapid development. It implemented the first satellite-to-earth optical communications link worldwide together with American Jet Propulsion Laboratory in 1995, which demonstrated the feasibility of satellite-to-earth optical communications. Main research institutes of Japanese in satellite optical communications include Communications Research Laboratory (CRL) of Ministry of Posts and Telecommunications, and National Space Development Agency of Japan (NASDA). NEC Corp and Toshiba Corp were also responsible for the development of part of the communication devices.

CRL is the leading organization of Japan's satellite-to-earth optical communication research, and has made detailed plans, gathering many human and material resources to do the research, which was carried out in 3 steps.

- In the first step, middle-rate communications system (300 Mb/s×4) at 0.8 μm wavelength and high-data rate communications system (1.2 Gb/s×2) at 1.5 μm were fulfilled. This step finished in 2002.
- The second step aims at making practical application of the middle-rate communications system, and conducts simultaneously research on middle-rate communications system of 0.8 μm wavelength (1.2 Gb/s×4) and high-rate communications system at 1.5 μm (10 Gb/s×2), scheduled to complete by 2006.
- The third step aims at making practical application of high data rate communications system (10 Gb/s×2).

Currently Laser Communications Experiment (LCE) and Laser Communication Demonstration Experiment (LCDE) are two representative research projects concerning satellite-to-earth optical communication in Japan.

(1) Laser Communications Experiment

LCE device carried on Engineering Test Satellite VI (ETS-VI) from Japan implemented the first satellite-to-earth laser link worldwide. ETS-VI was launched in August 1994, but did not enter the destined Geostationary Earth Orbit (GEO) owing to propelling rocket failures and shortened its life cycle. With the joint effort from CRL and American Jet Propulsion Laboratory, new hardware and software methods were used to ultimately finish all tests. The main results are detailed in article[11] and [12].

(2) Laser Communication Demonstration Experiment

Japan set up an assemble Japanese Experiment Module (JEM) called "Kibo", which means hope in Japanese. It's on the first permanent manned international space station, and carried LCDE at the experiment platform outside the cabin to carry on ultra high rate optical communications experiments with the ground and other satellites. Major parameters are shown in Table 1[13].

1.3 Comparison of Transmission Data Rates of Satellite-to-earth Optical Communication Research between USA and Japan

According to the research status quo and development trends, a statistical and predictive comparison chart of satellite-to-earth optical communication transmission data rates between Japan and the US is shown in Figure 2.

2 Satellite-to-earth Optical Communications Development in China

Research on satellite optical communications started late in China compared to international developed countries, mainly because of the lack of devices and conditions in initial stages.

▼Table 1. Main parameters for laser optical communication apparatus

Parameters	Values
Antenna Diameter	15 cm
Communication Data Rate	2.488 Gb/s
Modulation Mode	Intensity Modulation Adopting Return-to-zero Pulse
Receiving Mode	Charge Coupled Device Receiver
Demo Scheme	Direct Detection Using Polarization Maintaining Erbium-doped Fiber Amplifier
Ground Antenna Diameter	10 cm (Transmitter), 50 cm (Receiver)
Tracking and Targeting Wavelength at Communication	680 nm
Communication Wavelength (Uplink)	1 562 nm
Communication Wavelength (Downlink)	1 552 nm
Uplink Power	1 W
Downlink Power	0.4 W

Since the 1990s, with the progress in laser communications devices and the opening of China, many domestic research units began research on satellite laser communications, and some breakthroughs have been made in certain areas.

2.1 Research Status of Electronics Department of Peking University

Peking University started research on satellite-to-earth optical communications since the late 1980s. Currently, National Lab on Local Fiber-optic communications networks and Advanced Optical Communications Systems of Peking University is exploiting two directions: optical phased array and new types of satellite-to-earth communications.

In the early 1990s, atomic filters FADOF and Voigt Anomalous Dispersion Optical Filter (VADOF) were first developed at Peking University, and applied in APT technologies for satellite optical communications, and made significant progress. Peking University utilized the property of exceeding narrow bandwidth of FADOF to acquire better SNR under big FOV conditions, and the multi-peak and tunable properties could also be used to handle the Doppler Effect generated by the satellite motion[14]. Other progress in optical communication receiver were achieved at Pecking University, which implemented autodyne receiving adopting multi-quantum trap devices[15], and raised the receiving SNR using a combination of Turbo code and channel interweave encoding[16].

Currently, optical phased array (i.e. using phased array of optical antennas to implement high speed deflexion of beams) has high precision, no inertia and quick response. In satellite-to-earth optical communication, it could be used as a new solution for beacon beam targeting. Certain progress has also been made in this area at Peking University[17]. The objective of satellite-to-earth optical communication is to raise communication rates while lowering Bit Error (BER). A communications scheme using one transmitter-multiple receiver and relay platforms at high altitude is also under development at Peking University to find the optimized optical signal detecting modes and signal processing technologies from the viewpoints of wavelength, channel, and systems.

2.2 Other Research Units

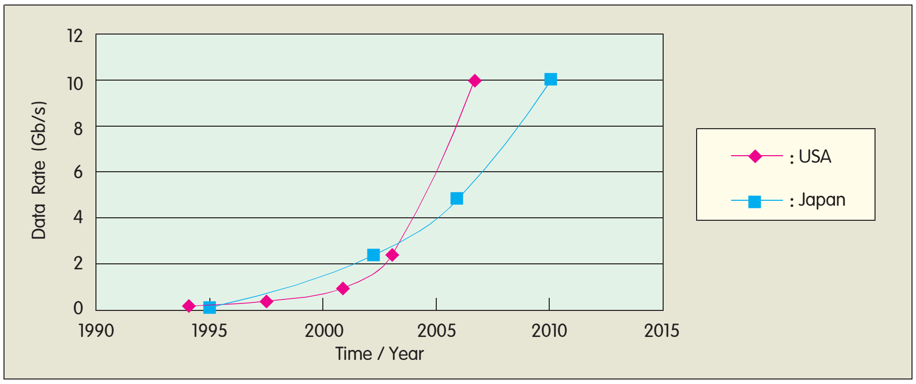
Laser Communications Laboratory in the School of Physical Electronics, University of Electronic Science and Technology of China, started research on satellite optical communications since 1990s. The research focuses on the influence which atmospheric channels have to air-to-ground optical communication and corresponding solutions, APT technologies and system design, modulation/demodulation and optical encoding scheme. Furthermore, it conducts research on background light suppression, optical antenna design, and simulations on satellite laser communications systems. Some research results are approaching world level.

Tunable Laser Laboratory of Harbin Institute of Technology started research on satellite optical communications in early 1990s. They made progress in satellite APT technologies and scanning scheme, influences of satellite vibration on BER and elimination scheme, suppression of background noise from fixed star, and satellite laser communication system design. Since 2005, they have also made certain exploitation into the feasibility of establishing moon-to-earth laser links[18].

Laser Communication Laboratory of Wuhan University and Shanghai Institute of Optics and Fine Mechanics from China Academy of Science also made some exploring research into inter-satellite optical communications[19].

3 Trends of Satellite-to-earth Optical Communications

Researches on satellite-to-earth optical communications in countries worldwide



▲Figure 2. Comparison of satellite-to-earth optical communications transmission rate between Japan and the US.

are progressing very rapidly with unique features. Major research organizations in China have their research focus. Possible future development trends for research on satellite-to-earth optical communications include: improving the performance of APT systems, raising communications data rates and lowering BER, and connecting satellite to ground optical fiber networks.

(1) Improving Performance of APT Systems

Although APT technologies have been developing have been developing worldwide for several decades, space experiments have shown that current APT technologies cannot assure long time and stable laser links between satellite and the Earth. The reason is that a very small error may lead to failure of establishing the laser link. The failure of STRV-Ⅱ experiment is just one example. Therefore, further improving the performance of APT system (including tracking and targeting precision, scanning time, and system bandwidth) and overcoming the influence of satellite platform vibration will be a future development emphasis for satellite-to-earth communications technologies.

(2) Raising Communications Data Rate and Lowering BER

Satellite-to-earth optical communication was raised to solve the "bottleneck" of microwave communications between satellite and the ground. Current data rate of microwave communication can reach above 600 Mb/s, while published data rate for successful satellite-to-earth optical communication link is only 1.024 Mb/s. Therefore, how to raise data rate above 1 Gb/s to tackle challenge from future microwave communications is a development direction for satellite-to-earth laser communications. High-power laser instruments and high-rate modulation technologies will be the research focus. When raising communications rates, measures should be taken to control BER, and the application of atomic filters will become an indispensable ring tache for satellite-to-earth communications systems.

(3) Connecting Satellite to Ground Optical Fiber Networks

At early development stages of satellite-to-earth optical communications, many systems used 800 nm as laser communication wavelength, but a few systems with 1 060 nm or more also emerged. When successfully demonstrated by Bell Laboratory, SDL Corp, Lucent Corp, and USAF Phillips Laboratory that optical fiber communication technologies could be applicable for space technology application, more and more laser communication systems adopted 1 550 nm as the communication wavelength. This corresponds to mature ground optical fiber technology. The ground optical fiber technologies like MOPA are increasingly applied in satellite laser communication.

It could be anticipated that future satellite-to-earth communications system will be an interconnected system between satellites and ground optical fiber networks.

In a word, optical satellite-to-earth communications is a very promising direction for communications technology development. Research in this field should be strengthened in the interest of economic construction acceleration and science and technology development.

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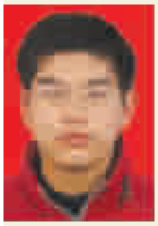
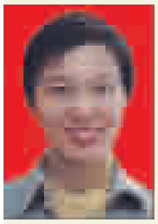


Zhang Cheng is an undergraduate in School of Electronics Engineering and Computer Science, Peking University, majoring in optical satellite-to-earth communications.



Hu Weiwei is an associate professor in School of Electronics Engineering and Computer Science, Peking University, majoring in ROF communications, optical phased array, and optical satellite-to-earth communications.

Xu Anshi, PhD, is a professor in School of Electronics Engineering and Computer Science, Peking University. He is the directors of National Lab on Local Fiber-Optic Communication Networks and Advanced Optical Communication Systems, the Photon and Communications Technology Institute, and Electronics Department of Peking University. He is also a member of the academic board of the school, member of Education Guide Committee for College Electronics, Information and Electric subjects of Ministry of Education, and the deputy director of Education Guidance Sub-Committee on Electronic Information Science and Engineering Professional Education of Ministry of Education. Moverover, he is the director of American Sub-sector of Euramerican Alumni Association, and a member of American Academy of Optics.