Optical Wireless Communication Theory and Technology

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Adaptive Optics Theory and Its Application in Optical Wireless Communication

Science Press
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ISSN 2731-5967 ISSN 2731-5975 (electronic)
Optical Wireless Communication Theory and Technology
ISBN 978-981-16-7900-1 ISBN 978-981-16-7901-8 (eBook)
https://doi.org/10.1007/978-981-16-7901-8

Jointly published with Science Press
The print edition is not for sale in China (Mainland). Customers from China (Mainland) please order the print book from: Science Press.
ISBN of the Co-Publisher's edition: 978-7-03-070350-7.

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Preface

Free-space-optical (FSO) communication is a communication method in which light is used as the carrier of information for the purpose of high-speed data transmission in free space. Compared to traditional radio frequency communication, FSO has the advantages of a wide spectrum, high security, and robustness to interference ability. As an emerging method of communication, its application prospects are immeasurable. FSO takes place through atmospheric channels; hence, the communication quality can be affected by atmospheric turbulence. The wavefront of the optical signal is affected by turbulence and produces random fluctuations, causing phenomena such as beam expansion, phase fluctuation, beam bending, and drift, which leads to an increase in communication error rate and a decrease in communication stability. When the extension of the communication distance is increased, the output power of the laser gradually increases, and the laser cavity mirror is thermally deformed. This causes a phase distortion in the laser wavefront, resulting in the beam quality and a decrease in communication quality.

Adaptive optics (AO) is a comprehensive optical technology. It covers the knowledge of multiple disciplines such as optics, communication, control, computers, and machinery. It is a comprehensive technology based on opto-electromechanical integration. It aims to correct the random wavefront distortion, caused by the changes in the external environment during process of light propagation in real time, thereby realizing automatic improvement. The beam quality improves the communication quality and maintains the good performance of the system. It has been widely used in laser communication, astronomical observation, fundus imaging, and other fields. The wavefront sensor and the deformable mirror respectively play the role of a wavefront detector and wavefront corrector. Establishing a precise mathematical relationship between the two and realizing an effective control algorithm are the two key steps in the closed-loop control of an AO system. A large number of experiments have proved that AO technology can correct wavefront distortion. Hence, AO is considered to be the most promising wavefront correction method.

This book conducts an in-depth investigation of AO theory and its application in wireless optical communication systems. There are ten chapters in the book.

Chapters 1–4 deal with AO control algorithms, and Chaps. 5–10 deal with distortion correction and correction experiments. AO control algorithms include adaptive control algorithms for wavefront distortion, proportional integral algorithms, iterative algorithms, and dual fuzzy adaptive PID control algorithms. Distortion correction methods include the SPGD algorithm for AO correction, deformable mirror eigenmode method, vortex beam with no wavefront detection, liquid crystal spatial light modulator, and Gaussian beams of different wavelengths in atmospheric turbulence. The wavefront difference and correction of the transmission in the medium, the AO wavefront distortion correction with wavefront tilt correction, and various distortion correction methods were experimentally verified, and the experimental results were analyzed to support related theories.

This book is a result of the dedicated efforts of the author and his graduate students, from the Optoelectronic Technology Research Center of Xi'an University of Technology, over a period of five years. The author and his graduate students have conducted a considerable amount of theoretical research and a number of experiments on the application of AO correction technology in wireless optical communications in recent years. Their efforts have contributed to the further development of wireless optical communication technology.

This book is a part of the work of the "14th Five-Year Plan" of the Ministry of Industry and Information Technology; related work has been supported by the Shaanxi Provincial Key R&D Program (Key Industrial Innovation Chain) Project (2017ZDCXL-GY-06-01) and is considered as one of Shaanxi Province's scientific and technological achievements. I would like to thank the promotion plan project (2020CGXNG-041), the special project (industrialization) plan project (20JC027) of the Shaanxi Provincial Department of Education for serving localities, and the Xi'an science and technology plan project (2020KJRC0083, 2020KJRC0085).

This book is the author's preliminary summary of AO and correction technology involved in wireless optical communication. Due to the limited level of the author, there may be some inevitable improprieties in the book. Readers are welcome to suggest corrections.

Xi'an, China

Xizheng Ke
Pengfei Wu

Introduction

This book introduces in detail the theory of adaptive optics and its correction technology for light wave distortion in wireless optical communication. It discusses the adaptive control algorithm of wavefront distortion, the proportional–integral control algorithm, the iterative control algorithm, and the double fuzzy adaptive proportional–integral–derivative control algorithm. The stochastic parallel gradient descent (SPGD) algorithm, adaptive optics correction, deformable mirror eigenmode method for wavefront distortion correction, vortex beam with no wavefront detection for wavefront distortion correction, liquid crystal spatial light modulator for wavefront correction, and Gaussian beams of different wavelengths in the atmosphere are also discussed. The wavefront difference and correction of transmission in turbulent flow and adaptive optics wavefront distortion correction with wavefront tilt correction are verified experimentally using verification of various distortion correction methods, and the experimental results are analyzed.

This book is suitable for reading by engineering and technical personnel, teachers of colleges and university teachers, graduate students and undergraduate students in their final year, who are engaged in the field of wireless optical communication.

Contents

Chapter 1
Introduction

In this chapter, the practical background of the application of adaptive optics (AO) technology in free space optical communication is analyzed, and progress in research on AO technology at home and abroad discussed.

1.1 Wireless Optical Coherent Communication Research Status

The modernization of information exchange is necessitating data transmission at higher rates and over longer distances [1]; however, the lack of spectrum resources limits further development of radio frequency (RF) communication. Free space optical (FSO) communication is a method of high-speed data transmission in free space using light as an information carrier [2]. Compared to traditional RF communication, FSO has the advantages of a wide spectrum, high security, and strong anti-interference capability [2]. As an emerging communication method, the application prospects of FSO are vast [3]. Early research focused on intensity modulation and direct detection (IM/DD) [3]; however, advancements in laser technology have resulted in a shift in focus towards coherent detection [4].

Coherent optical communication systems can be divided into four modules: the transmitting terminal; transmitting and receiving optical antenna; acquisition, pointing, and tracking (APT); and coherent receiving terminals. The transmitting terminal includes a signal source, modulator, optical signal, and an erbium-doped optical fiber amplifier (EDFA). The APT system consists of auxiliary equipment that ensure the alignment of the sight axes of the transmitting and receiving antennas. It is an indispensable component of long-distance FSO communication systems and includes a tracking mechanism, charge-coupled device (CCD) detector, and tracking control algorithm. The coherent receiving terminal is used to detect the received optical signal using a local oscillator light to recover the source information. The

X. Ke and P. Wu, *Adaptive Optics Theory and Its Application in Optical Wireless Communication*, Optical Wireless Communication Theory and Technology,
https://doi.org/10.1007/978-981-16-7901-8_1

use of coherent detection can significantly improve receiving sensitivity and realize the detection of weak optical signals. Its significance in research is also reflected in the following aspects: (1) the source information can be encoded and modulated using various methods, including frequency shift keying (FSK), phase shift keying (PSK), and amplitude keying; (2) the interference of stray background light on optical signal detection can be eliminated and the signal-to-noise ratio of the system can be improved; and (3) the optical power of the local oscillator is much higher than that of the optical signal, and the conversion gain of coherent detection is higher than that of IM/DD. Coherent detection has the advantages of high speed, high precision, good filtering performance, and a theoretical receiving sensitivity close to the quantum noise limit. It has been widely used in free-space optical communication [5], laser radar [6], radio and television [4], and other applications.

Factors such as wind field and heat conduction cause the atmospheric temperature, and in turn the atmospheric refractive index, to fluctuate randomly. When a beam propagates in this type of an atmospheric random medium, its coherence is destroyed. In practical applications, the transmitted optical signal exhibits phenomena including light intensity flicker, angle of arrival fluctuation, beam expansion, and drift when it is received. Turbulence effects on beam propagation adversely impact the performance of the coherent detection system; therefore, it is important to study this influence.

Beams emitted by lasers are generally considered to be ideal fundamental-mode coherent beams. However, laser light wave output is almost always only partially coherent in practical applications due to the influence of factors such as thermal effects and resonator size. Assuming that the turbulence effect will destroy the coherence of the beam [4], the optical signal arriving at the receiving end can be considered as a partially coherent beam containing a variety of modes. Therefore, studying the influence of the beam mode on the performance of an external error detection system under atmospheric turbulence has certain guiding significance for practical applications.

Research into coherent detection technology remained dormant for many years. However, at the end of the twentieth century, with improvements in laser devices, in-depth research on detection technology, and the need to expand the capacity of global communications, coherent detection technology has once again become a research focus. A number of FSO research programs have been established worldwide (including in the United States, Europe, and Japan) to conduct comprehensive research into FSO coherent detection communication systems and the factors affecting heterodyne detection systems.

1.1.1 Research Status in the United States

The United States of America (USA) pioneered FSO system research. Studies have been conducted by the National Aeronautics and Space Administration (NASA), Aerospace Corporation, US Air Force, Missile Defense Agency, Massachusetts Institute of Technology (MIT) Lincoln Laboratory (Lincoln), and Jet Propulsion

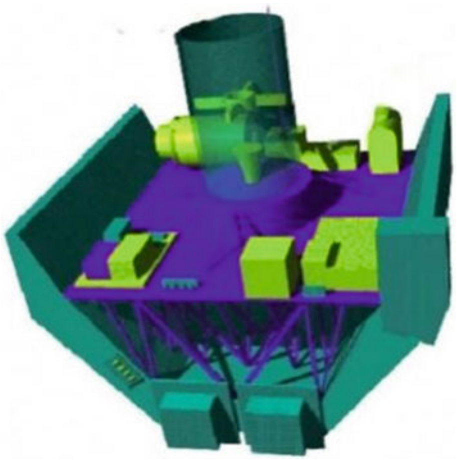


Fig. 1.1 Experimental setup for the Massachusetts Institute of Technology (MIT) Lincoln Laboratory laser intersatellite transmission experiment (LITE)

Laboratory (JPL). In the mid-1980s, Lincoln Laboratory developed laser heterodyne detection using the star communication experiment system (Laser Intersatellite Transmission Experiment; LITE). The system used the FSK modulation method with modulation rates of up to 220 Mbps. Plans were made to test each module of the system in the space environment; however, the project failed to make an actual flight test, and the demonstration experiment was completed on the ground [7]. Figure 1.1 shows the experimental setup for the LITE. This project laid the foundation for research into FSO coherent communication systems worldwide.

In the late 1980s, NASA developed a laser communication program with the goal of demonstrating laser communication from geostationary Earth orbit (GEO) to the ground through the development of Advanced Communications Technology Satellite (ACTS) terminals. The ACTS laser communication experiments included ground and airborne direct and heterodyne detection tests. Given their experience with LITE, researchers at Lincoln developed APT, optical, and heterodyne receivers. In the early 1990s, JPL conducted research on intersatellite coherent optical communication systems [8] and demonstrated a communication experiment using an intersatellite heterodyne detection system with a code rate of 100 Mbps using PSK modulation. Later, JPL shifted its focus to IM/DD communication systems. To improve the channel capacity of intersatellite communication, JPL began to focus on coherent optical communication systems in the late twentieth century [9]. During this period, Lincoln developed a space coherent communication system with a communication rate of up to 1 Gbps and conducted in-depth research into convolutional encoding and decoding technologies for space channels [10]. Under the vibration conditions of the intersatellite platform in low Earth orbit (LEO), Lincoln analyzed performance parameters including the signal-to-noise ratio and bit error rate (BER) of the coherent optical communication system when different modulation modes were

Table 1.1 Lincoln laboratory laser communication system parameters

Parameter	Value
Communication wavelength	0.8 μm
Detector responsiveness	0.517
Receiver optical efficiency	0.8
Transmitter optical efficiency	0.8
Bit error rate (BER)	10^{-6}
Distance between stars	3000 km
Transmission rate	2 Gbps

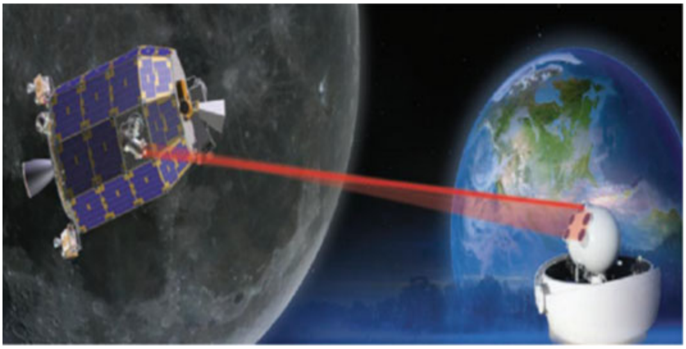


Fig. 1.2 NASA lunar laser communication demonstration (LLCD) program schematic

used. The parameters of the laser communication system used by them are listed in Table 1.1.

In 2008, the USA and the German Space Agency (DLR) established a communication link and tested the TESAT ground laser communication terminal [11]. In the same year, NASA launched the deep space optical communication (DSOC) program, including a Lunar Laser Communication Demonstration (LLCD); Fig. 1.2 to prove the feasibility of laser communication between the Earth and Moon. The Laser Communication Relay Demonstration (LCRD) project, which can be considered an extension of the LLCD program, aims to use a GEO satellite as a relay point to achieve continuous communication between two terminals on the ground. The LCRD program Fig. 1.3 represents an important step by NASA to improve space laser communication.

In 2013, NASA established a duplex communication link between the Lunar Atmosphere and Dust Environment Explorer (LADEE) in lunar orbit and a ground terminal using pulse phase modulation (PPM) with uplink and downlink communication rates of 20 and 622 Mbps, respectively [12–14]. In 2017, the DSOC program, one of NASA's space exploration missions, transmitted data from Mars at a rate of more than 250 Mbps. This transmission covered a communication distance of approximately 630 million km, had a terminal mass of 28 kg, and used 76 W of

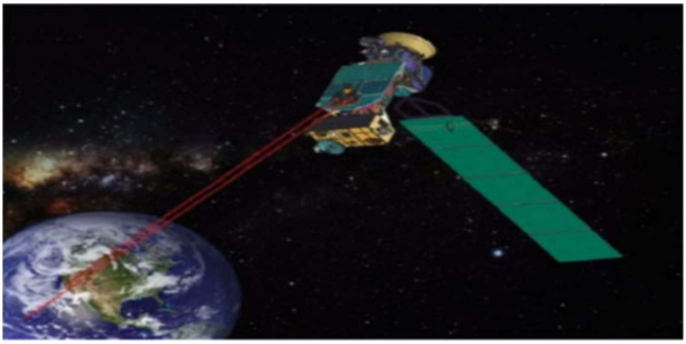


Fig. 1.3 NASA's laser communication relay demonstration (LCRD) program diagram

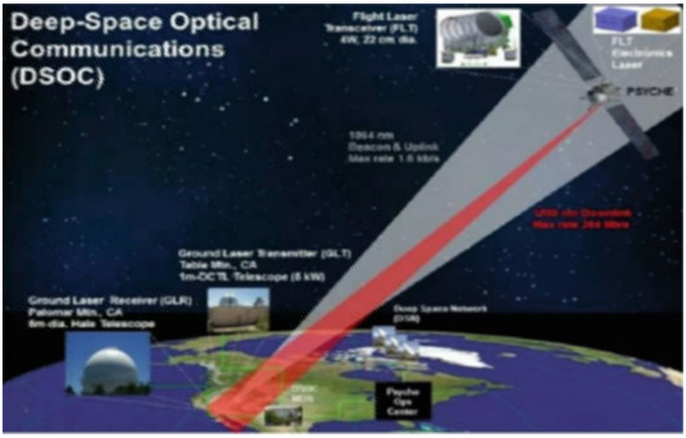


Fig. 1.4 Schematic of NASA's deep space optical communication (DSOC) project

power. There are plans to carry this system on board aircraft in 2023 to test the deep space laser communication technology [15, 16]. Figure 1.4 shows a schematic of the DSOC project.

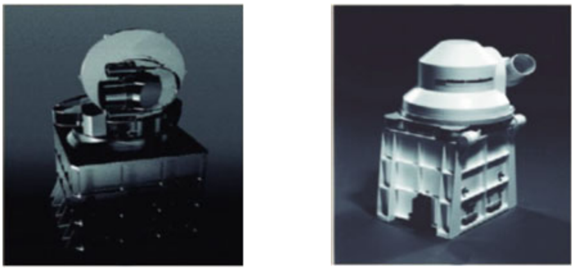
1.1.2 Research Status in Europe

European agencies have also made advancements in FSO communication research [17–19]. The main space research agencies in Europe are the European Space Agency (ESA) and DLR [20–22]. In 1977, the ESA commenced research into FSO communication [23–25], and in 1985, they initiated the Semiconductor Laser Inter-Satellite Link Experiment (SILEX) [26] to conduct experimental verifications of real-time information transmission between high- and low-orbit satellites. On November 20,

Fig. 1.5 Schematic of intersatellite communications between geostationary Earth orbit (GEO) and low Earth orbit (LEO) satellites for the European Space Agency's (ESA) semiconductor laser inter-satellite link experiment (SILEX) project

2001, SILEX planned the first laser intersatellite communication between the Artemis satellite in GEO and the French SPOT-4 satellite in LEO with a communication distance of 45,000 km and a BER of less than 10^{-6} [27], as shown in Fig. 1.5. SILEX had intended to use a zero-difference detection system with a communication wavelength of 1064 nm as its preferred communication solution; however, a well-developed direct detection solution was chosen instead because the technical specifications of the laser could not meet the requirements of the preferred solution.

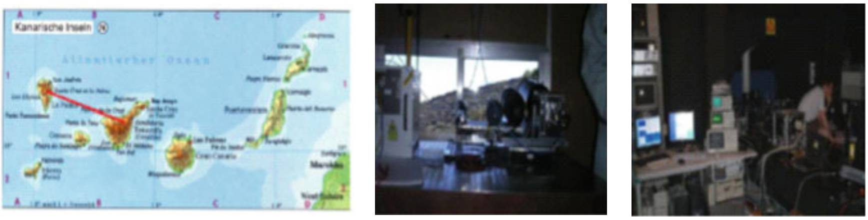
Throughout the development of the SILEX program, the ESA conducted in-depth research on coherent optical communication systems and other key technologies based on yttrium, aluminum, and garnet crystal (YAG) solid-state lasers since 1989. In 1996, the short-range optical inter-satellite link (SROIL) project was officially launched in Switzerland. This project aimed to develop a miniaturized, lightweight communication terminal for short-distance communication between small LEO satellites, and in 1998, a model of the optical demonstration terminal was successfully completed [28]. The terminal consumed approximately 40 W of power, had a mass of approximately 15 kg, and external dimensions of 30 × 20 × 50 cm. It had a communication code rate of 1.5 Gbps, a BER better than 10^{-6}, and used a wavelength of 1064 nm, a binary phase-shift keying (BPSK) modulation mode, and a zero-difference detection scheme. The transmitting and receiving antenna apertures were 350 and 40 mm, respectively. The SROIL program also developed medium- and long-range intersatellite laser communication terminals. The medium-range communication terminal had the same light source, modulation mode, and detection mode as the short-distance terminal and could realize a 6.5 Gbps communication rate between two LEO satellites at a distance of 6000 km with a BER less than 10^{-9}. The optical antenna aperture of the terminal was 100 mm and the mass was 25 kg.



（a） （b）

(a) Short range (b) Medium range

Fig. 1.6 Physical diagrams of ESA short-range optical inter-satellite link (SROIL) communication terminals



The communication link between La Palma and Tenerife

Terminal La Palma

Terminal Tenerife

Fig. 1.7 Schematic of the zero-difference binary phase-shift keying (BPSK) detection system communication link of length 142 km between La Palma and Tenerife in the Canary Islands, Spain

Figure 1.6a, b are physical pictures of the short-range and medium-range SROIL terminals, respectively.

In 1995, the ESA collaborated with Oerlikon Contraves Space in the United Kingdom to develop an improved series of high-speed, miniaturized, lightweight, and low-power OPTEL terminals for commercial applications [29]. Using a coherent detection mode, the ESA developed short (OPTEL 02), medium (OPTEL 25), and long (OPTEL 80) range inter-satellite communication terminals. The OPTEL terminals used a semiconductor laser with a communication wavelength of 1064 nm as the light source. The transmitting terminal used a BPSK modulation mode and the receiving terminal a zero-difference detection scheme.

Based on the planned SILEX communication terminal, Germany's TESAT-SPACECOM designed and developed a second generation laser communication terminal (LCT), which used the BPSK modulation mode and a zero-error detection scheme. In 2005 [30], the LCT established a 142 km long communication link between La Palma and Tenerife in Spain's Canary Islands with a transmission rate of 5.625 Gbps, as shown in Fig. 1.7. This link verified the feasibility of the zero-

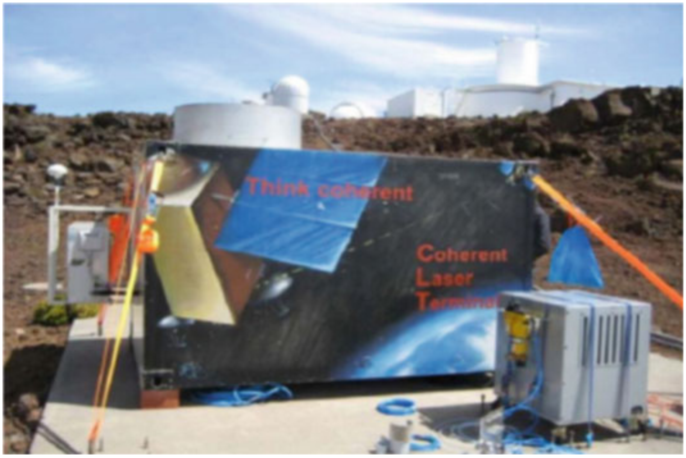


Fig. 1.8 Near field infrared experiment (NFIRE) ground communication terminal

difference BPSK scheme in near-Earth atmospheric turbulence channel communication and laid the experimental foundation for coherent optical communication between satellites and the Earth.

In 2008, laser communication terminals (LCTSX) were mounted on the American Near Field Infrared Experiment (NFIRE) satellite and the German TerranSAR-X satellite in LEO [31–34]. The zero-difference BPSK communication mode was used to realize inter-satellite two-way communication at a rate of 5.625 Gbps. This was the first experimental link to complete coherent optical communication between two satellites at a distance of 6000 km. Following this success, a coherent communication link between a satellite and the Earth was verified. In 2010, a 6.5 cm diameter TESAT coherent LCT was installed at the ESA Optical Earth Station in Tenerife shown in Fig. 1.8, establishing a satellite–ground communication link with the NFIRE communication terminal at a rate of 5.635 Gbps [35–37]. An AO system was used to compensate for the distorted wave front of the optical signal.

Germany continued to improve its second-generation LCT [38] and named the improved version LCT-TDP1, as shown in Fig. 1.9. The LCT-TDP1 could transmit at 1.8 Gbps up to a distance of 45,000 km. In 2014, the AlphaSat GEO satellite and Sentinel 1A LEO satellite carrying LCT-TDP1 communication terminals successfully established a coherent detection communication link and carried out data relay transmission experiments for the first time. To meet its increasing demand for space data transmission rate and capacity, the ESA launched the European Data Relay Satellite (EDRS) project. In 2016, the project's first laser communication data relay payload, EDRS-A, was successfully launched on the European General Satellite (EUTELSAT), which marked a shift in space laser communications from the experimental to commercial application stage. In 2018, the EDRS-C [38] satellite

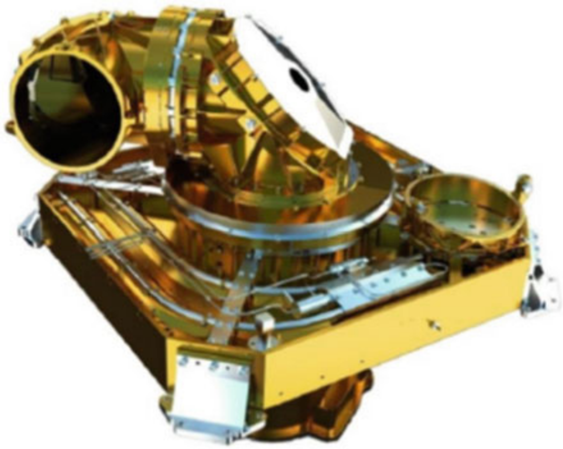


Fig. 1.9 Improved ESA communication terminal LCT-TDP1

relay communication payload carrying an LCT-TDP1 communication terminal was launched.

Numerous research institutions in Europe have participated in spatial optical coherence detection and successfully verified experimentally intersatellite, satellite–ground, and near-Earth communication links. Their advancements in high-speed coherent optical communication have now entered the project commercialization stage.

1.1.3 Research Status of Japan

In 1994, Japan successfully completed the ET-VI space optical communication program [39], which verified the feasibility of satellite–ground laser communication links. The Inter-Orbital Laser Communication Engineering Test Satellite (OICETS) was tasked with developing a miniaturized space communication terminal, and in 2005 [40], the OICETS laser utilizing communication equipment (LUCE) successfully launched an LCT with a communication rate of 49.3 Mbps at a distance of 600–1500 km. In May 2006, the LUCE terminal successfully established a two-way communication link between the National Institute of Information and Communication Technology (NICT) of Japan and a DLR ground station in Germany [41]. Both of these historic projects adopted simple and reliable direct detection methods and laid the technical foundation for subsequent spatial optical coherence detection methods.

The NICT successfully developed a BPSK modulation zero-difference detection communication terminal with a transfer rate of 3 Gbps [42] in 2008, and the Small Optical Transponder (SOTA) project, dedicated to the development of lightweight and compact satellite optical communication terminals [43] was launched the following year. In 2011, the Mitsubishi Corporation and the Japan Aerospace Exploration Agency (JAXA) jointly developed a BPSK modulation zero-difference coherent receiver [44]. By the end of 2016, international collaborative experiments, AO experiments, tracking tests, data transmission, and other related experiments had been conducted between Japan, the Centre National d'Etudes Spatiales (France), DLA, ESA, and numerous other research institutions. Japan expects to implement a 10 Gbps two-way communication link between GEO satellites and the ground by 2021.

1.1.4 Research Status of China

China has made significant efforts to develop FSO communication technologies in recent years. The main institutions involved in space optical communication research are the Changchun University of Science and Technology, Xi'an University of Technology, and the Chinese Academy of Sciences; however, numerous other universities and research institutes have achieved phased advancements in coherent optical communications [45–47].

In the 1980s, the University of Electronic Science and Technology of China employed a CO_2 laser with a communication wavelength of 1064 nm to verify the feasibility of a 5 km communication link using heterodyne detection. In August 2011, the Harbin Institute of Technology conducted in-depth research on satellite–ground laser communications [48–50]. Their communication terminal was successfully carried by the "Haiyang II" satellite, and a single-channel data communication rate of 50 Mbps was achieved [51]. In 2017, a laser communication terminal designed by the Harbin Institute of Technology and carried by the "Shijian-13" satellite was successfully launched, and a satellite–ground two-way communication link with a BER of less than 10^{-6} was established in January 2018 [52].

At the beginning of 2017, a high-speed satellite-ground coherent optical communication terminal developed by the Shanghai Optical Engineering Institute was successfully carried by the "Mizi" satellite for the purpose of in-orbit dual-channel communication verification [53]. The communication wavelength was 1550 nm. The uplink used PPM and achieved a communication rate of 20 Mbps, while the downlink used BPSK modulation and achieved a communication rate of 5.12 Gbps.

In 2013, the Beijing University of Posts and Telecommunications [54] built a 20 Gbps quadrature phase-shift keying spatial-coherent light experimental demonstration system in the laboratory with a communication wavelength of 1550 nm, laser line width of 100 kHz, and digital signal processing technologies such as clock recovery and frequency offset compensation to ensure the stability of the system. In 2015, the optical communication research team at Nanjing University [55] established a mathematical model to explain the influence of the frequency difference of the Costas optical domain phase-locked loop using a BPSK modulated zero-error detection system. They analyzed the influence of frequency offset, zenith angle, data transmission rate, and divergence angle on the system BER. An AO system was used to correct the distorted wave front phase of the optical signal and improve the coupled optical power at the Chengdu Institute of Optics and Electronics. In 2018, Chen et al. [56] developed a high-sensitivity fiber coupling device for a long-distance free-space coherent optical communication system. Their experimental results showed that the coupling efficiency of the system could be increased to 73.2%. In the same year, Chen et al. [57] used the single-mode fiber coupling and AO systems described above to improve the eye map and BER of an FSO communication system with a transmission rate of 5 Gbps for a satellite–ground communication link.

In recent years, the research team led by Professor Xizheng Ke at the Xi'an University of Technology has focused on several key FSO communication technologies, including beam transmission characteristics in atmospheric turbulence [58, 59], the decoding of wireless laser communication systems [60], channel estimation and equalization, ATP technology [61], coherent detection techniques [62–64], and the design of the optical transceiver systems [65]. The team has made great progress in theoretical research and experimental verification. Based on IM/DD modulation and detection methods, the team successfully developed a duplex FSO communication machine with a weight of less than 8 kg, a maximum transmission rate of 1.25 Gbps, and a BER of less than 10^{-6} for high-speed voice and image transmission. They also developed a heterodyne detection system and a differential phase-shift keying modulation communication terminal. Using this system, a successful real-time video communication link was established in March 2018 between two buildings 1.3 km apart and a 10 km communication link in Shanxi Province in July 2018, and a ground-based communication experiment at Qinghai Lake in September of the same year covering a distance of 100 km was conducted. These experiments represent a major breakthrough in FSO communications in China.

1.2 Adaptive Optics

AO is an integrated optomechatronics technology that has been widely used in laser communication, astronomical observation, fundus imaging, and other fields. The wave front sensor (WFS) and deformable mirror (DM) are used for wave front detection and correction, respectively. The establishment of a precise mathematical relationship between the two and realization of an effective control algorithm are the two key steps of a closed-loop AO system.

Free space optical communication is conducted through atmospheric channels; hence, its signal quality is affected by atmospheric turbulence [66]. Under the influence of turbulence, the wave front of the optical signal produces random fluctuations, resulting in beam expansion, phase fluctuations, beam bending, and drift [67, 68], which in turn increase the BER and decrease communication stability [69]. With increased communication distance, the power output of the laser also increases gradually, and the ensuing thermal deformation of the laser cavity mirror causes phase distortion of the laser wave front, resulting in reduced beam quality and degradation of the transmission [70]. The wave front refers to the "light wave vibration phase of the same point formed by the surface," and is also called the wave surface. Wave front distortion is principally a change in the optical path difference, and is usually measured by an interferometer. Wave front distortion is caused by the fact that the optical path of a beam is not equal to n $\times$ d; where n is the refractive index of the material and d the distance traveled by light. The wave front, also known as the isophase surface, is the wave surface. If the wave front changes after passing through a certain transmission medium prior to transmission, it is no longer a spherical or plane wave and is considered to be distorted. If the transmission medium is a flat optical material, the unevenness of the plane will cause wave front distortion.

AO is a comprehensive optical technology [71]. It combines knowledge from optics, communication, control, computer, machinery, and other disciplines to achieve real-time correction of random wave front distortion due to changes in the external environment during light propagation. The technology also aims for automatic improvement of beam quality, enhanced communication efficiency, and maintenance of good system performance [72, 73]. Experiments have proved that the AO technique can effectively correct wave front distortion [74–76] and is considered the most a promising wave front correction method.

In astronomical observations, AO has become an important part of almost all large solar telescopes [72]. For example, the Institute of Optoelectronic Technology of the Chinese Academy of Sciences in cooperation with the Yunnan Observatory established a 37 unit solar AO system for the 26 cm solar fine structure telescope, and obtained solar observation results after AO correction for the first time in China [67] In laser devices, AO has been widely used to improve beam phase distribution. It has also been used in inertial confinement fusion and high-power laser weapon systems, such as the China's Shenguang device [73], and human eye aberration manipulation and retinal imaging using a Hartmann–Schack wave front sensor and DM [77]. In laser processing, AO can be introduced into system optimized DM control algorithms, such as the genetic algorithm [70] and stochastic parallel gradient descent (SPGD), which are used for pulsed and high-energy laser beam shaping. It is clear that AO technology has entered an era of rapid development with broad applications across many fields.

1.2.1 International Research Progress in Adaptive Optics

The framework for AO technology was developed in the mid-twentieth century [71]. Astronomers Babcock (USA) and Linnik (former Soviet Union) put forward similar assumptions in 1953 and 1957, respectively, hoping to reduce the influence of atmospheric turbulence random disturbance on the wave front and reduce wave front distortion through the combined work of real-time measurement and correction compensation. The idea of controlling the operation of related devices by detecting wave front signals and changing the wave front error was both the initial concept of AO and a new idea for solving optical dynamic interference. In 1972, the USA built a 300 m real-time compensation imaging system based on AO technology and carried out a horizontal disturbance correction experiment, proving that the image resolution after AO technology correction was close to the diffraction limit [72]. In 1977, ITEK (USA) developed an AO system to improve two-dimensional image resolution [74]. In 1982, the USA adopted a 168 unit DM and shear interferometer to conduct an atmospheric turbulence distortion compensation correction experiment and observe space targets in LEO [75]. These results provided strong proof for the practical application potential of AO. After the European Southern Observatory launched the world's first astronomical AO program (COME ON) in 1985 [76, 78], many countries commenced AO research and the application of AO technology in astronomical observations [79]. By the end of the twentieth century, most of the world's large telescope research teams had incorporated AO technology into their research.

In 2002, the Lawrence Livermore National Laboratory (USA) carried out simulations and experiments on the application of AO technology in long-distance optical communication systems. They found that the coupling efficiency of optical fiber could be increased by 2.5 times following AO correction under medium turbulence conditions; however, the system bandwidth was limited [57, 80]. In 2004, Thomas Weyrauch and a research team from the University of Maryland (USA) used the SPGD algorithm to conduct communication experiments on horizontal atmospheric transmissions over 2.3 km. They found that the maximum signal strength at the receiving end following AO correction for inclination and atmospheric aberration was 2.3 times higher compared to that when only the inclination aberration was corrected. This proved that atmospheric aberration correction could effectively improve signal strength [79]. In 2005, JPL (USA) developed an experimental platform for AO in atmospheric laser communications and studied the influence of AO on the communication system by simulating the atmospheric turbulence effect. They found that the receiving signal of the communication system impacted by strong turbulence could be improved by 2–4 dB following AO closed-loop correction [77]. In 2014, Ali Hashmi and researchers from the Pakistan National University of Science and Technology used AO technology in a numerical simulation of inter-satellite communication to reduce interference from background noise and turbulence disturbance. They successfully increased the Strehl ratio of the system from 0.30 at the open-loop moment to 0.75 after attaining closed-loop stability [81]. In 2015, JPL (USA) spent three months to complete a performance study of the AO module in the laser communication system, and found that AO closed-loop correction could effectively reduce the impact of atmospheric scintillation on optical signals and improve the coupling efficiency of optical fibers [82]. In 2018, Carlos et al. proposed a phase retrieval technique to indirectly determine the unknown phase wave front and improve the coupling efficiency of a single-mode fiber. Through experiments, they demonstrated that this method could significantly improve coupling efficiency and signal stability in strong turbulence [77].

1.2.2 Chinese Research Progress in Adaptive Optics

Chinese research into AO began in the 1980s, and the first Chinese reflector was successfully developed in 1982. The DM had seven actuator units and adopted a piezoelectric drive mode, filling the gap in China's AO technology field [83]. In 1985, the Chengdu Optoelectronic Technology Research Institute of the Chinese Academy of Sciences used a 19 unit DM to triple the focal spot energy of the Shenguang I laser nuclear fusion device by employing the "mountain climbing method" optimization principle, and demonstrated the effectiveness of AO technology in laser nuclear fusion devices [84]. In October 1990, the Institute of Optics and Electronics (IOE) applied the AO technique to astronomical observations. A 21 cell infrared AO technique was used to correct the wave front and take pictures of stars with the observatory's telescope, showing that the AO technique could greatly reduce the turbulence effect between stars and the Earth [85]. The IOE added a 61 cell AO system to the telescope in 2000 and further upgraded the system in 2004 by changing the subaperture distribution of the Hartmann–Shack sensor to improve system accuracy [85]. In 2000, IOE developed a 19 unit micro-AO system, which was successfully applied in the imaging of living human retina [86], making China the second country after the USA to realize high-resolution retinal imaging using AO technology. Two years later, the IOE upgraded the system to 37 units, further improving its accuracy.

In 2009, Xia et al. introduced AO technology to optical communication to compensate for the influence of atmospheric turbulence in a wave front correction experiment [87]. In 2010, Han et al. added AO technology to an FSO communication system to study changes in the BER of the communication system. They found that the performance of FSO communication could be greatly improved by only correcting relatively low-order aberrations after adopting AO [88]. In 2011, the IOE cooperated with Wuhan University to conduct optical communication experiments and used AO technology to correct simulated atmospheric turbulence, which improved the quality of the optical communication system and reduced light intensity fluctuations [89]. In 2014, Liu et al. systematically analyzed the influence of AO on the mixing efficiency of coherent optical communication, and proved through experiments in 2016 that AO could improve the performance of coherent optical communication systems [90, 91]. In 2017, Xizheng Kem Jiali Wu and their research team from the Xi'an University of Technology conducted experiments on a coherent optical communication system without wave front detection. Experiments showed that wave front-free detection AO technology could suppress the influence of atmospheric turbulence on optical signals and improve the coupling power of single-mode fibers [81]. In 2018, Li Xuan and her team from the Chinese Academy of Sciences successfully developed a fast liquid crystal AO system suitable for open-loop control and obtained clear images of binary stars through experiments on a 1.2 m telescope, successfully improving the energy utilization of the system [92].

In 2019, Xizheng Ke, Mei Li, and others from Xi'an university of Technology used DMs to study the Eigen mode of wave front AO correction technology for use in FSO communication. Their method was shown to effectively correct the wave front and improve the convergence speed [93]. In the same year, Xizheng Ke, Namei Cui, and others applied an algorithm based on phase differences with no wave front AO correction technology to the vortex field. They found that the wave front AO algorithm could effectively correct the vortex beam wave front, reduce crosstalk between models, and improve the convergence speed [94].

China's AO technology is developing rapidly and will play an important role in coherent FSO communication. However, research advancements in China are limited compared to the current level of international research. Atmospheric turbulence uncertainty, system complexity, signal acquisition and tracking accuracy, and research duration are all important factors that have restricted the development of AO technology in China.

1.2.3 Adaptive Optics Development Trends

The research focus in AO has shifted over time from astronomical imaging observations to laser communication. In terms of coherent optical communication, AO technology has become the predominant method for correcting wave front distortion [95]. With the continuing expansion of the research field, the evaluation index of the AO correction effect has expanded from a single optical index, such as the image resolution limit, wave front peak–valley value, and wave front root mean square value, to the coupling power and communication BER. Studies have shown that communication quality can be significantly improved by correcting for only low-order aberrations, and research has now extended to atmospheric turbulence suppression. Experiments have also shown that AO technology can significantly improve communication quality under the influence of strong turbulence. Furthermore, research into the coupling efficiency of single-mode fiber revealed that communication quality can be enhanced by improving coupling efficiency into a single-mode fiber. Researchers from the Chinese Academy of Sciences have carried out research on numerous AO applications, while studies have also focused on the development of deformation mirrors, control algorithms, and other key components of the AO system to improve its corrective performance. To date, AO research has mainly focused on satellite–ground communication and its various influencing factors.

AO have been widely used in astronomy, communication, and numerous other fields due to the system's ability to measure wave front signals in real time and in turn correct for wave front distortion, improve imaging accuracy, and communication quality [96]. With the ongoing improvement and expansion of AO, the technology is being used for applications such as optical beam splitting, device surface flatness detection, powerful laser weapon systems, human eye aberration manipulation, and laser pulse shaping. The size and correction accuracy of the AO system varies according to different application fields; however, the number of wave front sensor sub-apertures and DM drivers in the system generally show an increasing trend. In particular, the scale of the AO system can reach thousands of units in long-distance communication. Accordingly, atmospheric turbulence disturbance, wind