SCIENCE CHINA
Information Sciences

• REVIEW •
Special Focus on Deep Space Communications

April 2018, Vol. 61 040301:1–040301:12
https://doi.org/10.1007/s11432-017-9216-0

Overview of deep space laser communication

Weiren WU[1,2], Ming CHEN[1,3*], Zhe ZHANG[2], Xiangnan LIU[3] & Yuhui DONG[3]

[1]*School of Aerospace Engineering, Beijing Institute of Technology, Beijing* 100081*, China;*
[2]*Lunar Exploration and Space Engineer Center, Beijing* 100037*, China;*
[3]*Beijing Research Institute of Telemetry, Beijing* 100076*, China*

Received 5 June 2017/Accepted 28 July 2017/Published online 12 December 2017

Abstract The deep space probe is a vital technology for observing and exploring the universe. It is thus intensifying as an aerospace research focus on an international scale. Despite improving the frequency band, the conventional microwave communication technique has difficulty satisfying the increased demand for the enormous volume of scientific data returning to the Earth. With a carrier frequency that is several orders of magnitude higher than the microwave, free-space optical communication is a robust and promising method for achieving both high bit rates and long distances in deep space communication. In this article, the history of this technology is summarized and the objective laws are formulated, while key techniques and development trends are analyzed. Finally, useful concepts and suggestions are proposed for the development of deep space laser communication in China.

Keywords deep space communication, deep space observation, development process, free space communication, laser communication

Citation Wu W R, Chen M, Zhang Z, et al. Overview of deep space laser communication. Sci China Inf Sci, 2018, 61(4): 040301, https://doi.org/10.1007/s11432-017-9216-0

1 Introduction

Deep space exploration is a key means for humans to investigate the Earth, solar system, and universe. This exploration may eventually reveal the origins and evolution of the universe and enable exploration of inhabitable space. Since 2003, a considerable amount of international effort has focused on deep space exploration, thus leaving satellite footprints on every planet in the solar system and beyond. China began such a project with lunar exploration and attained impressive achievements. Recently, it initiated the first Mars exploration program [1–3].

Compared to near-Earth satellites, deep space exploration exhibits the features of longer distances, more severe signal attenuation, longer transmission delays, and more highly complex environments, all of which present great challenges to transmission performance. In addition, launch window limitations require various scientific tasks to be simultaneously performed. This introduces technical challenges for various payloads to utilize multiple transmission channels and achieve excellent transmission performances. Thus, effectively transmitting the detector information and various kinds of scientific data back to the Earth under time limitations is a key concern [4, 5].

To this end, the frequency bands for microwave communication span from the S- and X- bands to the Ka band. Nevertheless, the future demands for high bit-rate data transmissions will continue to be difficult to meet. For example, the Voyager deep space probe, whose design parameters nearly reach

* Corresponding author (email: admirebird@sina.com)

the limits of present engineering techniques, could only achieve transmission rates of 100 kbps between Jupiter and Earth and 10 kbps between Neptune and Earth. Even when the Ka band was used, the transmission data rate could not exceed four times the X-band. Consequently, it is difficult for microwave communication technology to achieve the 1-Mbps to 1-Gbps data rates required for future planetary telemetry technologies, such as synthetic aperture radar, multispectral/hyperspectral imaging, and high-definition video communication [2].

Deep space laser communication is a wireless communication method for transmitting images, video, and sound between deep space explorers and the Earth. It modulates the electrical signal on the optical carrier via electro-optic modulation. After the acquisition, tracking, and pointing phases, the communication terminals can establish and maintain laser links in which the beams carrying information are transferred via the deep space communication channel, and the signal is received and demodulated at the receiving terminal. These laser communication links provide various benefits, including high data rates, enhanced security, higher reliability, and more powerful networking flexibility. Moreover, their communication terminals are small, lightweight, and have low power consumption [6–8].

Compared with microwave communication, laser communication operates on higher carrier frequencies and provides lower diffraction losses, better directivity, and greater transmission efficiency. It can thereby achieve high transmission rates and outstanding communication performances with lower transmitting power and smaller antenna sizes. Therefore, optical communication is particularly suitable for the future deep space exploration demands of high-speed and extremely-long-distance transmission [9–11]. In addition, with the development of deep space probes, the need to study deep space laser communication is becoming increasingly urgent. In the 1980s, the US National Aeronautics and Space Administration (NASA) proposed a deep space laser communication plan to promote the gradual development of key relevant techniques [12].

The present study was based on comprehensive research of the development of deep space laser communication abroad. Accordingly, in this paper, the related objective laws are presented, prospective future trends are discussed, and suggestions are presented to promote the development of this field in China.

2 Development status and future trends

Because the transmission distances of deep space exploration are much longer than those of satellites in orbit around the Earth, both the technical difficulties encountered and the funds required are much higher than those of satellite laser communication. Therefore, only a few countries and organizations have launched relevant studies in this field. In its 30 years of development, deep space laser communication has made significant advances. In particular, US researchers have developed several key technologies, including the pointing, acquisition, and tracking (PAT) technique, high-sensitivity optical receivers, and ground-based arrayed telescopes. In addition, the US has successfully demonstrated lunar-Earth laser communication [13,14], while other countries, including Russia, some European nations, and Japan, have developed several space laser communication research projects [15–20].

As a reference for the development of deep space laser communication in China, the development history of deep space laser communication in the US is systematically presented.

As shown in Figure 1, the development of deep space laser communication in the US can be divided into three stages: demonstration and experiments, Moon-Earth verification, and deep space verification.

2.1 Demonstration and experiments

In the first stage, the system scheme and experimental demonstrations, terminal techniques, and the development of information receiving systems for deep space laser communications were gradually performed. The programs in the scheme demonstrations included the Venus Radar Mapper (VRM) program, X2000 Optical Communication Terminal program, and Mars Laser Communication Demonstration (MLCD) program [21–25]. In terms of the information receiving systems, the ground-based, space-based, and

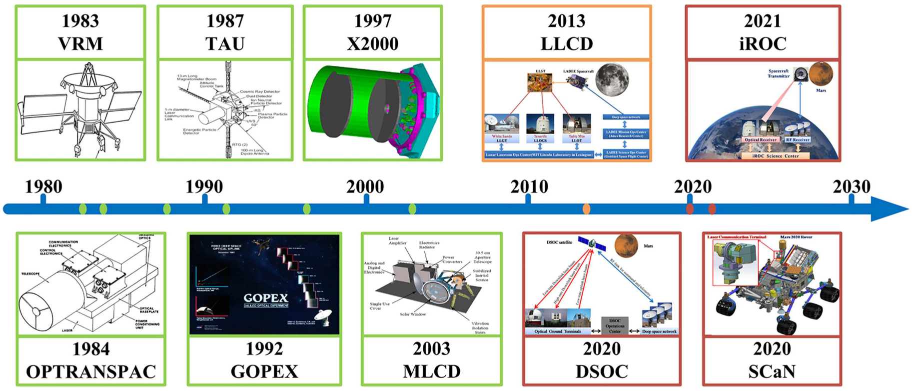

Figure 1 (Color online) Development of deep space laser communication in the US.

air-based schemes were comprehensively analyzed and compared. Ultimately, the ground-based receiving system was determined to be the best option. Thus, a complete ground-based receiving system that had a ground-based receiving net resolution satisfying the all-day and all-weather requirements was designed [26–29].

2.1.1 *System scheme demonstration and experiments*

(1) Venus Radar Mapper (VRM) mission. In 1983, the VRM mission, which later became known as the Magellan mission, was utilized to map the surface of Venus using imaging radar. The map information was then transmitted to Earth via laser communication. A 98-kg flight terminal was designed to transfer 4 Mbps of data to a 5-m ground-based telescope antenna. However, the plan was never implemented because of the immaturity of the flight terminal technology [21].

(2) X2000 optical communication terminal program. The flight terminal of the X2000 system, which began in October 1997, had a 30-cm optical antenna that provided both laser communication and ranging abilities based on the use of the same light signal. The transmission rate from Europa to Earth was designed to be between 100 and 400 kbps, while the rate between Mars and Earth was upgraded to several megabits per second. Owing to budget limitations, only the structural design of the X2000 flight terminal was completed [22, 23].

(3) Mars Laser Communication Demonstration (MLCD). In response to the growing demands for deep space communication, NASA formulated a plan to achieve high data rates between 1 and 1000 Mbps in such scenarios. In 2003, the NASA Goddard Space Flight Center (GSFC), Jet Propulsion Laboratory (JPL), and Massachusetts Institute of Technology (MIT) Lincoln Laboratory collaboratively undertook an MLCD project that was intended to demonstrate downlink data rates of 1 to 30 Mbps and uplink rates of 10 kbps. The flight terminal used in the transceiver design possessed an optical antenna with a 30.6-cm aperture that utilized both 32-ary and 64-ary pulse position modulation (PPM), whereas the ground receiving system contained two terminals with antenna apertures of 5 m and 1.6 m [24, 25].

The flight terminal was scheduled to be launched along with the Mars Telecom Orbiter (MTO). It was eventually terminated because of revised plans. However, the system requirements, analysis, and preliminary design of both the flight and ground subsystems had already been completed and resulted in significant breakthroughs for various key technologies, including deep space beam stabilization, and efficient photon counting, and daytime ground operation. These advancements established an important foundation for realizing the demonstration programs of subsequent lunar laser communications [24, 25].

2.1.2 *Information receiving system study*

(1) Ground-based receiving system scheme. In terms of their respective costs, performances, and stability statuses, ground-based net solutions have obvious advantages over other solutions [26]. In 1994, NASA began a program of ground-based antenna receiving technology in which two sets of network structure schemes were proposed. One was the linearly dispersed optical subnet (LDOS), in which six to eight

mutually redundant optical stations were distributed equally around the Earth. The other was the clustered optical subnet (COS), in which three 10-m antennas were placed near each of three wireless deep space communication receiving stations. Each antenna in a group was separated by hundreds of kilometers along the same longitude, ensuring that they would be under different weather conditions. The results indicated that the weather availabilities of both schemes were as high as 97% and that LDOS was more economical.

(2) Space-based receiving system scheme. In 1993, a NASA-funded mission named the Earth Orbit Optical Reception Terminal (EOORT) was jointly undertaken by Stanford Telecom (STeL) and TRW Inc. For this endeavor, STeL designed a 16-m multichip master telescope, and TRW designed a remotely controlled 10-m aperture telescope for direct detection and a 4-m aperture coherent detection space-based telescope with a diffraction limit. In 1998, JPL analyzed a 7-m aperture telescope for the direct detection of an optical relay satellite with a capability equivalent to that of a 10-m aperture ground-based antenna operating at an elevation of 30° and with a weather availability of 70%. Moreover, the EOORT receiver had an aperture of the same size and could operate with a weather availability of 98%, a laser wavelength of 1064 nm, and less than 18 W of power. It could even support a 100-W beacon light as a 10-Mbps laser communication link between Mars and the Earth. Although it could ignore the effects of both cloud cover and atmosphere refraction when use in outer space, it was less cost-competitive than the ground-based system [27].

Furthermore, a combine-receiving scheme with a 70-cm aperture space-based receiving station and several ground stations was proposed to solve the problem of cloud cover [28]. However, the stability and continuity of deep space laser signals received by space-based receiving systems with small apertures still require further investigation.

(3) Air-based receiving system scheme. Working above both the clouds and most of the atmosphere, air-based schemes include balloons, airships, and airplanes. An air-based terminal can mitigate the effects of both the sky background and atmosphere turbulence, thereby increasing the number of links available and reducing the aperture size requirement [29, 30]. With respect to the platform attitude noise, single-point failure, field-of-view blockage, and cost, an air-based receiving system scheme is not the optimal choice.

2.2 Demonstration of Lunar-Earth laser communication

In 2008, NASA began the Lunar Laser Communication Demonstration (LLCD) program [31] in which bi-directional communication links between a lunar satellite and a ground station on Earth were established to verify the feasibility of operating compact, lightweight flight terminals at high data rates. In early 2013, a grayscale image of the Mona Lisa was transmitted from the Goddard Space Flight Center to the Lunar Reconnaissance Orbiter (LRO) aboard the Lunar Atmosphere and Dust Environment Explorer (LADEE), which represented the first laser transmission of an image between the Moon and Earth [32, 33]. In October 2013, the flight and ground terminals achieved downlink and uplink data rates of 622 Mbps and 20 Mbps, respectively. Moreover, the first continuous ranging between the Moon and Earth achieved sub-centimeter accuracy [34].

An overview of the LLCD, including its system composition, scheme features, and future development is provided in the following subsection.

2.2.1 *LLCD system composition*

As shown in Figure 2, the system consists of the Lunar Lasercom Space Terminal (LLST), Lunar Lasercom Ground Terminal (LLGT), and Lunar Lasercom Operations Center (LLOC). In consideration of weather variations, LLCD includes three ground stations: the LLGT in New Mexico, the Lunar Lasercom OCTL Terminal (LLOT) in California, and the Lunar Lasercom Optical Ground Station (LLOGS) in the Canary Islands. To reduce the effects of inclement weather on the LLCD, different ground stations are coordinated by the Lunar Lasercom Operations Center (LLOC) at the MIT Lincoln Laboratory in Lexington, MA [13, 14, 34].

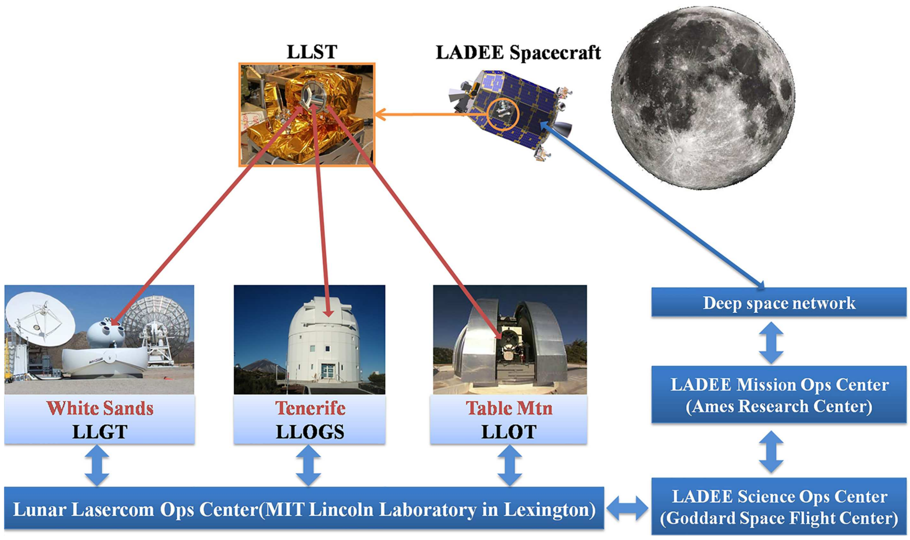

Figure 2 (Color online) LLCD system composition.

2.2.2 *Scheme features of LLCD*

(1) Scheme features of LLST. As shown in Figure 3, LLST consists of an optical module, modem module, and control module, each of which has a mass of 30 kg and a power consumption of approximately 90 W [35].

The optical module includes a Kassai Green telescope with a 10-cm aperture on a two-axis gimbal. The telescope and backend optical assemblies use magneto-hydrodynamic inertial reference units (MIRUs) to reject high-frequency vibrations caused by the spacecraft. The telescope is fixed on the gimbal to enable the laser link to conduct coarse aiming over a wide range. Meanwhile, the acquisition and tracking detector includes an InGaAs quadrant detector with a view of 2 mrad and is used to acquire and track the uplink signal. Its laser beam is transmitted from the telescope to the photoelectric detection assemblies in the modulation and demodulation module via a single-mode optical fiber [36–38]

The modem module adopts a modular design strategy and consists primarily of four boxes placed longitudinally. The electro-optics box includes a 0.5-W main oscillation power amplifier, a preamplifier, and a detector for both generating and amplifying the downlink data and receiving and demodulating the uplink signal. The module also contains a high-speed data interface board connected to a LADEE detector for transmitting both detector telemetry and scientific payload data in the downlink communication. An advantage of the modular design is that all of the boxes can simultaneously operate, reducing both the installation and testing times. Another advantage is that each box can be flexibly configured on demand [35–38].

The LLST controller module is an aerospace electronics module based on a single-chip microcomputer that is connected to both optical and modulation/demodulation modules as well as to the detector. This module has both an input/output interface to the optical module sensor as well as an actuator that provides a closed-loop control algorithm for the optical actuator. It can configure and transmit instructions to control the modulation/demodulation module. In addition, the control module provides instructions and telemetry data to both the LADEE and LLST payload for transmitting received uplink instructions, downlink telemetry data, and other information obtained from LADEE, such as time and detector attitudes [35–38].

(2) Scheme features of LLGT. The LLGT system is the primary ground terminal for the LLCD, as shown in Figure 2. This system consists of both a telescope array and control room. Including a temperature-controlled cover, its overall height is approximately 4.6 m, and its total weight is approximately 7 t. The system adopts a portable design, and its weight and volume are each only 25% of those of the radio frequency (RF) antenna [39].

In the telescope array, four groups of 15-cm refraction antennas are used for uplink transmission,

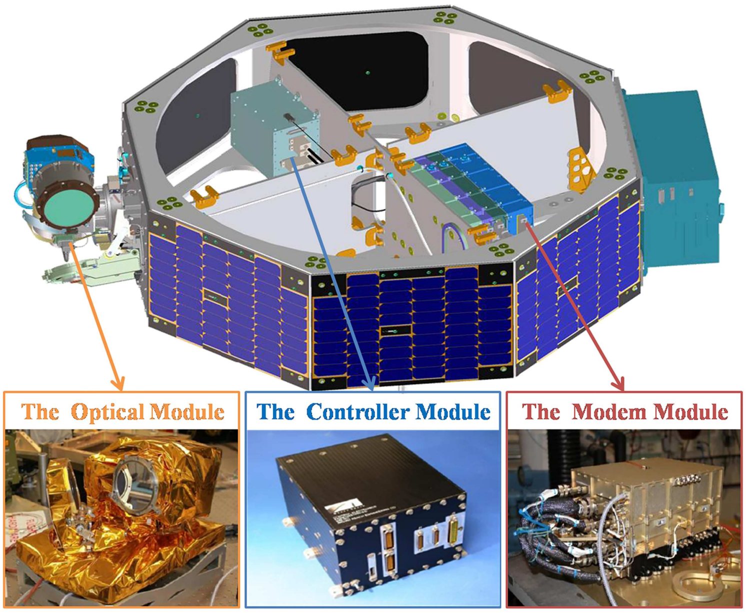

Figure 3 (Color online) Optical module, modem module and controller module of LLST.

and four groups of 40-cm reflective receive antennas are used for downlink reception. The array can be extended to reduce costs. In addition, it utilizes spatial diversity to mitigate the effects of atmospheric turbulence on its laser links. Meanwhile, the control room contains the laser transmitter, optical receivers, all electronic devices, control and monitoring devices, air processors, and operating areas. The nearby cooling unit is used to cool the telescope, compressor, and control room [39–43].

The receiver system adopts a superconducting nanowire detector array (SNDA). This SNDA, which consists of four superconducting nanowire single photon detectors (SNSPDs), is installed inside a cryogenic refrigeration vessel. Each SNSPD contains four niobium nitride nanowires. An SNDA can provide a high (higher than 50%) detection efficiency, a low jitter (of half the full width of about 60 ps), low noise (with a dark count rate lower than 50 kHz), and a fast response (an approximately 15-ns restart time), all of which are required for a high-data rate downlink. A rack is equipped with a high-speed electronic device and has interfaces with various data sources and targets that can be used to process the output of the SNDA and compare the uplink and downlink clocks [39–43].

The transmitter system transmits four PPM signals using four 10-W optical transmitters based on erbium-doped fiber amplifiers. An ultra-large single-mode fiber with a 125-μm^2 effective core cross-sectional area is used to reduce the nonlinear optical effects that occur when a high-peak power signal is transmitted to the telescope by a single EDFA, and its power ratio is adjusted for each different application scenario [39–42].

2.2.3 *Follow-up development to LLCD*

The LLCD represents NASA's first substantial step toward verifying the feasibility of deep space laser communication. Although it is a short-term mission that cannot provide sufficient application experience to support deep space laser communication into the future, its successful implementation remains very important.

As a follow-up to LLCD, NASA initiated the Laser Communication Relay Demonstration (LCRD) mission. Both the flight and ground terminals of the LCRD are being developed based on those used in the LLCD. The LCRD will be NASA's first mission that demonstrates and verifies long-term optical communications at both near-Earth and deep space distances. The mission cycle of the LCRD is 2–5 years. It is intended to solve the problems remaining in near-Earth optical communication applications to demonstrate and verify a high-reliability, low-cost laser communication technology for use in near-Earth

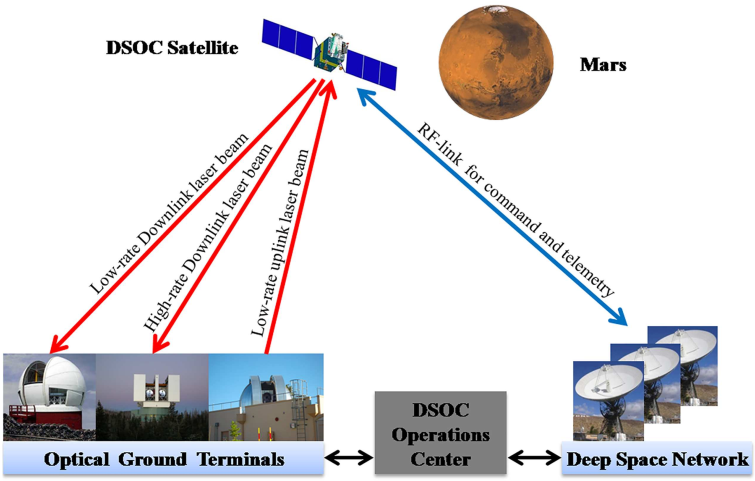

Figure 4 (Color online) Composition and communication technical indices of the DSOC system.

and deep space systems, and to promote the development of near-Earth and deep space communication network technology [44, 45].

2.3 Deep space laser communication verification phase

Based on the achievements of the LLCD, the US intends to accelerate the laser communication schedule that is used for deep space and planetary exploration, including the Deep Space Optical Communication (DSOC) plan, the laser communication terminal used for the Mars 2020 rover mission, and the Integrated Radio and Optical Communication (iROC) plan.

2.3.1 *Deep Space Optical Communication (DSOC) plan*

The success of the LLCD experiment invigorated the development of JPL's Deep Space Optical Terminals (DOT) project. According to its mission plan, the laser terminal developed in the DSOC plan will be used for laser communication links among near-Earth asteroids, Jupiter, and the Earth, and it will support 250-Mbps communication rates between Mars and the Earth. The DSOC plan is expected to be presented online in 2020 with a wavelength of 1550 nm, power consumption of 4 W, terminal mass of approximately 28 kg, and design life of five years, as shown in Figure 4 [46, 47].

Compared to LLCD, the additional challenges faced by DSOC include a laser-link loss greater than 60 dB, a kilowatt-class ground uplink laser transmission power, a space-borne single photon counting detector array, a fine-beam pointing control, and a larger point-ahead angle in the downlink. In addition, DSOC will simultaneously adopt a 5-m Hale antenna as a larger ground receiving antenna to receive communication data from Mars at a rate of approximately 100 Mbps and valuate a 12-m receiving antenna scheme. Compared to the highest current communication rate between the Mars Ka-band transmitter and the Earth, which is only 6 Mbps, the DSOC communication rate is expected to be two orders of magnitude higher [46, 47].

2.3.2 *2020 Mars rover laser communication terminal*

Space Communications and Navigation (SCaN) designed a laser communication terminal for the Mars 2020 rover, as shown in Figure 5. This terminal can support both 20-Mbps data transmission with the laser relay terminal on the Mars orbiter as well as 200-kbps direct communication from the surface of Mars to that of Earth. Moreover, it has a mass of approximately 6 kg and a power consumption of 50 W. The diameter of the laser communication terminal's transmitter antenna is only 5 cm, which is shorter than that of current X-band communication and it offers significant advantages [46, 47].

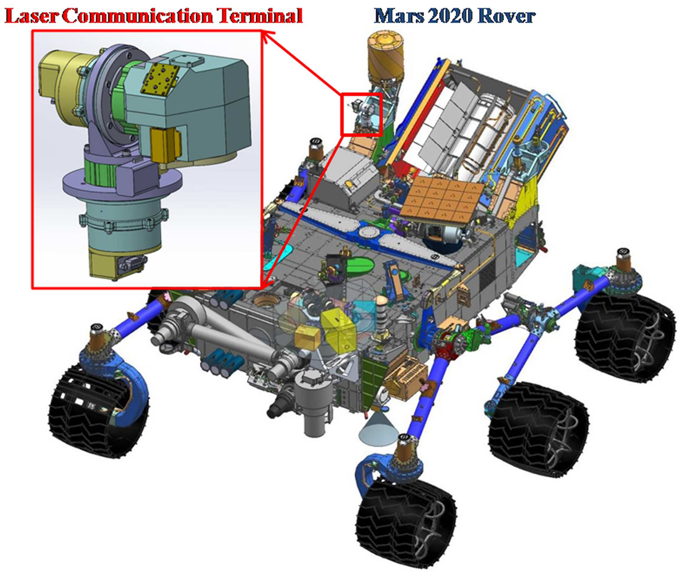

Figure 5 (Color online) Terminal installation location for Mars 2020 rover.

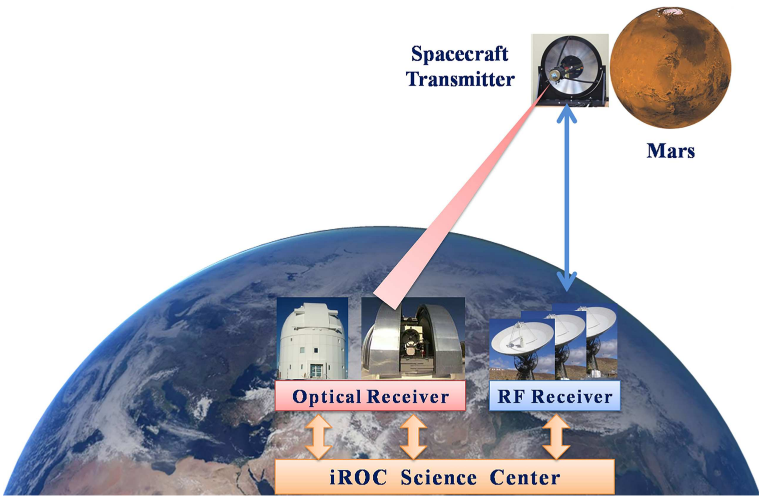

Figure 6 (Color online) System diagram of iROC.

2.3.3 *Integrated Radio and Optical Communications (iROC)*

Owing to the strict constraints of space-carrying conditions, the integration and multi-mode demands of deep space detectors on communication payloads are increasing. Thus, NASA has begun to study deep space RF and laser-integrated communication systems. The iROC program to analyze the feasibility of both RF and laser-hybrid communications for future deep space missions began in 2012. The 2021 Mars exploration mission is intend to apply such a system, as shown in Figure 6. Its system integrates a 3-m diameter RF antenna with a 30-cm optical antenna, and it shares a set of software-defined modems. Although the technical maturity of the iROC system is low, its prospects for application are high [46, 48, 49].

In addition, the European Space Agency (ESA) plans to conduct experiments to verify deep space laser communication technology. As part of its Asteroid Impact Mission (AIM), in 2022, ESA plans to place a lander on the surface of the Didymos asteroid, launch at least two cube stars from its detector to collect scientific data, and use its laser communication link to pass the collected data back to the optical ground station. This data will be highly valuable for an in-depth understanding of the formation of the solar system.

The deep space laser communication terminal utilized in AIM is the OPTEL-D, which was developed by RUGA Space. Its communication distance is between 1.5×10^7 and 7.5×10^7 km, its uplink communication wavelength is 10.6 μm, and its downlink communication wavelength is 1550.12 nm. In addition, its downlink modulation mode is 16 PPM and its downlink communication rate is 0.1 to 2.5 Mbps [50].

3 Development characteristics

3.1 Significance of deep space laser communication as a development direction

Despite the continuous enrichment of deep space exploration missions and improvements in the ability to satisfy higher precision requirements, the traditional microwave communication mode cannot meet the needs of future deep space exploration. Consider communication between Mars and Earth, for example, laser-communication data rates can reach up to 250 Mbps, while microwave-communication rates rarely achieve 100 Mbps. Moreover, even in cases of the same data rate, laser-communication terminals have advantages in terms of weight, volume, and power consumption. It is probable that laser communication will become the optimal choice for deep space communication, thus representing an important future development direction.

3.2 Law of development from close to distant proximity

Throughout the development of deep space laser communications, only the US has performed demonstrations and verifications of Moon-Earth laser communications, which have been gradually extended to Mars-Earth communications. Relying on the development of deep space exploration, the targets of deep space laser communications have progressed from the Moon to other planets, including Mars, Venus, Saturn, Mercury, Uranus, and Neptune and its satellites, thus following the law of development from close to distant proximity.

3.3 Significance of Moon-Earth and Mars-Earth laser communications

The Moon is a deep space exploration destination of high interest because of both its short distance from the Earth and its unique resources. Mars is the most similar planet to the Earth in the solar system, thus presenting the possibility of supporting life. Among all of deep space missions that have occurred over the past 50 years, the detection frequency between the Moon and Mars was the highest. High data rate transmissions are necessary for sending information back to the Earth during future missions to either the Moon or to Mars. Free-space optical communication is thus the most promising technology for satisfying the requirements of these missions.

3.4 Ground-based reception design limitations

Limited by launch costs, the mass, power, and volume of the flight terminal must be strictly controlled. Therefore, the ground-based receiver and space-based terminal are simultaneously considered in the system and link designs of deep space laser communication missions. To design a simple flight system, a large aperture and high power consumption are adopted in the ground transmitter.

3.5 Significance of measurement and communication integration

The LLCD measured the distance between the Moon and Earth to an accuracy of a centimeter using a laser communication link. In deep space laser communication missions, it is necessary to integrate the functions of communication and measurement.

4 Key techniques for future deep space laser communication

Compared to common laser communication, deep space laser communication encounters unique challenges because of its special application environment. To adapt to the particularities of this environment, many technical difficulties must be addressed, including the achievement of high precision PAT techniques, high sensitivity optical detectors, ground-based arrayed small aperture telescopes, space-based environmental adaptability, and small and lightweight lowpower design.

4.1 High-precision PAT technique

The PAT technique is critical for deep space laser communication because the received signal power is extremely sensitive to the pointing error and spacecraft jitter is much greater than the beam width. Detection of the position of the station on Earth and directing back the downlink light are the fundamental issues of the PAT system. A cooperative beacon, which represents a good solution to uplink beam tracking, can easily reject the background-scattered power, however, it is limited by the distance, ground laser power, and Sun-Earth-probe (SEP) angle. When the SEP angle is smaller than 30°, the influence of the Earth's background cannot be neglected. Therefore, a beaconless tracking method is introduced with reference sources that include visible light images of the Earth, long-wavelength infrared images of the Earth, and visible stars. After acquiring the uplink beam angle information, a fast steering mirror is used to both adjust the micro-vibrations of the platform and direct the downlink beam back to the station on the Earth.

4.2 High-sensitivity optical detector

It is a tremendous challenge for a ground-based station to receive a light signal from a deep space transceiver after it has travelled a long distance. To solve this problem, sufficiently high photo-detection efficiency is required at the wavelength of interest. Moreover, to measure the time-of-arrival of photo pulses, a high detector bandwidth is also necessary. The influence of the atmospheric turbulence, which spreads the received signal out and increases the sky's background noise, degrades the situation even further.

4.3 Ground-based arrayed small aperture telescopes

The bit error rate (BER) performance of a communication system increases and the quality of its received signal decreases when a laser from deep space spreads out in the Earth's atmosphere and is disturbed by the atmospheric attenuation and turbulence. There are several methods for solving this problem, including the uses of adaptive optics (AO), large single-aperture receiving telescopes, and space diversity techniques. AO, which is an essential tool for removing the effects of the atmosphere, cannot be applied to deep space optical communication because of its large energy requirements. Although the use of a large-aperture telescope is an effective method of increasing the received power, these telescopes are difficult to construct, maintain, and expand. It has already been shown that the arrayed small-aperture telescope achieves the same performance as a large-aperture telescope. Moreover, it is robust, scalable, and easily recombined.

4.4 Lightweight low-power design

Limited by both the carrying capacity and launch costs of deep space missions, the flight Lasercom terminal needs a minimized volume, mass, and power consumption while still maintaining an adequate communication performance. Therefore, a lightweight low-power design is a key technique for future deep space laser communication, which includes the lightweight designs of telescopes and mechanical structures as well as the low power designs of optical devices.

4.5 Space-based environmental adaptability

The deep space Lasercom terminal must adapt to unique demands, including launch vibrations, ionizing radiation, thermal gradients caused by solar irradiation, depressurization, pyroshock, electromagnetic compatibility, and others. All of the critical parts used in deep space missions need to be initially designed and constructed based on the above requirements. Then, a series of complex and stringent tests consisting of a visual screening test, an initial stabilization bake, electrical measurement, a high-temperature burn-in, and high-stress shocks must be carried out to satisfy the requirements of deep space missions.

5 Conclusion

Laser communication is believed to be the most promising strategy for future high-data rate deep space exploration. The LLCD demonstrated duplex laser communication between the LADEE in lunar orbit and a ground receiver on the Earth, which represented an important step for deep space optical communication. Laser communication techniques will play important roles in future interplanetary networks. Based on the engineering background provided by the lunar and Mars exploration programs, China should adopt key techniques and gradually perform system-level demonstrations.

References

1 Wu W R, Liu W W, Qiao D, et al. Investigation on the development of deep space exploration. Sci China Tech Sci, 2012, 55: 1086–1091
2 Wu W R, Dong G L, Li H T, et al. Engineering and Technology of Deep Space TT&C System (in Chinese). Beijing: Science Press, 2013
3 Ning X L, Li Z, Wu W R, et al. Recursive adaptive filter using current innovation for celestial navigation during the Mars approach phase. Sci China Inf Sci, 2017, 60: 032205
4 Wu W R, Yu D Y. Development of deep space exploration and its future key technologies (in Chinese). J Deep Space Explor, 2014, 1: 5–17
5 Fu K, Zhao G Q, Li X J, et al. Iterative spherical simplex unscented particle filter for CNS/Redshift integrated navigation system. Sci China Inf Sci, 2017, 60: 042201
6 Cai Y G, Sun J F, Li G Y, et al. Self-homodyne free-space optical communication system based on orthogonally polarized binary phase shift keying. Appl Opt, 2016, 55: 4514
7 Ma J, Li K, Tan L Y, et al. Performance analysis of satellite-to-ground downlink coherent optical communications with spatial diversity over gamma-gamma atmospheric turbulence. Appl Opt, 2015, 54: 7575–7585
8 Meng L X, Li L, Zhang L Z, et al. Research on optic antenna of space laser communication networking. In: Proceedings of the 5th International Symposium on Photoelectronic Detection and Imaging, Beijing, 2013
9 Luo J J, Li H Z, Tang Y F, et al. Research on laser communication technology development for deep space exploration (in Chinese). Spacecraft Eng, 2013, 22: 94–97
10 Ma J, Xu K H, Tan L Y, et al. Analysis for mars laser communications system in USA (in Chinese). Chin J Space Sci, 2006, 26: 364–369
11 Han H S, Chen J. 21st century foreign deep space exploration development plans and their progresses (in Chinese). Spacecraft Eng, 2008, 17: 1–22
12 James R L. Deep space optical communication development program. Proc SPIE, 1987, 56: 15–16
13 Boroson D M, Robinson B S. The lunar laser communication demonstration: NASA's first step toward very high data rate support of science and exploration missions. Space Sci Rev, 2014, 185: 115–128
14 Boroson D M, Robinson B S, Murphy D V, et al. Overview and results of the lunar laser communication demonstration. Proc SPIE, 2014, 8971: 89710S
15 Grechukhin I A, Grigoriev V N, Danileiko N O, et al. Russian free-space laser communication experiment "SLS". In: Proceedings of the 18th International Workshop on Laser Ranging, Fujiyoshida, 2013
16 Grigoryev V, Kovalev V, Shargorodskiy V, et al. High-bit-rate laser space communication technology and results of on-board experiment. In: Proceedings of International Conference on Space Optical Systems and Applications (ICSOS), Kobe, 2014
17 Renny A F, David A K, Harold T Y, et al. 5.625 Gbps bidirectional laser communications measurements between the NFIRE satellite and an optical ground station. Proc SPIE, 2011, 8184: 81840D
18 Heine F, Mühlnikel G, Zech H, et al. LCT for the European data relay system: in orbit commissioning of the alphasat and sentinel 1A LCTs. Proc SPIE, 2015, 9354: 93540G
19 Hideki T, Yoshihisa T, Yoshisada K, et al. Study on coding parameters for a small optical transponder. In: Proceedings of International Conference on Space Optical Systems and Applications (ICSOS), Kobe. 2014

20 Mukai T, Inagawa S, Suzuki K, et al. A study of free space laser communication experiment on the ISS Japanese experiment module for space explorations. In: Proceedings of IEEE International Conference on Space Optical Systems and Applications (ICSOS), New Orleans, 2015

21 Hemmati H. Deep Space Optical Communications. Hoboken: John Wiley & Sons, 2005

22 Hemmati H. Status of free-space optical communications program at JPL. In: Proceedings of IEEE Aerospace Conference, Big Sky, 2000. 101–105

23 Hemmati H, Page N A. Preliminary opto-mechanical design for the X2000 transceiver. Proc SPIE, 1999, 3615: 206–211

24 Boroson D M, Roy S B, Scozzafava J J. Overview of high rate deep space laser communications options. Proc SPIE, 2004, 5338: 37–49

25 Biswas A, Boroson D M, Edwards B L. Mars laser communication demonstration: what it would have been. Proc SPIE, 2006, 6105: 610502

26 Shaik K, Wonica D, Wilhelm M. Optical subnet concepts for the deep space network. Telecommun Data Acquisition Prog Rep, 1993, 42: 153–181

27 Wilson K E, Wright M, Cesarone R, et al. Cost and performance comparison of an earth-orbiting optical communication relay transceiver and a ground-based optical receiver subnet. Interpla Netw Prog Rep, 2003, 153: 1–12

28 Levitt B, Wilson K, Roberts T, et al. Hybrid optical DSN architecture: interleaved PPM concept. In: Proceedings of JPL Internal Conference, Pasadena, 2004

29 Badesha S S. SPARCL: a high altitude tethered balloon-based optical space-to-ground communication system. Proc SPIE, 2002, 4821: 181–193

30 Mecherle G S, Akle W, Starkus C, et al. Direct detection optical relay satellite for deep-space communication. Proc SPIE, 1994, 2123: 134–155

31 Boroson D M, Scozzafava J J, Murphy D V, et al. The lunar laser communications demonstration (LLCD). In: Proceedings of the 3rd IEEE International Conference on Space Mission Challenges for Information Technology, Pasadena, 2009. 23–28

32 Sun X L, Skillman D R, Hoffman E D, et al. Free space laser communication experiments from Earth to the lunar reconnaissance orbiter in lunar orbit. Opt Express, 2013, 21: 1865–1871

33 Sun X L, Skillman D R, Hoffman E D, et al. Simultaneous laser ranging and communication from an Earth-based satellite laser ranging station to the lunar reconnaissance orbiter in lunar orbit. Proc SPIE, 2013, 8610: 861003

34 Boroson D M, Robinson B S. Status of the lunar laser communication demonstration. Proc SPIE, 2013, 8610: 861002

35 Robinson B S, Boroson D M, Burianek D A, et al. The NASA lunar laser communication demonstration-successful high-rate laser communications to and from the Moon. In: Proceedings of International Conference on Space Operations, Pasadena, 2014. 1–7

36 Boroson D M, Robinson B S, Burianek D A, et al. Overview and status of the lunar laser communications demonstration. Proc SPIE, 2014, 8971: 89710S

37 Constantine S, Elgin L E, Stevens M L, et al. Design of a high-speed space modem for the lunar laser communications demonstration. Proc SPIE, 2011, 7923: 792308

38 Burnside J W, Conrad S D, Pillsbury A D, et al. Design of an inertially stabilized telescope for the LLCD. Proc SPIE, 2011, 7923: 79230L

39 Murphy D V, Kansky J E, Grein M E, et al. LLCD operations using the lunar lasercom ground terminal. Proc SPIE, 2014, 8971: 89710V

40 Grein M E, Kerman A J, Dauler E A, et al. Design of a ground-based optical receiver for the lunar laser communications demonstration. In: Proceedings of International Conference on Space Optical Systems and Applications, Santa Monica, 2011. 78–82

41 Caplan D O, Carney J J, Lafon R E, et al. Design of a 40 Watt 1.55 μm uplink transmitter for lunar laser communications. Proc SPIE, 2012, 8246: 82460M

42 Schulein R T, Lafonb R E, Taylora M B, et al. Nonlinearity mitigation of a 40 Watt 1.55 micron uplink transmitter for lunar laser communications. Proc SPIE, 2013, 8610: 86100F

43 Grein M E, Kerman A J, Dauler E A, et al. An optical receiver for the lunar laser communication demonstration based on photon-counting superconducting nanowires. Proc SPIE, 2015, 9492: 949208

44 Edwards B L, Israel D, Wilson K, et al. The laser communications relay demonstration. In: Proceedings of International Conference on Space Optical Systems and Applications (ICSOS), Ajaccio, 2012. 1–9

45 Edwards B, Israel D, Caroglanian A, et al. A day in the life of the laser communications relay demonstration project. In: Proceedings of International Conference on Space Operations, Daejeon, 2016. 1–13

46 Cornwell D M. NASA's optical communications program for 2015 and beyond. Proc SPIE, 2015, 9354: 93540E

47 Cornwell D M. NASA's optical communications program for future planetary and near-Earth missions. Study Rep SCaN Program, 2016, 1–2

48 Fielhauer K B, Boone B G, Raible D E. Concurrent system engineering and risk reduction for dual-band (RF/optical) spacecraft communications. In: Proceedings of IEEE Aerospace Conference, Big Sky, 2012. 1–7

49 Raible D, Hylton A. Integrated RF/optical interplanetary networking preliminary explorations and empirical results. In: Proceedings of the 30th AIAA International Communications Satellite System Conference (ICSSC), Ottawa, 2012

50 Sodnik Z, Heese C, Carnelli I, et al. Multi-purpose laser communication system for the asteroid impact mission (AIM). In: Proceedings of IEEE International Conference on Space Optical Systems and Applications (ICSOS), New Orleans, 2015. 1–7