Non-coherent ranging method and realization in laser communication

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***Abstract*— The space laser communication system based on the OOK communication system has been widely used, especially in the satellite-ground high speed data transmission link and inter-satellite communication system. With the demand for distance measurement based on the OOK communication system becomes shistronger, especially for satellite internet systems based on laser links, the traditional OOK ranging accuracy, which is about meter level, could not meet the needs for modern ranging application. With the introduction of asynchronous response OKK ranging methods, the accuracy has increased to centimeter level, but the system has become more and more complex with the increase of the communication rate. This paper proposes a new OOK system laser link ranging method, that the ranging accuracy is not related to communication rate and sampling rate, but only to the phase detection accuracy of the phase detector, which solves the problem of positive correlation between communication rate and system complexity under the requirement of high-precision ranging. At the same time, this method can guarantee millimeter level ranging accuracy at a communication rate of 300Mbps to 10Gbps.**

Keywords: non-coherent ranging; lasr communication; OKK modulation

I. Introduction

In recent years, space laser links have been widely used in the high-speed transmission of massive data. Since the carrier frequency of laser is more than three orders of magnitude higher than that of microwaves, laser links can achieve higher communication rates, and at the same time, laser terminals have smaller volumes, weight, and power consumption. Due to the advantages of high communication rate, high signal-to-noise ratio, and strong anti-interference ability, the inter-satellite laser link is one of the development directions of the future inter-satellite link [1-6]. Future earth observation satellites, communication satellites, relay satellites, space-based integrated information networks, deep space exploration, manned spacecraft, and space stations all put forward urgent requirements for accelerating the development of space data transmission technology.

The laser communication technology system is divided into two categories: coherent communication system and non-coherent communication system. At present, the main systems of space laser communication mainly include OOK modulation/direct detection, PPM modulation/direct detection two non-coherent detection systems and PSK modulation/coherent receiving detection. Among them, the OOK modulation/direct detection modulation, reception and demodulation technology is simple, low in cost but low in sensitivity, and is generally used for building links in civil and commercial aerospace systems; PPM modulation/direct detection has low bandwidth utilization, but its power per unit time The utilization rate is high, and it is generally used in the field of laser communication for deep space exploration; the PSK modulation/coherent receiving detection system has high receiving sensitivity and anti-background interference ability, and is generally used for inter-satellite links of military spacecraft [7,8] .

In August 2011, China's first space-borne laser communication terminal was launched on Haiyang-2 satellite, realizing a low-earth orbit OOK satellite-ground laser communication rate of 504Mbps downlink [9]. In April 2017, China's first high earth orbit satellite-to-ground laser communication terminal was launched on the Shijian-13 satellite (Zhongxing-16) and completed the 5Gbps uplink and downlink communication experiment of the OOK modulation/direct detection system at 36,000km from the geosynchronous earth orbit to the ground [10]. In January 2016, the launch of the EDRS-A satellite equipped with TESAT's LCT laser communication terminal is a new generation of data relay system of the European Space Agency. The satellite operates in a 36,000km geosynchronous orbit (GSO), offering communication rate at around 1.8Gbps [11]. In September 2013, NASA launched the lunar atmosphere and dust environment detector spacecraft, equipped with the Lunar Laser Communication Delay Verification (LLCD) system, and completed a 622Mbps lunar downlink PPM laser communication test, ground receiver system is based on single photon technology superconducting nanowire array [12].

II. Ranging Methods and Problems

According to current applications, inter-satellite ranging is divided into three types: BPSK coherent ranging, OOK non-coherent ranging, and PPM communication ranging for deep space exploration. The first two methods are generally used in the application of inter-satellite links in multi-satellite networking.

A. BPSK coherent Ranging

For coherent ranging, in the cooperative project between Zhejiang University and Harbin Institute of Technology, the ranging function test in the process of BPSK laser coherent communication was completed, and a symbolic technology ranging method based on timing synchronization algorithm was proposed. This project has completed the simulation then applied the algorithm in FPGA, obtained centimeter-level ranging accuracy under 1Gbps high-speed communication [13]. The power consumption of the entire communication and ranging signal processing module has reached more than 40W, and the cost of localized hardware components costs millions of yuan. The characteristics of high energy consumption and high cost greatly limit large-scale commercial networking applications.

B. OKK Non-coherent Ranging

In 2009, Xing Qianglin [14] proposed the idea of a unified laser measurement and control system, and in 2020, according to the asynchronous response ranging method, developed a prototype of a laser unified measurement and control system based on the OOK [15]. The signal processing module of the prototype uses large-scale FPGA with high-speed ADC processing hardware architecture. The specific measurement principle of the asynchronous response ranging method is shown in the figure down below.

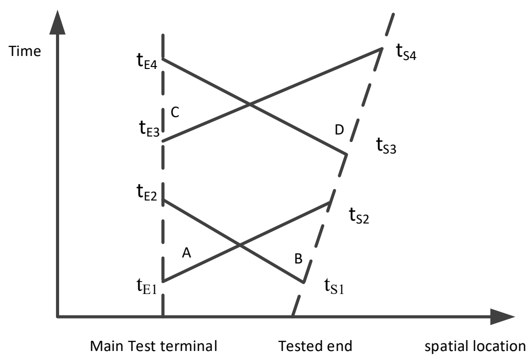


Figure 1. Asynchronous response ranging method

This method uses an ADC chip with a sampling rate above 5Gsps and an ultra-large-scale FPGA to complete the ranging function at a communication rate of 2.5Gbps, which complicates the OOK communication method and increases the system complexity as well as power consumption only to slightly improve the ranging accuracy of the system. This method does not suit for higher-speed optical communication ranging requirements, especially for commercial aerospace companies that require OOK space laser communication rates above 5Gbps, which need ADC chip with sampling rate above 10Gsps and super-large-scale FPGA, and may lead to unexpected high power consumption of the communication ranging module, as well as causing problems in parallel processing and synchronization of high-speed signals inside the FPGA. So far, this method has been difficult to be applied in real world engineering applications.

C. Summary

Traditional space optical communication terminals support up to 2.4Gbps inter-satellite links, and do not support high-precision ranging functions. Some commercial aerospace companies use laser communication terminals to increase the inter-satellite link interaction rate to 10Gbps and propose a 1/2/ 5/10Gbps multi-rate switching function. At the same time, the laser ranging function requirement was proposed for the first time, and the test accuracy was set to 1cm. The proposal of the above gauge puts forward higher requirements for the laser-focused communication ranging module, which needs adaptation of new methods and new technologies that meet the requirements of high-speed communication and high-precision ranging of inter-satellite links.

This paper realizes the transmission rate and ranging gauge mentioned above using FPGA with high-precision phase detector and improve the ranging accuracy of the system under the premise of reducing system power consumption and software complexity.

III. System Design

A. FPGA + Integrated Optical Modue Design

China's on-orbit OOK space laser terminal generally uses discrete photodetectors and FPGAs in the photoelectric receiving and conversion circuit. This method is complex to integrate and difficult to test. With the development of space optical communication technology, integrated photoelectric conversion modules gradually release to the market, this article will use the aerospace-grade radiation-resistant photoelectric conversion module and the AC coupling connection of the GTX interface of the FPGA to finish the photoelectric conversion circuit for 10Gbps data, as shown in the figure below.

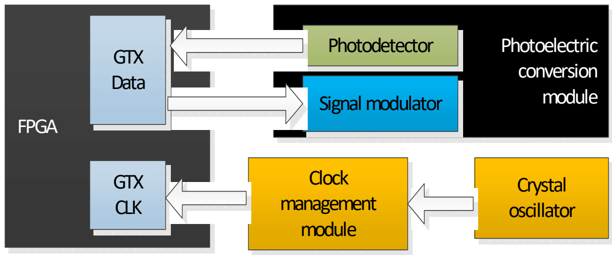


Figure 2. Photoelectric conversion principle

B. Us Ranging Methods and Error Analysis of Phase Detector + Low-speed ADC

The two-way OOK laser communication ranging system will adopt the non-coherent ranging method, and the data transmission frame structure design should be reasonably designed to ensure that 1s contains integer numbers of data frames. Assume performing two-way laser communication and ranging between laser terminal A and laser terminal B, the schematic diagram of the measurement process is shown in the figure below [16-19].

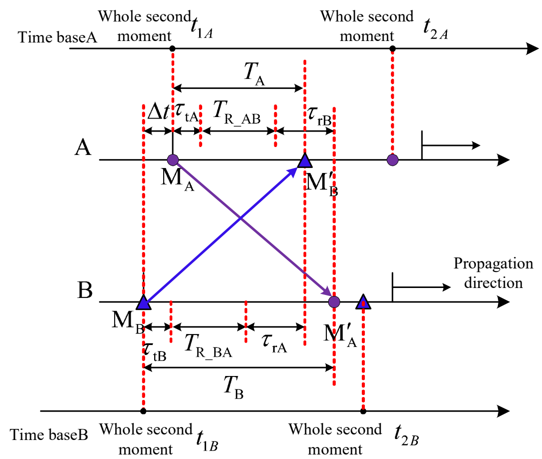


Figure 3. Non-coheren ranging principle

During the ranging process, the corresponding moment of the falling edge of the last bit of the frame synchronization code group is used as the sampling point of the frame synchronization signal, and the laser terminal time value corresponding to the sampling point is measured and recorded. During the measurement process, laser terminal A sends a transmission frame with a cycle frame count from 0 on the rising edge of the clock signal 1PPS (the falling edge of the last bit of the frame synchronization code group is aligned with the rising edge of 1PPS), and records the cycle second count number of the sending frame at the same time count and the absolute time value corresponding to the sampling point of the frame synchronization signal (local BDT). After the laser terminal B receives the laser communication signal and performs data demodulation, it judges whether the cycle frame count of the transmission frame is zero. If it is zero, measure and record the received cycle second count of the frame and the time value corresponding to the sampling point of the frame synchronization signal (local BDT). Similarly, laser terminal B sends a transmission frame to laser terminal A, and records measurement data at both ends.

Distance between laser terminal A and B:

$$R = c \cdot T_R = c \cdot \left[\frac{T_{\mathrm{A}} + T_{\mathrm{B}}}{2} - \frac{(\tau_{\mathrm{tA}} + \tau_{\mathrm{rA}}) + (\tau_{\mathrm{tB}} + \tau_{\mathrm{rB}})}{2} \right] \tag{1}$$

In equation (1): $(\tau_{\mathrm{tA}} + \tau_{\mathrm{rA}}) + (\tau_{\mathrm{tB}} + \tau_{\mathrm{rB}})$ can be calculated through system zero calibration, T_{A} and T_{B} is measured at the sampling point of frame sync.

This paper proposes a combined ranging method based on high-precision phase detector and ADC chip. For the local clock (TXUSRCLK) and recovered clock (RXUSRCLK), the phase identification is completed through the phase detector module inside the unit, and the error estimation is given after processing as shown in the figure down below:

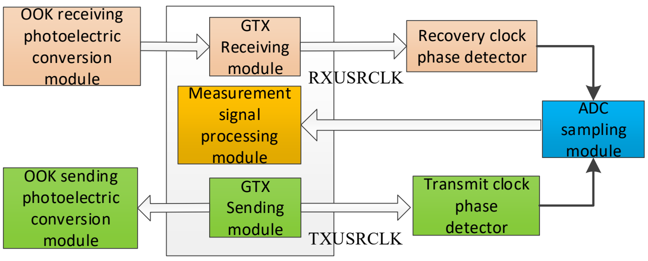


Figure 4. Phase detector + ADC ranging

In equation (1), T_{A} and T_{B} are the time measurement results of the frame synchronization signal sampling points in the ranging frame received by laser terminal A and laser terminal B, respectively, and are also key factors affecting the ranging gauge. The frame synchronization signal sampling point is obtained by serial-to-parallel conversion of high-speed serial data. The time value of the sampling point is mainly determined by the phase deviation between PPS and the processing clock, the parallel-to-serial conversion of the transmitting terminal, the parallel-serial conversion of the transmitting terminal, channel transmission, high-speed serial data, phase jitter and time measurement accuracy. Ranging errors include systematic errors and random errors. The error and its values are listed in the table below, showing that ranging accuracy meet the requirement of 1cm.

TABLE Ⅰ. ERROR ANYLYSIS

Index	*Name*	*Category*	*Error*
1	phase deviation between 1PPS and processing clock	system	zero calibration correction
2	parallel to serial conversion error of transmitting terminal	system	zero calibration correction
3	High-speed serial data phase jitter error	random	1mm
4	timing accuracy error	random	6mm (Phase detection accuracy better than 1°)
5	clock short-term stability error	random	6mm (short-term stability 1E-7)
total ranging error			better than 0.9mm

IV. Simulation and Validation Testing

A. *System Construction*

In order to verify the feasibility of the communication system, the rationality of the system design and the correctness of the ranging method, this paper designs and implements a prototype of the laser communication module that can be used to test the performance of the OOK system's high-speed communication ranging function, and also uses two prototypes to build a ground wired two-way test environment at 5Gbps communication code rate, the topography of the system is illustrate in the figure below.

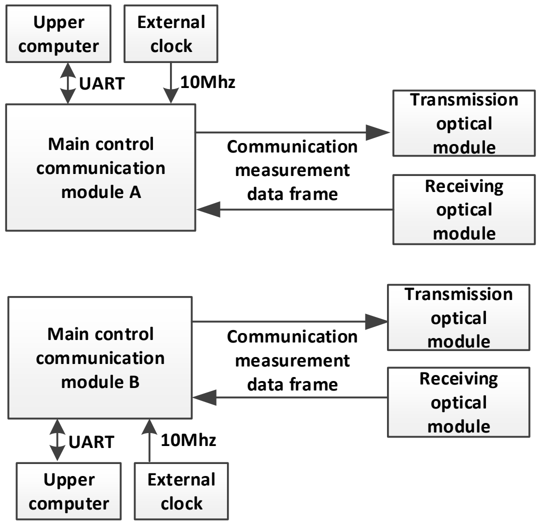
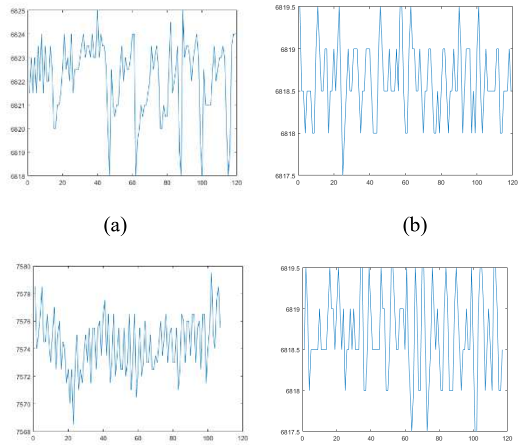


Figure 5. Block diagram of two-way ranging principle

B. *Ranging accuracy test under different clock source and PPS*

The communication modules A and B are tested with different clock sources and different intervals of 1PPS in three states: 1ms, 300ms and randomly set. The interval of 1ms is the 1pps interval between the simulated satellite constellations. For satellites with on-board GNSS receivers, the difference between the PPS of each satellite platform will not be greater than 1ms. The random interval is mainly used to test the generality of the method proposed in this paper; however the problem is that random intervals will bring certain errors. This errors mainly come from the short-term stability of the clock at the interval time and the accuracy of the clock frequency. In orbital applications, satellite constellation ranging requires atomic clocks with high stability and accuracy. The test results are shown in the figure below.



(a) (b)

(c) (d)

Figure 6. Ranging result under dfferent PPS interval and clock setup (a) unsynchronized clock 1pps 1ms interval (b) synchronized clock 1pps 1ms interval (c) unsynchronized clock 1pps random interval (d) synchronized clock 1pps random interval

The ordinate in the figure above represents the average distance between the two terminals after processing by the phase detector and FPGA in degrees, and the abscissa is time in seconds. The two-way communication rate is 5Gbps, the GTX processing clock in the FPGA is 125Mhz, and the speed of light in the optical fiber is 2/3 of the free space. Through calculation, it can be known that 1° corresponds to 0.44cm, and the distance at different times in different modes is within ±1°. The specific results are shown in the table below.

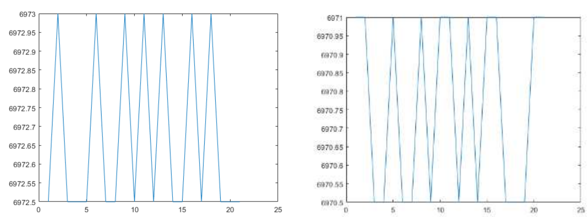
TABLE II .ERROR ANALYSIS

Clock setup	***Interval***	***SD(cm/ σ)***
unsynchronized clock	*1PPS 1ms interval*	*0.7cm*
	1PPS 1ms random	*0.91cm*
synchronized clock	*1PPS 1ms interval*	*0.19cm*
	1PPS 1ms random	*0.24cm*

When the clocks are synchronized, there is no significant change in the standard deviation of different intervals and the average value of ranging. When the two terminal clocks are unsynchronized, due to the impact of short-term stability, the increase in the sending interval will lead to a worsening of the standard deviation. Using clock with better shot-term stability can avoid the ranging error caused by pps. For reference, clock for inter-satellite ranging needs to use an atomic clock with a short stability of 1E-11.

C. *Plugging and unplugging optical fiber ranging test*

Using clock form same source to test at 5Gbps, then compare the ranging value before and after plugging, and verify the ranging function performance of the method in this paper after the laser link is cut down and re-established.



(a) (b)

Figure 7. Ranging result before and after inserting optical fiber (a)befer (b)after

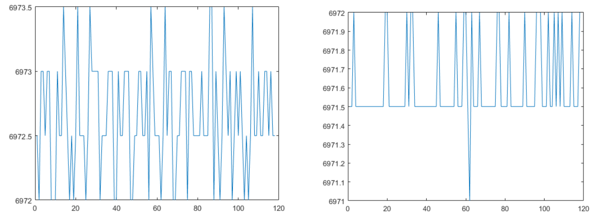
TABLE III. RANGING RESULT BEFORE AND AFTER INSERTING OPTICAL FIBER

Average ranging result before inserting optical fiber(m)	***Average ranging result after inserting optical fiber(m)***	***Error before inserting optical fiber(m)***	***Error after inserting optical fiber(m)***
30.9895	*30.9857*	*0.21*	*0.20*

The test shows that after the fiber is plugged and unplugged, the average value of the ranging results changes by less than 1cm, and the error does not change.

D. *Ranging value test before and after power failure*

Using clock form same source to test at 5Gbps, then compare the ranging average value and ranging error before and after power-on.



(a) (b)

Figure 8. Ranging value before and after power failure

TABLE IV. RANGING VALUE BEFORE AND AFTER POWER FAILURE

Status	***Raging Error***	***Average Ranging Value***
before power failure	*0.19*	*30.9895*
after power failure	*0.18*	*30.9894*

The test shows that the ranging error is less than 0.5cm after the power is turned on again, and the average value of the two changes is less than 1cm. The method in this paper has little impact on before and after the power off.

V. CONCLUSION

This paper focus on the needs of commercial aerospace that Uses laser terminal to communicate and measure distance. According to the existing space optical communication ranging problems, a ranging method based on FPGA+phase detector+ADC is proposed, the error matrix model of this method is analyzed, and the communication ranging verification method is developed. The prototype was built, and the method has been tested. Moreover, the ground wired test was carried out to test and verify different situations such as clock source, PPS interval, and laser disconnection/reconstruction. Through the test, in the case of communication rate at 5Gbps, the ranging accuracy can meet the requirements of 1cm in various cases. The result effectively verifies the communication ranging method proposed in this paper and provides a theoretical basis for future missions.

REFERENCES

[1] Marioni F., Media Lario S r l., Sodnik Z.: 2.5 Gb/s free-space optics link over 1.1 km with direct fiber coupling to commercial devices. SPIE 5550(11), 60-69(2004).

[2] Caplan D O., Carney J J., Lafon R E.: Design of a 40-watt 1.55 um uplink transmitter for lunar laser communications. Proceedings of SPIE 8246, 82460M (2012).

[3] Koyama Y., Toyoshima M., Takayama Y.: SOTA: small optical transponder for micro-satellite. Proceedings of 2011 International Conference on Space Optical Systems and Applications, 97-101. IEEE (2011).

[4] Progress of research on satellite-borne laser communication technology[J].Chinese Optics,2019.

[5] Trakalo M., Giles G.: Design flow for implementing image processing in FPGAs. SPIE 6558(65580C), 3-4(2007).

[6] ZHANG Liang,Guo Li-hong,Liu Xiang-nan.Latest Progress and trends of development of space laser communication[J].Journal of Spacecraft TT&C Technology,2013, 32(4):286-293.

[7] Jiao Zhong-ke.Research on key technologies in intersatellite optical communication[D].Chengdu:Institute of Optics and Eletronics,Chinese Academy of Sciences,2015.

[8] Jiang Hui-lin,An Yan,et al.. Analysis of the status quo,development trend and key technologies of space laser communication [J]. Journal of Spacecraft TT&C Technology2015,34(3)：207-217.

[9] Zhang Qing-jun,et al.. The study of HY-2A satellite engineering development and in-orbit movement [J].Engineering Science ,2013(3).

[10] China'S First High Throughput Satellite SJ-13 Launched Sucdessfully[J].Aerospace China 2017.4.

[11] Ping,Li Hui.Developmeng of Space Laser communication based on EDRs.Aerospace China. 2016(3)

[12] Guo Li-Hong,Zhang Liang, et al.. A Survey of Lunar Laser Communications Demonstration of NASA[J].Journal of Spacecraft TT&C Technology, 2015,34(1)

[13] Tian Yang.Research on Key Technologies for Free-Space Laser Communication.Hang Zhou:Zhe Jiang University,2020

[14] XING Qiang-lin ,LI Jiang-Ting, Tang Jia.Conception of a unified laser TT&C System[J].Journal of Spacecraft TT&C Technology, 2009, 28(2) :36-44.

[15] ZHU Hong-quan,XING Qiang-lin, FU Yi-wen,HAN Hang-cheng. Design and Realization of OOK-Based Unified Laser TT&C System[J].Journal of Spacecraft TT&C Technology, 2020, 40(11) :1203-1206.

[16] LI Yong-bo. One Method for Improving Pseudocode Noncoherent Ranging Precision in Transponder[J].Telecommunication Engineering, 2009, 49(3).

[17] Pseudo Code Ranging Method and Precision Analysis of Aerospace Spread Spectrum TTC&DT System[J].Telecommunication Engineering, 2009, 49(3).

[18] Berner J B,Layland J M,Kinman P W. Tegenerative Pseudo-Noise Ranging for Deep-Space Applications[R].TMO Progress Report.1999:42-137.

[19] The Analysis of Pseudo Noise Code Ranging in Satellite TT&C[J].Communication Technology.2003(10).