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Key technologies implementation of high-repetition-rate satellite laser ranging

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Abstract: Satellite laser ranging (SLR) is one of the major space geodetic instruments, which has various applications in earth science. In this paper, we introduce several issues regarding the key technology implementation of high-repetition-rate SLR system. Compared with traditional technology, using kHz and 8ps pulse width laser component, the data quantity and quality of high-repetition-rate satellite laser ranging (SLR) can be significantly improved. The characteristics of high-repetition-rate laser ranging and the key technologies are presented, including the event timer with the precision of picosecond, the generation of range gate signal, and so on. All of them are based on the Field Programmable Gate Arrays (FPGA) and tested on China mobile SLR system-TROS1000. Finally, the observations of satellite Beacon-C are given.

Key words: high repetition rate; event timer; range gate; field programmable gate arrays; Satellite Laser Ranging (SLR)

1 Introduction

In Satellite Laser Ranging (SLR) system, the distance between satellite and observation station can be measured by recording the round flight time of laser pulse. For the traditional lower-repetition-rate (10 - 20Hz) SLR, there is only one pulse flying between the satellite and ground station. Therefore, the observation is extremely limited, and the ranging precision would be affected seriously by the width of laser pulse, usually at several centimeters. With the development of the semiconductor Diode-pumped Mode-locked Laser techniques, a new type laser with the repetition rate of kHz and the pulse width of about 8 ps has been implemented. Using this kind of laser component, the quantity and quality of observations will be increased significantly. More than one laser pulse would exist simultaneously and interfere with each other, hence, it will be big issue to distinguish and pair different start and stop pulses, range gate controller and time measurement during the process of the pulse flight[1-3]. In this paper, some key technologies will be addressed to solve these problems, including range gate controller and high repetition rate event timer, and then the observational results will also be demonstrated.

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2 Implementation of key technologies

The timing sequence of high-repetition-rate SLR is shown in figure 1. A laser pulse is transmitted at the n moment, and returns at the n' moment, while before the n' moment, $N-1$ laser pulses have been received[4]. Using the traditional time interval counter, it is impossible to identify the return pulse corresponding to the transmitted pulse. So it is necessary to design a new equipment to count the round trip flight time of laser pulse.

2.1 Event timer based on time-to-digital conversion chip

Event timer is a new time counting device, and the laser pulses transmitting and returning are treated as a series of events, whose corresponding times are recorded. The interval between any pair of events can be recognized and calculated. Nowadays, many event timers have been successfully developed, such as the product manufactured by Dassault Ltd. in France, and ET-A032 provided by Riga University in Latvia. However, their interfaces are very complex. To meet the need of integration in mobile SLR system, an integrated event timer is designed and equipped in high repetition rate laser ranging, based on the time-to-digital conversion chip and FPGA technology.

The principle of event timer has been given in figure 2. There is a stable system clock derived by 100 MHz reference clock and PLL (Phase Locked Loop). Due to the needs of satellite observation, the system clock should be synchronized to the UTC time.

For example, there are two events (E_1, E_2), which happen during the time (02 : 30 : 00 – 02 : 30 : 01). If we enlarge this time period, like E_1, the constant of the rising edge of the reference time is already known, equal to t_{M+2}. So if ΔT_1 is obtained, the constant of the event E_1 can be written as:

$$E_1 = T_{M+2} - \Delta T_1 \tag{1}$$

Similarly, the constant of event E_n can be written as:

$$E_n = t_{M+n+1} - \Delta T_n \tag{2}$$

By this way, the measurement of event constant can be converted into the measurement of corresponding time interval ΔT_n. For the SLR precision at the order of several centimeters, the precision of ΔT_n measurement should be much higher. If a general counter is used, the clock frequency of the counter must exceed 30GHz, which is impossible and unstable at present. Currently, the widely used methods are capacitive

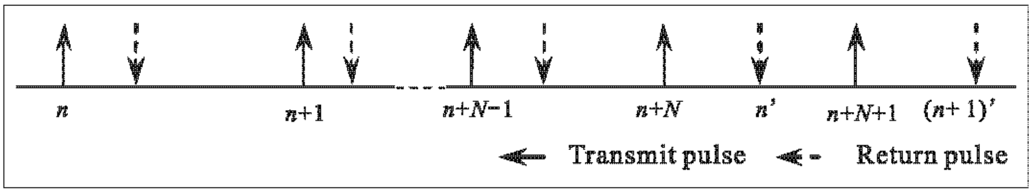

Figure 1 Timing diagram of kHz satellite laser ranging

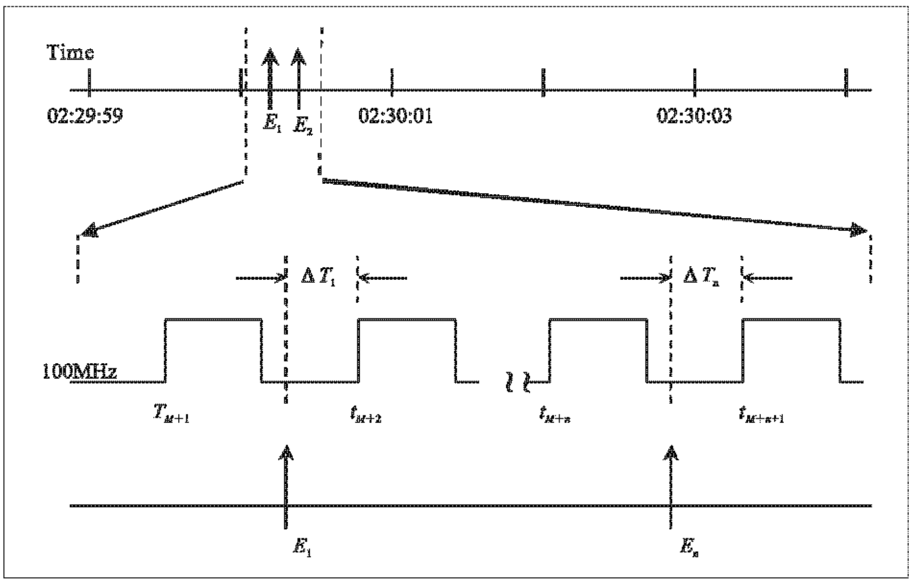

Figure 2 Measurement principle of event timer

charge and discharge, digital circuit phase shift comparison, delay line tracing comparison, and so on. By comparison, a time-to-digital converter chip named GPX from ACAM Company in Germany is chosen to achieve the event timer in our system. Mode-M, which has the best resolution of GPX's four work modes, is configured by FPGA with soft core CPU. The event timer can reach a high repetition rate of about 10 kHz. Besides, a standard width pulse calibration is arranged after every transmitted pulse, to reduce the temperature drift and voltage drift[5].

Compared with the common instrument of SR620 and ET-A032, the resolution of the event timer system with FPGA technology and GPX can reach 10 ps, and the accuracy can be better than 25 ps, and the nonlinear deviation is less than 5 ps.

2.2 The receiver time-domain filtering by FIFO

C-SPAD (Single-Photon Avalanche Diode) is one of the widely used receivers for SLR system. Normally, C-SPAD is in standby status, and will not start to work until a trigger signal is received. Once a single photon arrives, it will output a synchronous signal, and then revert to standby mode and wait for the next trigger signal. In the process of ranging, the constant of laser pulse returns can be calculated from the ephemeris of satellites, and just several ns before, a trigger signal will be sent to C-SPAD. In this way, the noise before laser pulse returns can be filtered in time-domain, and hence, this method is called the range gate for SLR[6].

The time-domain filter is achieved by FIFO (first in, first out) buffer in FPGA chip, which is shown in figure 3.

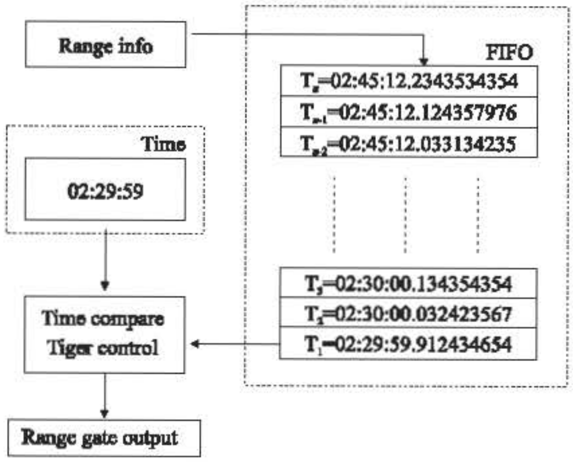

Figure 3 Principle of the time-domain filter

After a laser pulse is fired, the event timer will record the transmission constant. According to the prediction of satellite, the return constant can be calculated and then written into FIFO buffer. There is a reference clock synchronized to the UTC time. Timer comparator will check the UTC time and the values of FIFO all the time. When two parts are the same, a signal will trig the C-SPAD, and then each data sample in FIFO will replace the former one automatically. For example, in figure 3, after T_1 output, T_2 will replace T_1, and T_n will replace T_{n-1}, in turn.

3 The observational results

High-repetition-rate satellite laser ranging techniques have been developed since 2005, and several critical problems have been resolved gradually. Figure 4 shows the satellite observations of Beacon-C in June, 2009.

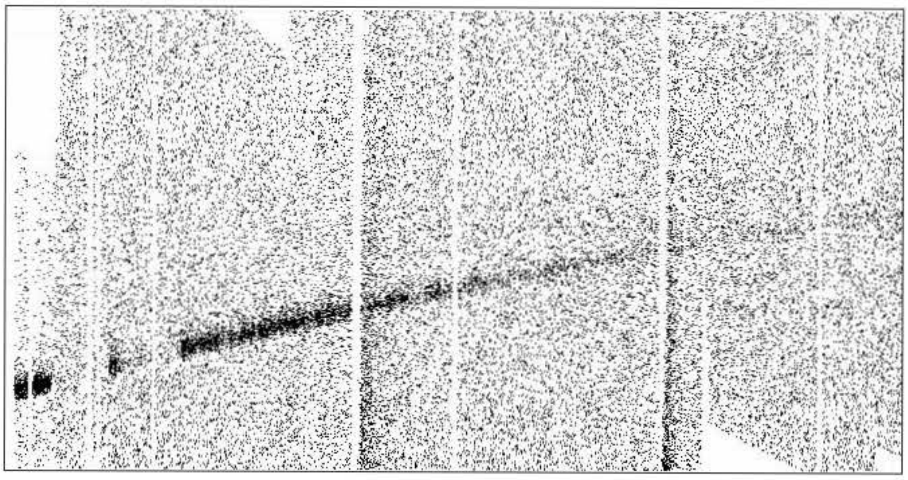

Figure 4 Beacon-C observation result

The abscissa is time, and the ordinate represents the errors between the measured laser pulse time of flight and the theoretical prediction. Compared with the traditional SLR, the noise increased significantly, but among them, there appeared clearly a bold line that represents the satellite orbit, corresponding to an observation time of 2.6 minutes, and the total data points including noise received by C-SPAD are 61789. The effective observations are nearly 5000 points and the accuracy is better than 1.8 cm. While for the low-repetition-rate SLR, even with the 50% efficiency, the quantity is just a few hundreds every minute[7].

The key technologies of the high-repetition-rate SLR proved to be effective and were applied successfully in China mobile SLR system-TROS1000. It's proved that our high-repetition-rate SLR provides significant benefits in the quantity and quality of observations. In the future, these new technologies would also be used widely for lunar laser ranging and space non-cooperative object recognition.

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