Identification and calibration of one-way systematic biases in SLR system

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Abstract

We are reporting on identification and calibration of one-way systematic biases in Satellite Laser Ranging systems. SLR is a standard technique to measure the distance of satellite as a function of time with millimeter precision and accuracy. For one-way laser ranging, laser time transfer ground to space and for bi- and multi-static laser ranging to space debris the identification and measurement of biases related separately to transmitting and receiving parts of the system are needed. The epochs of transmission and reception of optical signals have to be referred to the co-ordinated time scale with the accuracy reaching one nanosecond level or better. This requirement is about one hundred times more accurate than in standard SLR applications. A new procedure of calibration of one-way delays related to the SLR systems have been developed and tested. The necessary hardware components needed for calibration measurements were designed and developed. The calibration procedure and related hardware were tested in a real measurement at the SLR sites in Graz, Austria and Herstmonceux, UK. The one-way systematic biases were determined with the accuracy better than 20 ps.

Introduction

Satellite Laser Ranging (SLR) is a standard and mature measurement technique used in space geodesy and related disciplines since late sixties. It is used to determine the range of space object on a principle of optical radar. Its precision and accuracy is permanently improving and it is reaching millimeters value now. Recently a number of new applications of existing SLR ground infrastructure are appearing: one-way laser ranging over long distances [1], laser time transfer ground to space [2], bi-and multi-static tracking of orbiting space debris [3] and others. However, for application of SLR systems in these applications a different kind of system calibration has to be used. The reason for that is a fact that in these measurements the system biases are strictly separated into transmitting and receiving channels. In contrast to it the standard SLR calibration procedure provides a value of calibration constant, which is characterizing both these contributions together. In addition to it the relations of the epochs of transmission and reception have to be referred to the coordinated time scale UTC with the accuracy reaching one nanosecond level or better. This requirement is about one hundred times more accurate than in standard SLR applications.

Satellite laser ranging system biases

The simplified block scheme of the SLR system with its signal propagation delays is plotted in Fig. 1. Although the individual contributors to system delay ***DTi*** and ***DRi*** may be identified and their values determined independently, such a procedure is not used due to serious reason: the resulting accuracy of a number of parameters would be limited. In addition, such a procedure would be quite complex. That is why the systematic bias of the SLR ground segment for SLR applications is determined in a procedure called "ground target ranging". It means the sum of signal delays is determined in a ranging to a ground target of known distance. The resulting calibration constant ***G*** expresses the difference between the distance measured via signal propagation delays and a real distance of the target from the reference point. This calibration constant is applied to the SLR data acquired in an early stage of data processing. The ground target calibration technique has been well elaborated within the last decades. Its accuracy and long term stability is reaching millimeter level now.

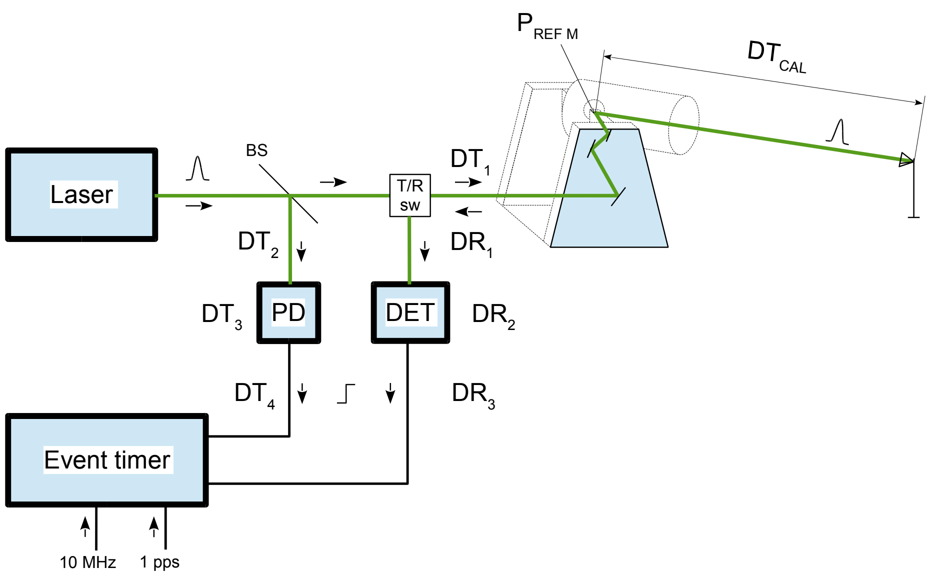

Figure 1: Simplified block scheme of the SLR system, the values $\mathbf{DT_i}$ and $\mathbf{DR_i}$ denotes the delays related to transmitting and receiving signal path respectively. *PD* is a photodiode monitoring the laser pulse output. *DET* is an echo signal optical detector. The Event timer is recording the epochs *ET* and *ER* of transmission and reception of optical signal respectively.

The ground target calibration enables to determine the sum of individual delays for transmitting and receiving signals together. However, for the new applications the separate signal delays for transmitting and receiving signal passes are required. The signals propagation delay of related to transmitting part of the system may be determined using an independent addition measurement tool. It consists of an optical detector, signal propagation cable and an epoch timing system. These additional hardware components are designed in such a way, that their signal delays may be simply determined with desired accuracy and kept stable for a long period of time. The block scheme of the measurement setup to determine the one-way ranging system biases related to a transmitting part is plotted in Fig. 2.

In Fig. 2 the left part represents the transmitting part of the SLR system, the epoch timing device ET_{ST} is determining the epoch of transmitting of the optical pulse. In a distance of L the additional optical detector *DET* is located. Its photon to electrical signal delay ***Dd*** was determined with accuracy better than 15 ps. Both the Event Timers (ET_{ST} and ET_{CD}) are referred to the common time scale and clock frequency. One common signal cable for "1pps" has to be used to synchronize the Event Timers ET_{ST} and ET_{CD} consecutively. In addition equal values of trigger slope and level regarding the "1pps" signals have to be set on both timing systems. The timing unit ET_{CD} of the Calibration Device is constructed in such a way, that it accepts all the possible triggering configurations used on various SLR ground stations.

The calibration constant ***C*** is expressing a difference between the laser fire epoch reading ET_{ST} and the epoch, when the laser pulse center of mass is crossing the system invariant point. To determine the absolute delay ***C*** related to a particular ground system

$$\boldsymbol{C = (E_{CD} - E_{ST}) - L / c - (Dd + Dc)} \tag{1}$$

where ***L*** is a separation of reference points, ***c*** is a group speed of light, $\boldsymbol{E_{CD}}$ and $\boldsymbol{E_{ST}}$ are the epoch readings of Even Timers of the Calibration Device and a ground station respectively, ***Dd*** is a photon to electrical signal delay of detector package, ***Dc*** is signal cable delay. The delay constants ***Dd*** and ***Dc*** were determined in a Calibration Device assembly phase with the accuracy of 15 ps and 2 ps respectively.

The one-way delay related to a receiving part of the SLR system ***F*** may be determined as a combination of SLR calibration constant ***G*** for a given SLR system and transmitting part delay ***C***

$$\boldsymbol{F = G - C} \tag{2}$$

where ***F*** is a one-way bias related to receiving part, ***G*** is a ground target calibration constant and ***C*** is a bias related to a transmitting part of the SLR system.

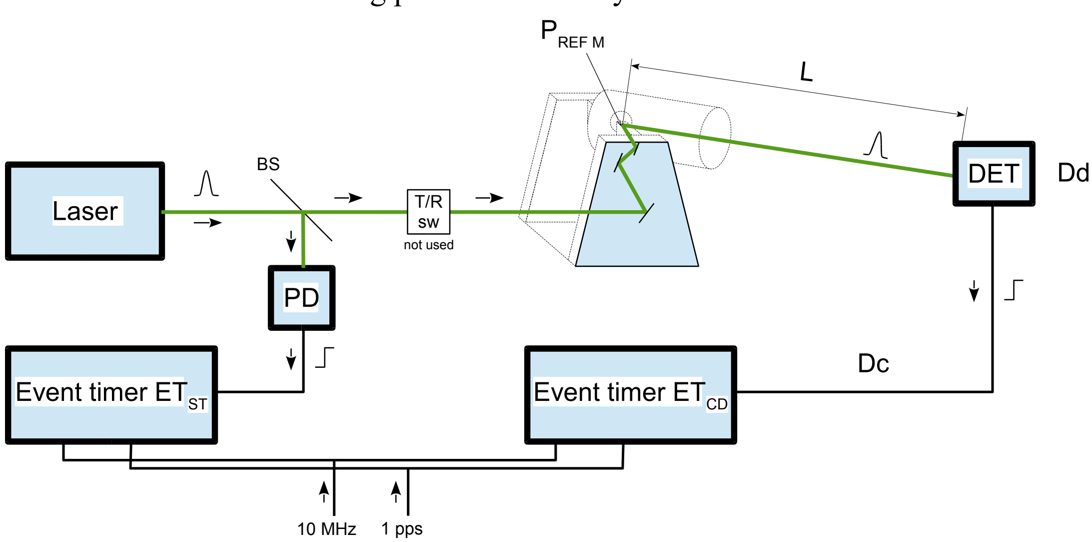

Figure 2: The block scheme of the measurement setup to determine the one-way ranging system biases related to a transmitting part.

The calibration technique related to a transmitting part of the SLR system and necessary hardware have been developed at Czech Technical University in Prague for applications in

European Laser Timing project (ELT) within the last years [2]. The epoch of transmitting or receiving the optical signal has to be referred to UTC. The calibration procedure described above enables to determine the one-way calibration constants in a setup, in which the epoch is referred to the input connector of the timing device of the SLR system. The exact definition of reference slope and level is an indivisible part of definition. Each SLR station has to determine the relation of the local representation of UTC time scale and the epoch signal on the SLR reference point.

Calibration Device design and construction

Photon counting detector – is based on a Single Photon Avalanche Diode (SPAD) developed by our group [4]. Active area diameter of the detector is 100 microns, it is operated without cooling. The active gating and quenching operation mode is used. The detection chip is operated 1.8 Volts above its breakdown voltage. The detection chip, control electronics, bias power supply and receiving optics are built in a compact mechanical housing, see Fig. 3. The optical to electrical delay of the detector has been determined [5] as 2.107±0.014 ns.

Figure 3: The Single Photon Avalanche Detector package used for Calibration Device on a tripod installed in front of the SLR telescope

Epoch timing system – The standard New Pico Event Timer [6] device was adopted for this purpose. The optional clock frequency source 10 to 100 MHz phase locked loop frequency source is installed. The unit contains also a control circuits for the photon detector package power supply and gating.

Signal cabling – The detector package signal output is connected to the timing unit input using a dedicated signal cable. Its signal propagation delay ***Dc*** was determined to be 7.114±0.002 ns at +25 °C.

The correct operation and performance of the Calibration Device was tested in a series of indoor laboratory experiments. The long term stability of all the claimed parameters was verified within more than one year of testing.

System one-way biases calibration experiment

The calibration of one-way delays – biases – was experimentally verified at the SLR station in Graz, Austria. The experiment was completed according to the block scheme in Fig. 2. The Detector package was installed in front of the SLR system transmitter telescope on its optical axis. The distance L of the detector reference point to the SLR system horizontal axis was measured repeatedly by two different surveyors and using two independent scales. The resulting distance was 1175±1 mm. The detector was externally gated by a signal from the laser control unit. It was activated about 450 ns before photons of interest arrival. The SLR system was operated on its standard repetition rate of 2 kHz. The optical signal strength has been adjusted by inserting optical neutral density filters of total attenuation of seven orders of magnitude. The optical attenuation was set to a configuration when the useful signal strength corresponded to clearly single photon echoes. It was secured by an echo signal rate of 3–5 %. The SLR system and the calibration epoch timing system used a common clock source of 200 MHz. The epoch signal "1pps" was applied using a common cable. It represented the common time scale. It was based on a GPS timing receiver "1pps" signal output. The signal was connected to the SLR and calibration unit synchronization inputs consecutively. The trigger slopes and levels were set to identical values on both devices.

Each measurement series consisted of 60 seconds of data acquisition by both systems (SLR and Calibration device). The calibration data were acquired by a maximum data rate for the Calibration epoch timing unit which is 500 readings per second. Considering the echo signal strength corresponding to a data rate of 3 % it means typically 1000 signal photons have been detected and time tagged in 60 seconds. Recursive "2.2×sigma" data filtering algorithm has been used to process the measured data. The resulting one-way calibration constant related to transmitting part $\boldsymbol{C}$ was calculated from mean value of the measurement series according to eq. (1) as 94.60 ns. The standard SLR ground target calibration constant $\boldsymbol{G}$ was measured 112.26 ns. The resulting receiving part calibration constant $\boldsymbol{F}$ was calculated according to eq. (2) as 17.66 ns. According to the reference [7] the long term reproducibility of the Graz SLR ground target calibration constant $\boldsymbol{G}$ is typically ±0.045 ns over one year of operation. As a first approximation one can estimate that the long term reproducibility of the one-way calibration constants $\boldsymbol{C}$ and $\boldsymbol{F}$ of the SLR station in Graz will be the same or better.

Conclusion

We have identified and calibrated one-way systematic biases in satellite laser ranging systems. A new procedure of calibration of one-way delays related to the SLR systems have been developed and tested. The necessary hardware components needed for calibration measurements were designed, developed and tested both in laboratory and in field operation. As a result the biases related separately to transmitting and receiving parts can be determined with accuracy better than ±20 ps. Thanks to these values the epochs of transmission and reception of optical signals can be referred to the local coordinated time scale with this accuracy. The calibration procedure and related hardware were tested in a real measurement at the SLR site in Graz, Austria.

Acknowledgment

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