

# Advances in laser ranging technology at CTU in Prague for new SLR applications

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## Abstract

We are reporting on recent results in detector and timing technology development for satellite laser ranging and related applications. The laser time transfer ground to space and space to ground is a fast emerging application, which is based on a use of existing SLR ground infrastructure. However it puts new challenging requirements on a ground stations. Along with low timing jitter and high stability the key parameter is the system timing performance characterized by time deviation. We optimized our Start detector, NPET epoch timing system and SPAD photon counter to provide extremely low time deviation. We demonstrated laser time transfer in ground experiment, which provided time deviations better than 0.3 ps for averaging times longer than 200 s. It was based on a standard Graz SLR hardware and a photon counting receiver developed for European Laser Timing project. In addition we did develop new SPAD photon counting receiver for future laser time transfer mission. In first experiments we demonstrated the single shot jitter well below 20 ps (3 mm) rms and the time deviation as low as 80 fs for averaging times of 2000 s. Even lower single shot jitter for single photon signals is expected to be achieved in a near future. This SPAD receiver might be attractive for future Lunar laser ranging as well. For applications in space debris tracking, one way ranging and similar experiments, the one-way delays of existing SLR systems must be determined. We did develop both the calibration hardware and measurements procedures to determine these delays with accuracy reaching  $\pm 20$  ps.

## Introduction

Satellite Laser Ranging (SLR) is a standard and mature measurement technique used in space geodesy and related disciplines since late sixties. Its precision and accuracy is permanently improving and it is reaching millimeters values 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 new applications an additional kind of system characterization is needed. In addition to single shot resolution, station systematic biases and ground target calibration value stability the system performance may be characterized by time deviation TDEV [4]. This kind of system characterization is routinely used in time and frequency community for a long time. Time deviation expresses in one value TDEV a combination of system long term stability, ultimate precision limit and data statistical properties. The time deviation criteria and its application in SLR were described previously on the 17<sup>th</sup> Workshop [5].

The TDEV performance is a key parameter for all the laser time transfer missions, among others. Both the short term (within one satellite pass) and the long term performance are of interest. For the operational space mission the TDEV performance within one pass of the laser time transfer mission is as follows: Compass LTT is providing the TDEV  $\sim 20$  ps @ 500 s, the T2L2 timing performance is typically 10 ps @ 200 s. For the laser time transfer mission European Laser Timing (ELT) the performance 3 ps @ 100 s is required. The pre-launch tests indicate that this value should be achievable with a great margin.

The time deviation may be used to characterize the SLR system long term stability, as well. On Figure 1 there is a TDEV of the ground target calibration one way propagation time of Graz SLR.

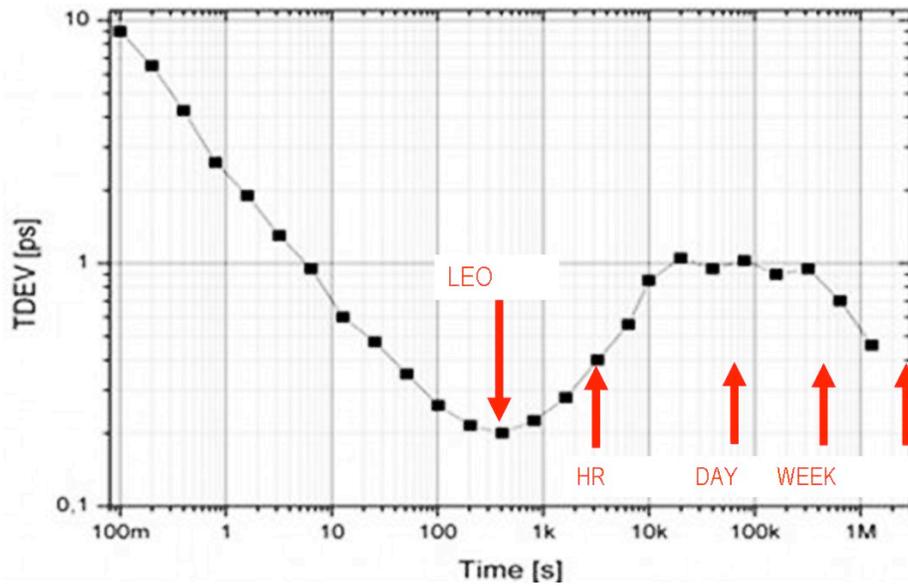


Figure 1: TDEV one way delay, ground target calibration Graz, the first half of 2013.

The graph was created combining a ground target calibration raw data over one hour and calibration mean values of series acquired in a first half of 2013. One can note the system long term stability in a sense of TDEV <1 ps over an integration time from several seconds to months. The TDEV requirements of laser time transfer mission under preparation are even more ambitious. The sub-ps values are required. Considering the new application – laser time transfer ground to space – and its requirements new SLR technology components for the ground segment have been developed and tested.

### New SLR technology

The new and/or modified components of the SLR ground seg. have been developed and tested:

**Start detector** – The compact electro-optical switch acting as a fixed threshold detector and discriminator is providing the single shot jitter lower than 1 ps, temperature drift lower than 0.5 ps. The device concept, compact design, RF insensitivity and ultrafast output pulse fall times (<100 ps) enable the top performance [6]. Its contribution to the TDEV is significantly lower than 50 fs.

**Epoch timing system** – The latest version of the New Pico Event Timer (NPET) was used for all the timing measurements [7]. The performance of this device is superb: timing jitter and timing non-linearity are typically <1 ps per channel, temperature drift is better than 0.5 ps/K, the performance in a sense of TDEV is better than 30 fs over measurement times of minutes up to hours. The limiting precision TDEV is as low as 6 fs @ 2000 s. All the values listed were measured for asynchronous events.

**Photon counting SPAD detector package** – The active quenching and gating circuit of the SPAD detector package – single photon version – was “tuned” with a goal to further increase its timing stability and TDEV performance. The new circuit is based on the fastest available components. The electrical scheme was modified to minimize the number of active components within a signal path. The same design philosophy was used in a construction of the photon counting detectors for the space segment of laser time transfer.

The performance of all the components listed above was tested in a series of indoor tests. As a laser source the Hamamatsu diode laser providing 40 ps long pulse at 789 nm wavelength was used. The pulse length of this laser is significantly longer in comparison to the lasers used by the best SLR systems recently (typically 10 ps long pulses). The signal cables having compensated temperature delay drift were used in all the experiments. In all the experiments the optical signal strength was on a single photon level. It was maintained by a useful signal rate typically 4–8 %. The example of measurement results of an indoor test of the laser ranging is in Figure 2.

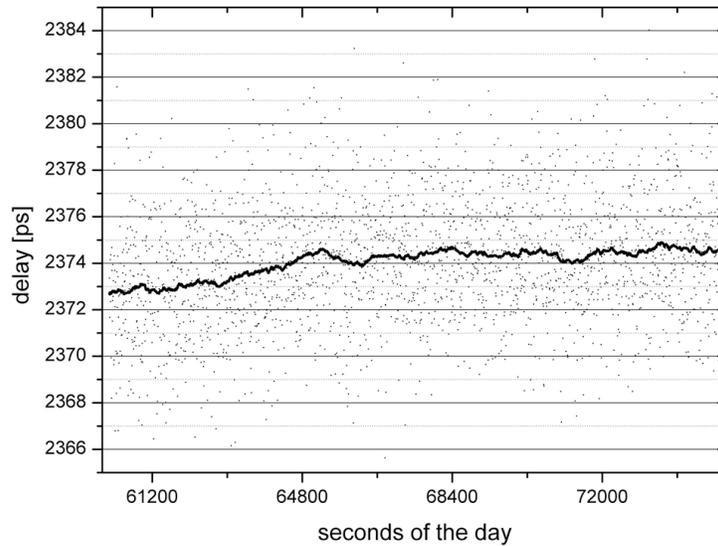


Figure 2: Long term stability of the entire laser ranging chain consisting of SPAD detector package (single photon, ver. 2014), NPET timing system and a electro-optical switch starting with Power ON warm up phase.

The experiment was completed under normal laboratory conditions, the temperature was within  $\pm 1$  K. The single shot jitter was typically lower than 20 ps rms. It was limited mostly by a laser pulse length. Its contribution to the overall timing jitter is 17 ps rms. The data were acquired immediately after Power On of all devices. One can recognize the warm up phase which took about one hour after Power On. Note the warm up delay change of 2 ps and the long term stability better than  $\pm 500$  fs over 3 hours.

The ultimate system performance in a sense of TDEV was tested in a similar experiment which lasted one day. The Power On phase was not included in data. The result in a sense of TDEV is plotted in Figure 3. The results plotted in Figure 3 demonstrate an ultimate precision of a complete laser ranging signal chain better than 100 fs for averaging time longer than 1000 s. In addition the excellent long term stability better than 100 fs over several hours was demonstrated. Both the previous results were acquired in laboratory conditions.

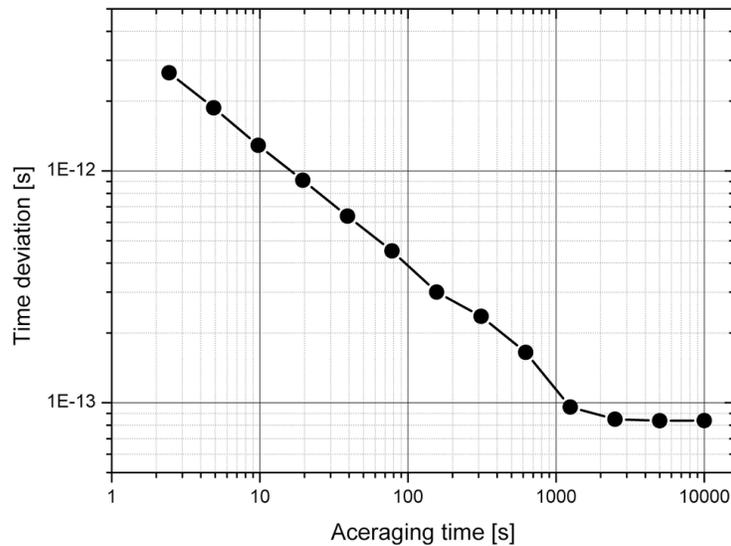


Figure 3: Timing performance of the entire laser ranging chain (SPAD 200  $\mu$ m, Start, Ham. laser, NPET, 1 kHz) expressed as Time deviation TDEV. Note TDEV < 100 fs for averaging times 1000 s to several hours.

During our calibration mission to Graz we have tested also the performance of the complete laser time transfer ground to space hardware chain. The ground segment was represented by Graz SLR in its standard configuration (10 ps laser, 532 nm, 2 kHz, Electro-optical switch Start device, GrazET timing). The space segment was represented by ELT photon counting detector package Engineering Model of the flying unit, the timing device was represented by NPET epoch timing system. The data were collected at the rate of 500 Hz, it was limited by the data acquisition system of the space segment hw. The results in a form of TDEV are plotted in Figure 4.

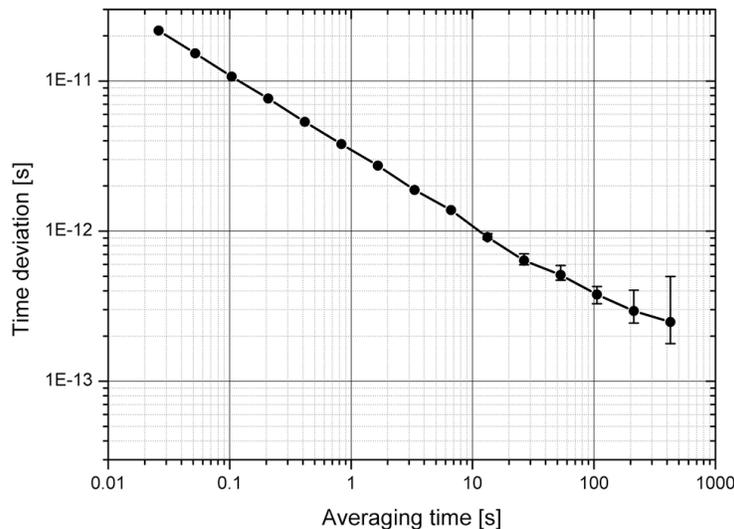


Figure 4: Laser time transfer demonstrated at Graz SLR, real field conditions. Note TDEV <250 fs for averaging times 400 s.

One can note the value TDEV < 300 fs for 200 s averaging time. It is worth to mention that this ultimate precision is valid for the entire measurement loop consisting of the SLR system part and of the simulator of a space segment part. Significant contribution comes also from radiofrequency interference, timing stability and others. Even better results are expected in the same experimental configuration when acquiring data at a rate of 2 kHz.

## Conclusion

We optimized our Start detector, NPET epoch timing system and SPAD photon counter to provide extremely low time deviation TDEVs. We demonstrated laser time transfer in ground experiment, which provided time deviations better than 0.3 ps for averaging times longer than 200 s. It was based on a standard Graz SLR hardware and a photon counting receiver developed for European Laser Timing project. In addition we did develop new SPAD photon counting receiver for future laser time transfer mission. In first experiments we demonstrated the single shot jitter well below 20 ps (3 mm) rms and the time deviation as low as 80 fs for averaging times of 2000 s. Even lower single shot jitter for single photon signals is expected to be achieved in a near future. This SPAD receiver might be attractive for future Lunar laser ranging as well. For applications in space debris tracking, one way ranging and similar experiments, the one-way delays of existing SLR systems must be determined. We did develop both the calibration hardware and measurements procedures to determine these delays with accuracy reaching  $\pm 20$  ps.

## Acknowledgment

This work has been carried out at the Czech Technical University (CTU) in Prague with a support of research framework RVO 68407700. We are acknowledging project DFG: FOR1503.

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