Calibration of SLR System Delays for the European Laser Timing Reaching 20 ps Accuracy

Ivan Prochazka*, Jan Kodet*‡, Josef Blazej*, K. Ulrich Schreiber‡, Johann Eckl‡

* Dept. of Physical Electronics, Czech Tech. University in Prague, Prague, Czech Republic
‡ Forschungseinrichtung Satellitengeodäsie, Bad Kötzting, Germany
e-mail: prochazk@cesnet.cz

Abstract

Recently the European Laser Timing (ELT) experiment is under preparation. It is an optical link prepared in the frame of the European Space Agency (ESA) mission "Atomic Clock Ensemble in Space" (ACES). The objective of this laser time transfer is the synchronization of the ground based clocks and the clock on board the International Space Station with precision of the order of units of picoseconds and the accuracy of 50 ps. The technique is relying on the existing ground based infrastructure used for satellite laser ranging (SLR). In order to reach the ultimate precision and accuracy the SLR ground systems participating in time transfer have to be properly calibrated for this purpose. The new tool "ELT Calibration Device" has been developed. It consists of an optical detector package, which is a "twin" of the flight module of the ELT detector operating in space, the second one is a picosecond timing system. The Calibration Device is planned to be operated successively on the participating SLR stations to characterize the ground segment timing performance prior to the mission launch. The first calibration results have been acquired at the SLR system WLRS at Wettzell March to May this year. The overall SLR system and Calibration Device epoch timing stability and reproducibility of 20 ps have been achieved. The calibration procedure and results will be described in detail.

1. European Laser Timing experiment

The European Laser Timing (ELT) experiment is under construction now. It is an optical link prepared in the frame of the European Space Agency (ESA) mission "Atomic Clock Ensemble in Space" (ACES) [1]. The objective of this laser time transfer is the synchronization of the ground based clocks and the clock on board the International Space Station with precision of the order of units of picoseconds and the accuracy of 50 ps. The laser time transfer ground to satellite is an extension of the standard measurement technique of satellite laser ranging (SLR) [2].

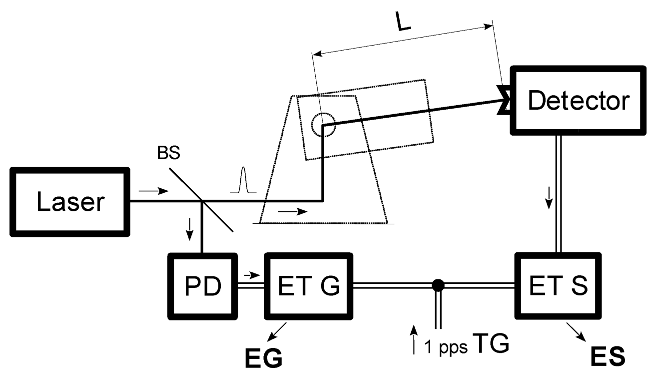

Fig. 1: Principle of the ELT system delays calibration. The "Detector" and ET S represent the ELT Calibration Device the rest corresponds to the SLR system.

2. ELT Calibration Device

The laser time transfer technique is relying on the existing ground based infrastructure used for satellite laser ranging. In order to reach the ultimate precision and accuracy the ground systems participating in time transfer have to be properly characterized – calibrated for this purpose. The new tool "ELT Calibration Device" is currently under construction. The device is a "twin" of the flight module of the ELT detector operating in space. It is planned to be operated successively on the participating SLR stations to characterize the ground segment timing performance prior to the mission launch. The calibration principle is plotted in Fig. 1.

Considering the experiment setup the calibration constant B for ELT related to the particular ground station can be evaluated as

$$B = L/c - (ES - EG) \tag{1}$$

where L is a separation of reference points, c is a group speed of light, ES and EG are the epoch readings of Even Timers. The distance L is of the orders of meters, it can be determined with accuracy better than one millimeter (3 ps). The accuracies of the Event Timers are of the order of units of picoseconds. Hence the accuracy of determining the calibration constant B well below 5 ps should achievable for this part of the setup. Considering the ELT principle and its systematic errors other contributors, one can conclude, that the resulting systematic errors of ELT of the order of tens of picoseconds is achievable.

3. ELT Calibration campaign at Wettzell Laser Ranging Station

To check and optimize calibration procedures and to complete a series of calibration tests of the breadboard of the ELT Calibration Device the calibration scheme described above has been tested at the Wettzell Laser Ranging Station (WLRS) March to May 2014.

The Wettzell Laser Ranging System (WLRS) has been upgraded for this experiment: the New Pico Event Timer (NPET) [3] timing system was installed next to the standard WLRS timing unit. The reason for this upgrade was the NPET capability to be synchronized to the local time scale with picosecond precision. The WLRS NPET data will be used for ELT laser fire epoch time tagging. The routine SLR operation will be performed using a standard WLRS timing device setup.

4. ELT Calibration Experimental setup

The ELT detector package Engineering Module (EM) was representing an ELT Calibration Device detector. It was installed in front of the WLRS telescope, see Fig. 2. The New Pico Event Timer (NPET) [3] timing system representing an ELT Calibration Device timing system ET S was installed next to it in a telescope dome.

Fig. 2: The ELT detector package EM installed on a tripod in front of the WLRS telescope.

The frequency reference for both SLR and ELT Calibration Device timing systems was provided by a station frequency master reference 5 MHz. For timing devices this frequency was multiplied using a common 5/200 MHz Frequency Multiplier by Thales Dassault. This Frequency Multiplier is installed next to the SLR timing system in a control room. To deliver the multiplied frequency to the dome the cable RG214 21 m long was used. The timing reference represented by a local "1pps" signal was connected consecutively to both timing system using identical cable Time Microwaves LRM240 of the approx. length of 21 meters.

The Calibration Device timing system NPET was interfaced via a RS232 cable to the control room. The experiment control and data collection was performed on a control PC using a dedicated set of programs and graphical data interface developed for this purpose.

The WLRS laser transmitter pulse length is typically 8 ps at the wavelength of 532 nm. For calibration purposes the laser output energy was kept at a level well below 3 μJ, which is the minimum pulse energy measurable with the used energy-meter by tuning the laser pump delay to higher pump-start times. In our setup this energy resulted in a single photon detected signals and a data rate typically < 10 %. This return data rate assures the single photon echoes.

5. ELT Calibration Device performance tests

The histogram example of measured echoes is plotted in Fig. 3. The raw data are plotted. They have been filtered using a recursive filtering algorithm eliminating the outliers out of "k × sigma" band. According to standard procedures used in SLR community in connection to the solid state photon counters the filtering procedure using a 2.2×σ has been applied.

In Fig. 3 one can note the measurements precision of 20 ps rms. The ultimate precision in a sense of time deviation TDEV was computed from the same series of measurements containing about 1000 valid data readings, see Fig. 4.

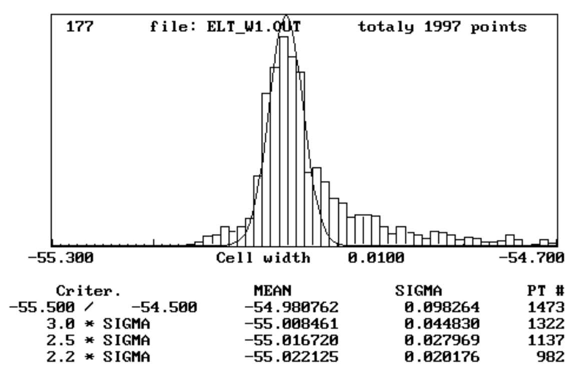

Fig. 3: Example histogram of measured echoes, calibration series lasted 700 seconds in this case.

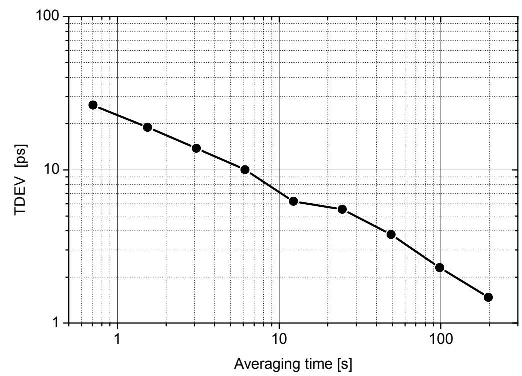

Fig. 4: European Laser Timing performance tests at the Wettzell satellite laser ranging system, ground tests results. The laser rate was 20 Hz, the useful signal data rate was 7 %. The precision below 3 ps for averaging time of 100 seconds may be seen.

In all the next standard calibration series typically 150 valid echoes per calibration were collected. This number of echoes has been selected to simulate estimated number of valid on-board ELT epoch readings in one ISS pass (about 100 s of stable tracking, mean data rate of 7 %, Wettzell SLR system operating at a repetition rate of 20 Hz).

System overall timing resolution and stability check was performed within 3 hours. The results are summarized in Fig. 5. One can notice the stability of the mean values within ±1 ps half peak to peak. This value corresponds to the statistical uncertainty of the data and demonstrates the delay stability of the ELT Calibration Device. The dynamical range was tested in a series of experiments, in which the signal strength was changed by changing a laser output power. The results are summarized in Fig. 6.

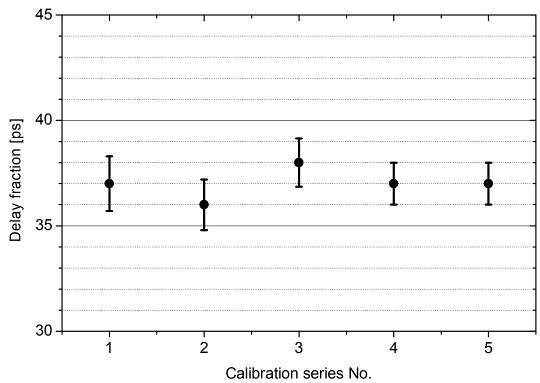

Fig. 5: The ELT calibration stability tests, the calibration series were collected within 3 hours.

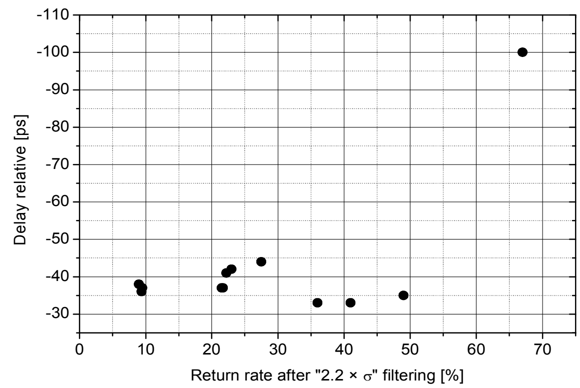

Fig. 6: Relative detection delay as a function of signal strength.

Relative detection delay is plotted as a function of signal strength. The signal strength is represented by a data (“return”) rate. The rates below 10 % represent pure single photon signals. From Fig. 7 one can conclude that even for data rates reaching 50 % the detection delay is constant within ±10 ps. This is caused by the “2.2×σ” filtering algorithm applied in data processing. Rather aggressive data editing algorithm eliminates, among others, also the sparse data points corresponding to multi-photon echoes. This fact will greatly simplify the real measurements once the return rates up to 45 % percent might be tolerated.

6. ELT Calibration results

To proceed the calibration procedure the geometrical distance L of the detector reference point from the SLR system invariant point was measured, see Fig. 2. The detector invariant point was represented by a pin located at the place of fixing screw of the detector package. The holder for detector is constructed in such a way, that the fixing hole is below an invariant point with the accuracy better than 0.2 mm. The distances were measured repeatedly by different observers and using two different scales. The resulting distance was

$$L = (2302 \pm 1)\ \text{mm} \tag{2}$$

what corresponds to a one way propagation delay

$$DT = (7673 \pm 3)\ \text{ps} \tag{3}$$

The full ELT calibration experiment was performed next. The time scales of the SLR and ELT epoch timers were set up consecutively using an identical cable. The time scales were synchronized using averaging over 32 consecutive “1pps” pulses. The timing jitter of “1pps” signal was typically 14 ps rms. The setting procedure based on averaging assured the time scales setting precision on 3 ps level. The calibration series consisting of ~150 valid single photon echoes were completed repeatedly within the period March 19 to May 7 2014. Both the time scales were re-synchronized daily and/or each 3 – 4 calibration runs. The epochs differences (ES−EG) are plotted in Fig. 7. In this figure the jumps of the epoch differences in

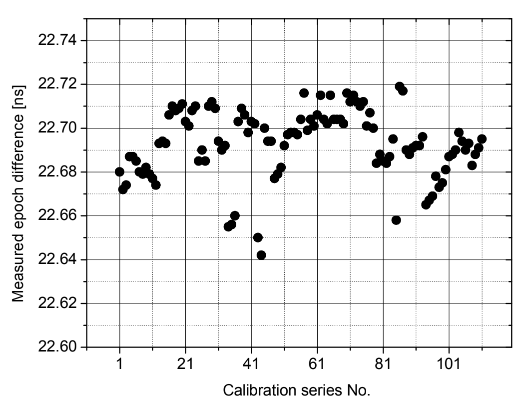

Fig. 7: The ELT calibration experiment results – epoch differences (ES−EG) as measured over a period of two months.

a range of 5 to 60 ps may be seen. It is expected that this effect was caused mainly by a difference in time scales setting. The “1pps” cable delay variations due to mechanical stress on a cable within its re-installations are expected to be responsible for this effect.

7. Results summary

The epoch readings differences within one group of measurements were stable within a statistical spread of 1 – 2 ps rms. The overall spread of mean values was ±13 ps rms and 24 ps half peak to peak when considering all the 110 measurement series over a period of two months of sparse operation. Most of the SLR station operation time was allocated to routine SLR measurements. The mean delay value (ES – EG) = (22.695 ± 0.013) ns. The geometrical distance L of reference points of SLR and ELT of (2302 ± 1) mm was measured what corresponds to a one way propagation delay DT = (7673 ± 3) ps. The ELT calibration constant calculated as a difference of epoch difference and one way propagation delay was determined:

$$B = (15.279 \pm 0.013)\ \text{ns} \qquad (4)$$

The main contribution to the error is expected to be caused by the “1pps” cable delay variations due to mechanical stress on a cable within its re-installations.

8. Conclusion

The first field demonstration of the ELT Calibration Device was performed. The concept of the Device and the performance of its hardware components: ELT detector package, epoch timing system and of the process control, data acquisition and analysis software package was proved. The overall system delay stability is on the 1 ps level, the resulting accuracy worst case estimate is well below 15 ps rms. This performance will enable the operation of ELT Calibration Tool and provision of ground – ground time transfer accuracy better than 25 ps.

Acknowledgment

This work has been carried out at the Czech Technical University in Prague. Numerous grants were provided by the Czech Grant Agency, Czech Ministry of Education and by international agencies. Recently, the research and development of time transfer technologies is supported by MSMT CR grant LH12005. The support of the Fundamental Station Wettzell, Germany, operated jointly by Federal Bureau of Cartography and Geodesy and the Technical University Munich is highly appreciated.

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