Technical Note

ESA P3-SST-I

Work Package: WP4210 Validation of passive-only bi-static SLR

Calibration campaign at Potsdam Satellite Laser Station

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Goals

Three main goals were specified in the Work package WP4210:

- Calibration of SLR station Postdam, Germany for passive-only laser tracking of orbiting space debris in bi- and multi-static arrangements,
- Testing of the existing calibration procedure in a new station configuration,
- Validation of the system via comparison of the results with an independent delay determination based on data acquired in laser time transfer space mission T2L2 with nanosecond resolution calibrate the SLR station in Postdam, Germany.

General

The technique of determining the one-way calibration constants of the Satellite Laser Station (SLR) was applied for its use in bi- and multi-static laser tracking of orbiting space debris at the satellite laser station in Potsdam, Germany. The dedicated Calibration Device has been used for measurements. The method and experiment are extensions of their analogy of measurement of system delays for laser time transfer in the European Laser Timing project. The experiment was completed May 20 – May 25, 2019.

Calibration Device Principle

To characterize the ground segment one way delays the following approach for the calibration of system delays was developed. The method is based on a presumption, that all the ground stations participating will be calibrated versus a dedicated set consisting of the photon counting detector, epoch timing system and signal cable. These components form the Calibration Device. The calibration principle is plotted in Fig. 1.

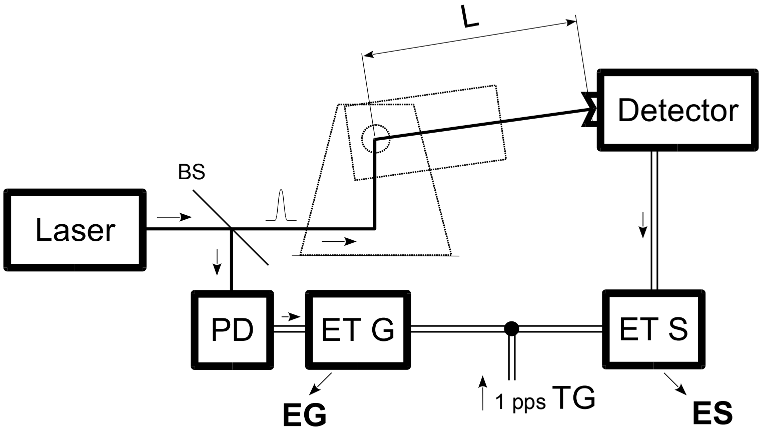

Figure 1. Block scheme of calibration of the laser time transfer ground segment by means of Calibration Device.

The *Detector* in Figure 1 is a twin of a photon counting detector developed for ELT project. Its photon to electrical signal delay ***Dd*** was determined with accuracy better than 15 ps. Both the Event Timers (ETS and ETG) are synchronized to a common time scale and clock frequency. One common signal cable for "*1pps*" has to be used to synchronize the Event Timers *ETG* and *ETS* 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 of the Calibration Device is constructed in such a way, that it accepts all possible triggering configurations used on various SLR ground stations. The calibration constant ***B*** related to the particular ground station can be evaluated as

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

Where B is the calibration constant, L is the separation of reference points, c is a group speed of light, ES and EG are the epoch readings of Even Timers of the ground and space segment respectively.

To determine the absolute delay ***C*** related to a particular ground system additional information is needed - namely the detection delay of the detector ***Dd*** and a delay of the signal cable ***Dc*** interconnecting these two devices forming the Calibration Device.

$$\boldsymbol{C = B - (Dd + Dc)}$$

The delay constants ***Dd*** and ***Dc*** were determined in a Calibration Device assembly phase with an accuracy of ±15 ps.

The calibration constant ***C*** is expressing a difference between the laser fire epoch reading ETG and epoch, when the laser pulse center of mass is crossing the system invariant point.

Test hardware

The experiment was carried out using the photon counting detector package with calibrated optical to electrical delay, the Epoch Timing unit, calibrated delay cable and a set of calibrated connectors and signal converters. The SLR system under test was the standard configuration of Potsdam SLR system. The experiment setup is illustrated in Figures 2a and 2b.

Figure 2a. Calibration Device detector package installed in a dome in front of the Potsdam SLR system transmitting telescope close to the system ref. point.

Figure 2b. Calibration Device components: Epoch Timing device (black box), oscilloscope and control and data acquisition PC.

The detector of the calibration Device was installed in a position in which its reference point coincided with the SLR system reference point.

Main parameters of the SLR system

Station name and ID		POT3
Laser	wavelength	532 nm
	nominal rep.rate	2 kHz
	energy / pulse	700 uJ
	beam divergence range	4 to 40 arc seconds
Time ref.	"1pps"source	GPS
	pulse (amp.,slope, slew r.)	TTL on 50 Ohms, see next

Freq. ref.	frequency	10 MHz
	source	GPS, Cs beam std.

Time reference “1pps”

The timing signal 1pps was delivered by identical cable consecutively to Calibration Device and to the SLR system to complete their time scales settings. The shape of the pulse leading edge is on Figure 3.

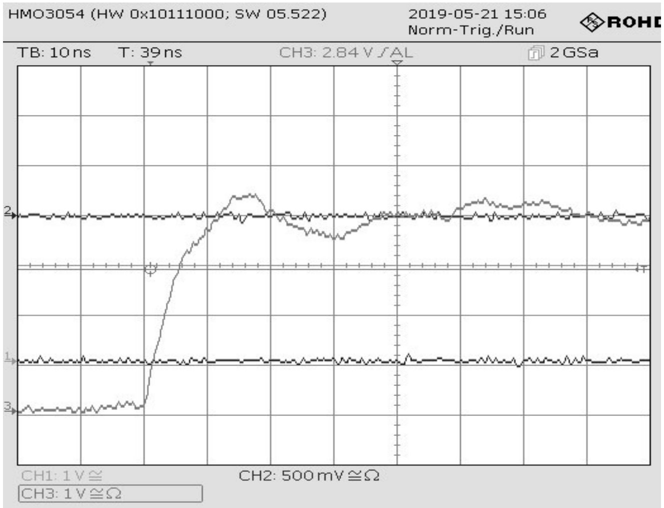

Figure 3. Time signal “1pps” on the input of the epoch timing devices used, signal slew rate is 0.500 V/ns for trigger level in a range of 0.7 to 2.7 Volts.

In Fig 4a. the timing stability of 1PPS signal with respect to the reference clock frequency as determined by the Calibration Standard is illustrated. The same data were used to characterize the stability using the Time Deviation TDEV in Figure 4b.

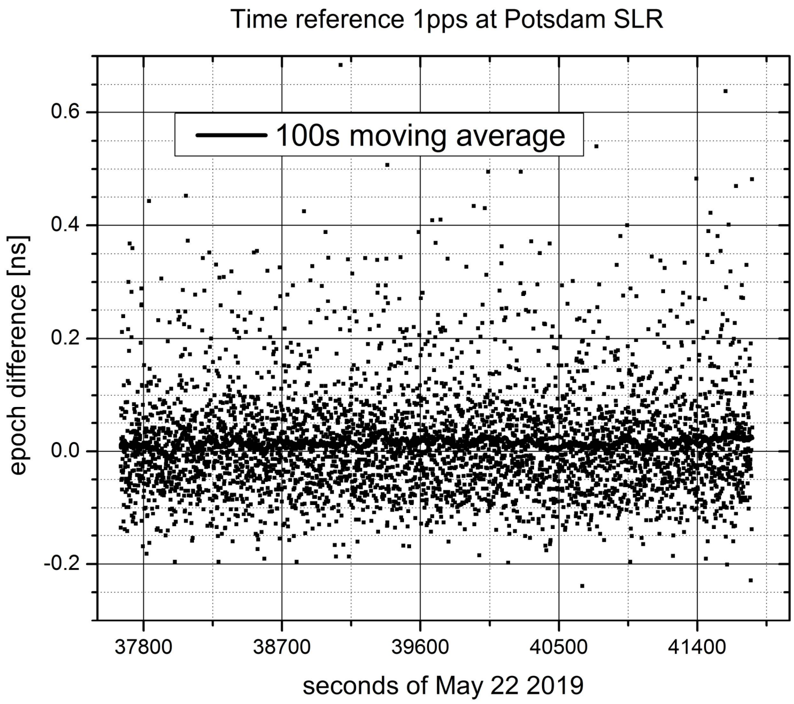

Figure 4a. 1PPS delay stability.

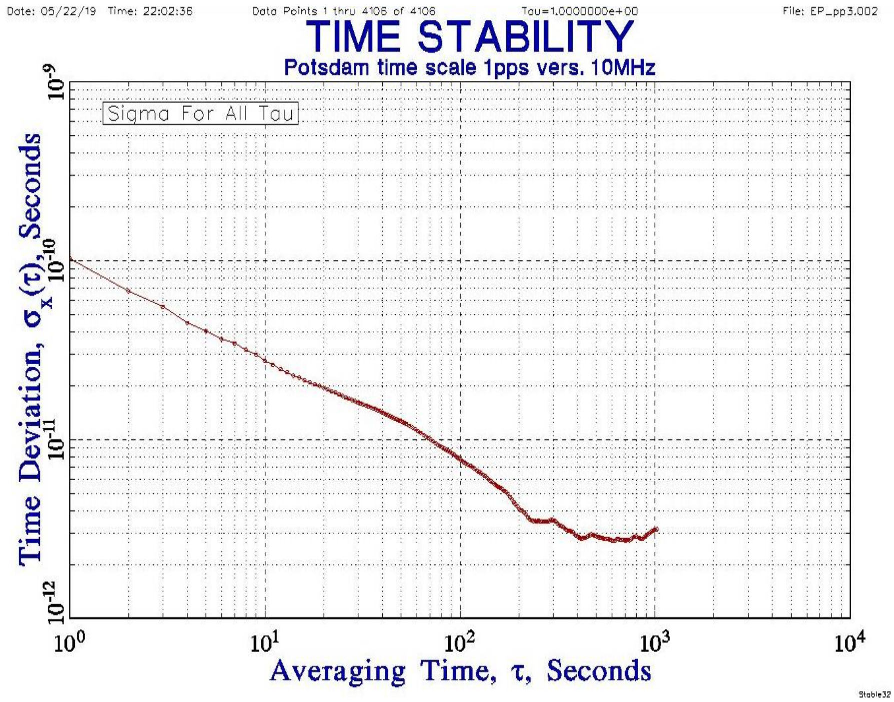

Figure 4b. 1PPS delay stability expressed in a form of Time Deviation, note the saturation at ~ 3 ps for averaging times longer than 200s.

From Figure 4b one can conclude that synchronizing the local time scale by a single "1pps" pulse might result in a systematic error / bias of typically 100 ps RMS. Averaging over many pulses will reduce this bias down to a few ps level. Before the calibration series the Calibration Standard was synchronized and the time scale defined by "1pps" averaged over 16 consecutive pulses. This approach reduced the epoch timing systematic bias well below 30 ps on the Calibration Standard side.

The actual trigger level of the SLR epoch timing system A033 is not known and was not measurable within the mission. Considering the analogy to similar systems (Zimmerwald 1, 2) the trigger level is expected to be in a range of +1.00 to +1.50 Volts. For calibration purposes the Calibration Device trigger level for "1pps" input was set to +1.00 Volts. The systematic error caused by a trigger level difference +/- 0.25 V corresponds to +/- 0.5 ns considering the 1pps pulse leading edge slope, see Figure 3.

Measurement procedure

Location and survey

The detector package was installed in front of the SLR system transmitter telescope on its optical axis. The distance of its reference point to the SLR system invariant point has been determined to be 0.00 +/- 0.01 m.

The non-standard configuration of Potsdam SLR tracking mount and telescopes requires modified approach to local survey and corresponding data processing. Although the calibrating detector package was installed close to the SLR system invariant point for our application - passive only bi-static laser ranging - the additional correction has to be applied. The effective distance of the detector to the transmitting / receiving telescopes invariant points is equal to 1.04 +/- 0.01m. This value is one half of the transmitting to receiving telescopes axes distance 2.07m.

Detector gating

The calibration instrument was gated from the SLR system at a 2 kHz rate. The detector was activated ~800 ns before photons of interest arrival. The laser was operated at its standard rate of 2 kHz.

Optical signal strength

The optical signal strength has been adjusted to standard SLR calibration output power value. The valid echo data rate was adjusted by detector geometry and obscuration to a value of 10%.

Time scales settings

The cable “1pps” was connected to the Calibration Device input via BNC/SMA convertor having an additional delay 96 ps. Considering the time scale setting uncertainties listed above, this value was neglected in next calculations.

Data acquisition and processing software

The SLR data acquisition and processing software was modified to preserve 12 significant digits of fractional part of second of the laser fire epoch. The resulting data were stored in a form of two column ASCII file containing integer and fractional part of epochs of recorded fires of the laser.

For the Calibration Standard the original data acquisition and processing software developed for European Laser Timing calibration was used. This software package was developed and tested at CTU in Prague and on several calibration missions of SLR systems within the last 5 years.

Setup performance

Each measurement series consisted of 100 to 600 seconds of data acquisition by both systems. The SLR data were acquired by 2 kHz, the calibration data were acquired by a maximum data rate for the Calibration Device which is 500 readings per second. Considering the echo signal strength corresponding to a data rate of a few percents it means typically several hundreds to several thousands of signal photons have been detected and time tagged in one series. The recursive “2.2 * sigma” data filtering algorithm has been used to process the measured data. This filtering algorithm is a standard one for processing of photon counting data acquired with a SPAD detector at 532 nm wavelength.

Results

Totally four valid data series were completed May 22 and May 23.

May 22, time scales settings of Calibration Device and SLR

Series # 1	mean -123.387 ns
Series # 2	mean -123.381 ns

May 23, time scales settings of Calibration Device and SLR

Series # 3	mean -123.502 ns
Series # 5	mean -123.487 ns

The example of the calibration data distribution acquired at the Calibration Standard is on Figure 5. The 2.2*sigma iterative data editing procedure was used. This editing criteria is standard for SLR data acquired with a SPAD based photon counting detectors. The complex non-gaussian data distribution is caused by the used detector.

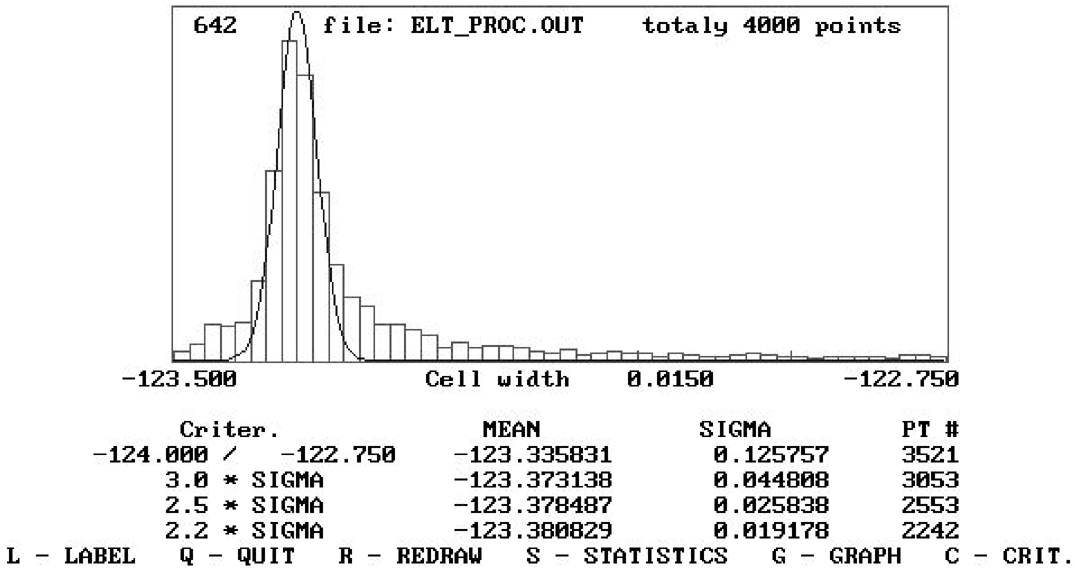

Figure 5 Data distribution of Series # 2

The single shot resolution of 19 ps RMS is well corresponding to the SLR system standard performance, laser pulse length etc. It fits also perfectly to calibration results acquired at other SLR systems (Graz 18 ps, Herstmonceux 20 ps, Wettzell 18 ps).

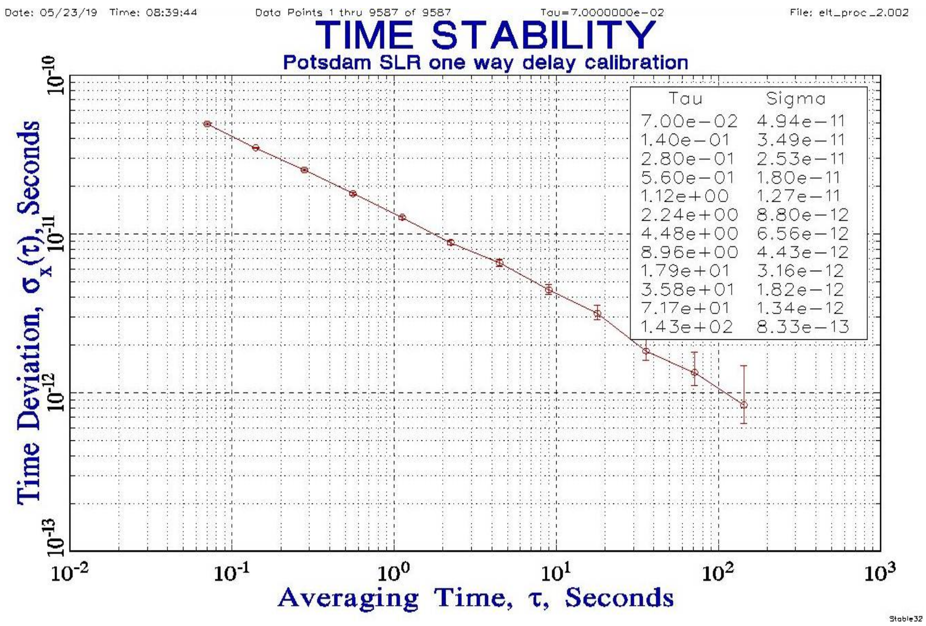

Figure 6 Example of data stability in form of Time Deviation TDEV, note TDEV < 1ps for averaging times longer than 100s.

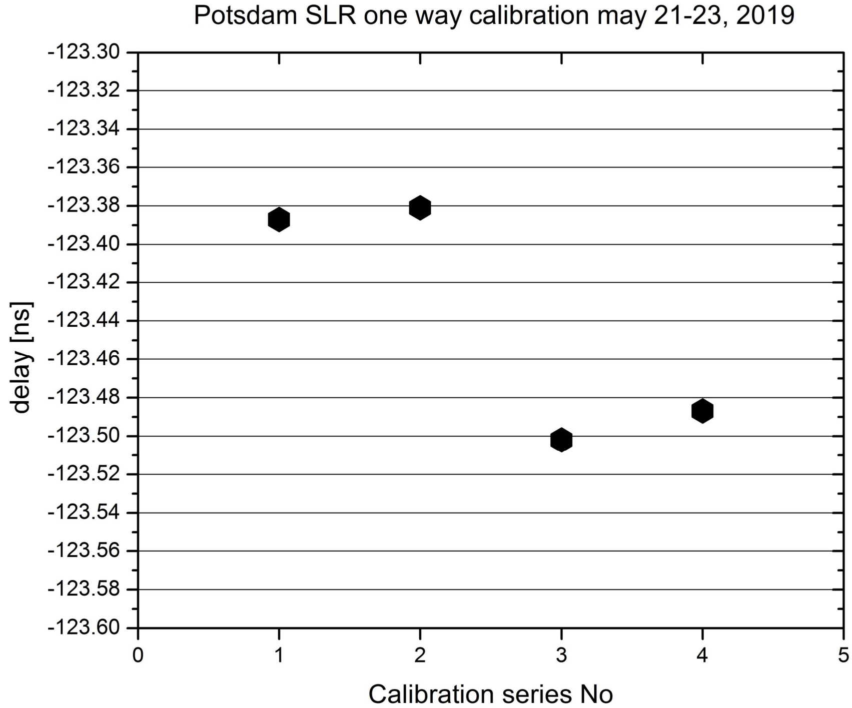

Figure 7 Calibration series mean values for valid series No 1 to No 4.

The reproducibility of calculated delays of series #1 versus # 2 and #3 versus #4 illustrate the overall stability of both the SLR and Calibration Device systems. The reproducibility is 5 ps RMS. The jump between series #2 and #3 was caused by re-setting of both time scales. Its value is close to -100ps. As illustrated on Figure 4a and 4b this value corresponds well to the property of a local time scale and way of synchronizing the SLR system time scale.

Calibration value calculation

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

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

where ***L*** is a separation of reference points, ***c*** is a group speed of light, E_{CD} and E_{ST} are the epoch readings of Even Timers of the Calibration Device and a ground station respectively (values see above), ***Dd*** is a photon to electrical signal delay of detector package and ***Dc*** is signal cable delay. The detector and cable delays were measured in a laboratory as 2.11 ns and 7.11 ns respectively.

Used values

$(E_{CD} - E_{ST})$			**- 123. 44 ns**
L / c	1.04 / c	=	**3.45 ns**
$(Dd + Dc)$	2.11+7.11	=	**9.22 ns**
C	-123.439 – 3.45 – 9.22	=	**- 136.11 ns**

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***

$$F = G - C \qquad (2)$$

where ***F*** is a one-way bias related to receiving part, ***G*** is a ground target calibration constant ("two way delay") and ***C*** is a bias related to a transmitting part of the SLR system. The two way ground target calibration constant was determined to be 63.63ns using a standard SLR procedure.

G			**63.63 ns**
F	63.63 – (- 136.11)	=	**199.74 ns**

Comparison of the results

Following the Work Package WP4210 Goals "…definition the validation of the system via comparison of the results with an independent delay determination in laser time transfer space mission T2L2 with nanosecond resolution should be completed…". The Potsdam SLR system mount and telescope(s) design is unique. It is based on a use of independent transmitting and receiving telescopes. The SLR system reference point is different from the one-way ranging passive only one. That is why the calibration constants measurements and results will be different for different system application. Due to this fact the comparison was not done in this case.

The Potsdam station team completed an independent calibration measurement of one-way delays before and after the calibration campaign described in this document. These calibrations were using the independent photon counting detector SPAD, signal cabling of known delays and a standard SLR epoch timing device. The detection delay of SPAD detectors was roughly estimated 5 +/-1 ns. An agreement for the Transmit Delay calibrated with this SPAD and station A033 Event Timer and Calibration Standard to 1 ns was found. Given the facts that the internal delay of the SPAD detector used was estimated with several ns accuracy, several cable connectors were used in the one but not in the other setup and that the SPAD detector was positioned manually the calibration results are considered to be in an agreement within units of nanoseconds.

Conclusion

- The one-way delays calibration of the SLR station in Potsdam has been performed May 21 - May 23, 2019.

- **The transmitting part calibration value "C" is - 136.11 ns**

- **The receiving part calibration value "F" is + 199.74 ns**

- All the calibration constants were determined with a consistency of +/- 0.1 ns. The limiting factor in determining these constants is mostly the local time scale reference pulse "1pps", namely its relation to a local clock frequency source. This value may be significantly reduced down to < 10 ps by implementing the averaging in time scales setting at the A033 epoch timing device in a future.

- In addition a systematic error of fraction of ns may be introduced by a real trigger level of the "1pps" input of the SLR timing unit A033. This level is not known recently. Once the actual trigger level will be known the correction of measured delays might be applied.

- The existing calibration procedure in a new station configuration calibration procedures applied in Potsdam showed a correct operation and expected performance.

- An independent calibration measurement of one-way delay was completed. The calibration result is in an agreement within units of nanoseconds to values listed above.

Potsdam, Prague May 26, 2019