Generic Calibration Test Procedure

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1. Calibration Device Principle

To characterize the ground segment, namely to measure the systematic delays in a laser time transfer ground segment, this approach to calibration of system delays was developed. The method is based on a presumption, that all the ground stations participating in the European Laser Time transfer experiment will be calibrated versus a dedicated set consisting of the photon counting detector identical to the satellite one, epoch timing system and signal cable. These components form a Calibration Device. The calibration principle is plotted in Fig. 1.

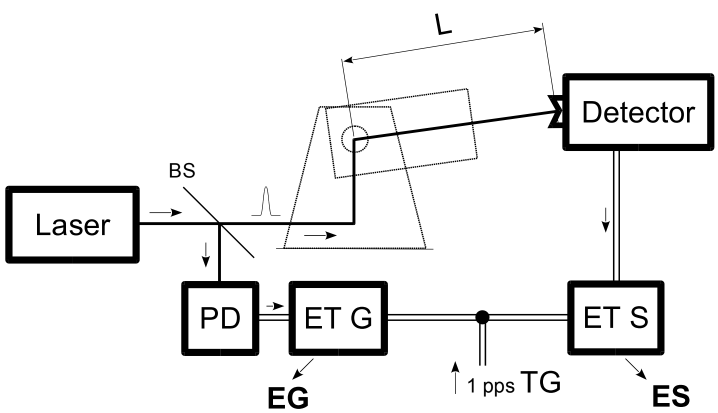


Figure 1. Block scheme of calibration of the laser time transfer ground segment by means of ELT Calibration Device.

The *Detector* in Figure 1 is a twin of a photon counting detector used in space segment. Its photon to electrical signal delay ***Dd*** was determined with accuracy better than 15 ps. Both the Event Timers (ETS and ETG) 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 *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 the possible triggering configurations used on various SLR ground stations. The calibration constant ***B*** for ELT related to the particular ground station can be evaluated as

$$B = (ES - EG) - L / c$$

Where *B* is the calibration constant, *L* is a 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 the 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 ELT Calibration Device.

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

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

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.

2. Generic Calibration Test Procedure

2.1. Satellite Laser Ranging Station Preparation

The minimum requirements on the SLR systems are as follows:

- Capability to perform routinely SLR of space targets of interest.
- Capability to time tag the laser fire epochs with a resolution not worse than 10 ps.
- Capability to generate the results data file in a standard ASCII form, where the first column is an integer second of a day and a second column is a fractional part of a second of fire of the laser
- Capability to fire the laser in pre-defined epochs on a shot-by shot basis with accuracy not worse than 100 ns,
- Time reference of SLR event timing unit in a form of "1pps" pulse, response to a well defined slope and trigger level. Both positive and negative levels and slopes may be used.
- The signal cable distributing the "1pps" signal must be long enough to be connected alternatively to the SLR timing system and to the Calibration Device.
- The available space in front of the SLR system telescope to install and operate the Calibration Device,
- The local time scale frequency source must be common for both SLR and Calibration Device. It means the SLR system must provide the clock frequency. The frequencies of (5) MHz, 10 MHz, 100 MHz and 200 MHz may be accepted by the Calibration Device. The suitable clock signal amplitude is within a range of 0.2 to 2 Volts peak to peak on 50 Ohms.
- The laser transmitter output energy of the SLR system must be reduced to provide on its output the energy density of the order of 1 $\mu J/m^2$ on the transmitting telescope output aperture. This reduction may be accomplished or by adjusting the final amplifier(s) of the laser or by inserting additional ND filters into the output laser beam. The attenuation procedure applied depends on a SLR system configuration. The attenuation procedure must enable fine adjustment of output energy density.

2.2. Installation of the ELT Calibration Device to the SLR site

2.2.1 Installation of the detector package

The Calibration Device detector package has to be installed in front of the SLR system telescope. The location must fulfill the following requirements:

- the installation of device should not restrict normal operation of SLR system,
- flat horizontal surface of minimal dimensions of 200 x 200 mm in front of the telescope for the detector unit,
- it should be located in an elevation close to the elevation of SLR system invariant point (horizontal axis of the telescope mount) with acceptable tolerance of ±100 mm,
- mechanical pin having a diameter of 6 mm and 10-15 mm long has to be installed close to the surface edge as a mechanical and geometrical reference,
- distance of the device from the SLR should be as small as possible, distance shorter than 5 meters is recommended to simplify the survey of distance(s),
- the detector will be oriented in a horizontal plane in such a way that the laser beam from the SLR system under test will hit its input optics under the angle of 45 degrees,
- The example of installation of the device at the SLR station in Graz is in Figure 1.

Figure 1 The Calibration Device installed in a dome in front of the Graz SLR system. SLR system telescope (right top), detector (black, top center), Calibration Device Timing unit (top, left), process control and data acquisition PC (low left).

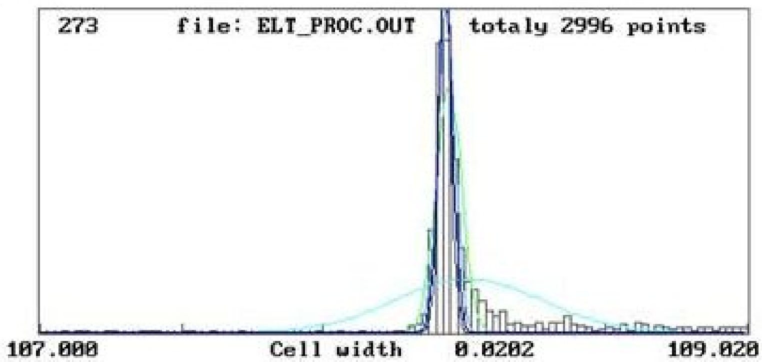
2.2.2. Installation of the timing electronics and control PC

- flat horizontal surface of minimal size 400x600 mm in a distance shorter than 1 meter from the detector unit for installation of timing electronics,
- available working space for a control PC,
- installation of devices should not restrict normal operation of SLR system,
- AC power (90.. 240 V, 50-60 Hz, 100 VA) must be available,

- signal “1pps” via coaxial cable common for both SLR and timing systems consecutive synchronization must be available,
- clock signal common for both SLR and Cal. Device timing systems, frequencies of 5 MHz, 10 MHz, 100 MHz and 200 MHz, amplitude within a range of 0.2 to 1 Volts peak to peak on 50 Ohms must be available,
- the Calibration Device will be assembled – the signal cables connecting the detector package with the timing system and the clock signal will be installed, the detector power and gate cable will be installed, the timing system and control PC will be interfaced via RS232/USB converter,
- prior to the connection of the clock signal to the Calibration Device the clock signal has to be checked on a wide bandwidth oscilloscope (amplitude, frequency, spurious spikes etc.).
- service oscilloscope will be connected to monitor the detector (positive) output signal,
- The Calibration Device timing system will be adjusted, namely its trigger slope and trigger level of channel IN2 (used for “1pps” signal connection) will be set to the values identical to that ones of the SLR system under test.
- Prior to the connection of the “1pps” signal to the Calibration Device it must be checked on a wide bandwidth oscilloscope (amplitude, frequency, spurious spikes etc.)
- AC power will be connected to timing system and a control PC.

2.2.3. Calibration tests and fine setup tuning procedures

- calibration software package will be enabled in a control PC,
- the alibration Device will be synchronized to the local time scale, the hr:min:sec will be obtained from GNSS timing receiver, the device internal timer will be synchronized using the "1pps" signal,
- the generation of detector gate signal with a rate of 100 Hz will be activated,
- the detector package output signal corresponding to a dark and background count rate will be checked,
- the detector package dark count rate will be measured and the phase of the gate signal (the delay of the gate signal after each integer second) will be measured and reported to the SLR crew,
- under standard operating conditions – no direct sunlight hitting the detector input aperture – the dark count rate should be lower than 1 MHz, typically 0.3 to 0.6 MHz,
- the laser transmitter of the SLR system will be activated,
- the laser transmitter will be triggered with the phase determined in steps described above,
- the transmitted laser beam will be pointed to the detector package input optics,
- the detector output signals on the oscilloscope should indicate the laser signals,
- the intensity of received optical signal will be tuned roughly by additional attenuation of the laser output power, fine attenuation will be accomplished by adjusting the laser beam incident angle on the detector,
- Calibration series will start, see next for details
- Calibration data collected both by Calibration Device and by SLR system will be processed,
- the effective data rate obtained in calibration series will be evaluated on a basis of acquired data sets, using an optical signal strength fine tuning the effective data rate will be adjusted within a range of 3 to 10 % to assure pure single photon echo signal strength,
- The distribution of recorded epoch difference will be plotted in a for of histogram, the data spread will be evaluated applying "2.2 * sigma " recursive editing process,
- Program PHISTF with parameters *epoch1.out, 3, 3* should be used for this procedure. The example of the histogram plot is in Figure 2.



Criter.	MEAN	SIGMA	PT #
107.000 / 109.020	108.225716	0.207510	1287
3.0 * SIGMA	108.165810	0.036343	1030
2.5 * SIGMA	108.158920	0.024069	909
2.2 * SIGMA	108.156059	0.019584	831

Figure 2 Histogram of measured epoch differences in series No. 10, Graz, August 2015. All epochs are in ns. Note the measurement overall jitter of ~20 ps rms.

- is necessary the setup fine tuning and calibration series will be repeated until the requirements on data rate and precision are fulfilled,

2.2.4. Determining the ELT detector package distance L

- The distance **L** of the ELT detector package and the SLR invariant points must be measured.
- The ELT invariant point is located just above the “6mm pin” on the detector location plate.
- The survey has to be completed several times by two independent operators and using two (or more) different scales.
- Detailed record of this survey procedure must be created. This record must be included into the final report.
- The final value of **L** will be computed as an average of obtained values. The measurements are considered acceptable once the spread of independent measurements is within ±1 mm peak to peak.
- The example of survey original plot from WLRS system in Wettzell is in Figure 3.
- The left column was measure by one surveyor, the right one by the second one.
- Two different scales has been used, each value has been measured 3 times.

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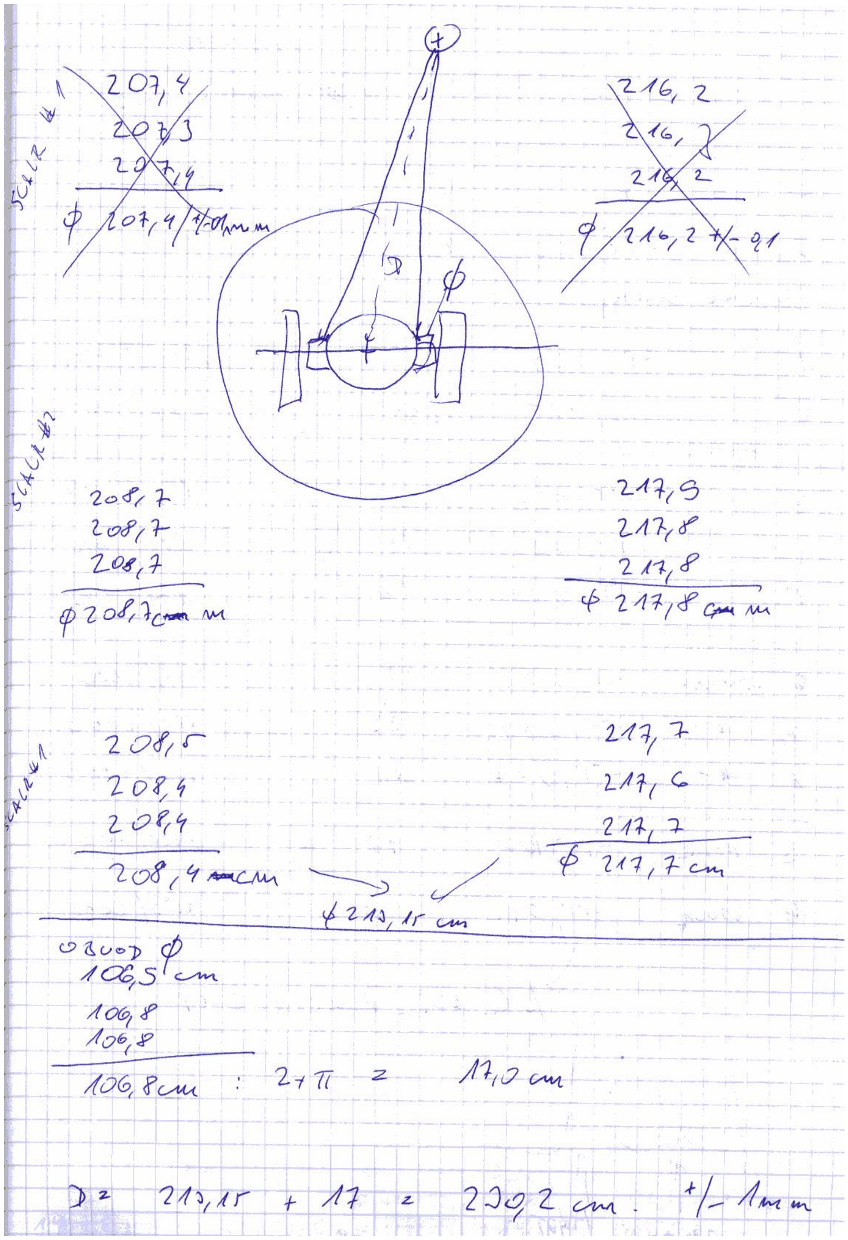

Figure 3 The example of survey original plot from WLRS system in Wettzell, 2 surveyors, 2 different scales were used.

3.1 Calibration procedure

3.1.1 General

- The SLR system and Calibration Device have to be ready and the entire calibration setup tuned according to items 2.2.1, 2.2.2 and 2.2.3.

3.1.2 Time scales of SLR and ELT synchronization and systems setup

- The time scale of the SLR system must be (re-)synchronized to a local time scale by means of the “1pps” signal.
- The “1pps” signal cable will be reconnected to the Calibration Device (CD) timing system input IN2.
- The program NSYNC has to be executed on a control PC to (re-)synchronize the CD time scale, the option with data averaging (4 or 16 times) must be used to minimize the influence of “1pps” signal jitter.
- The “Gate ON” signal must be activated by executing the program SET100.
- The phase of the gate signal (the delay of the gate signal after each integer second) must be determined by executing the program DCR, the measured value must be reported to the SLR crew.
- The SLR system namely the laser trigger epochs must be setup according to a phase value measure in a previous step.

3.1.3 Calibration data acquisition

- The program EPOCH must be started on a CD PC with the input parameters of COMx, 1, -10, 999, 2, where COMx is s number of com port used for device interfacing (1 or 2).
- The SLR system and a laser transmitter and data acquisition must be activated.
- Considering the data rate, laser repetition rate etc., the interval of one calibration series must be selected to collect about 1000 valid echo photoelectrons per series.
- The corresponding data sets of Calibration Device and SLR systems must be processed, see 3.1.4

3.1.4 Calibration data processing

- The output data file from the CD PC and the data file generated by the SLR systems have to be located on the CD PC.
- The SLR data file must be renamed to ELT_SLR1.OUT, the ELT data file must be renamed to ELT_CAL1.OUT.
- The program ELT_PROC must be started. It generates the results file ELT_PROC.OUT. It consists of three columns, ELT epochs (seconds of a day), SLR epochs (seconds of a day) and their difference in nanoseconds.
- The distribution of recorded epoch differences must be plotted in a form of histogram, the data spread will be evaluated applying “2.2 * sigma“ recursive editing process. The resulting precision should be better than 30 ps rms. Program PHISTF with parameters *elt_proc.out, 3, 3* should be used for this procedure. The resulting mean value is a difference of epochs in nanoseconds in a given calibration session. This value has to be recorded along with its precision.

3.1.5 Calibration series sequence

- Several calibration sessions should be repeated. It means without re-synchronizing the SLR and ELT time scales. The reproducibility of the mean values indicates an overall timing stability of measurements.
- Several calibration sessions should be repeated including the process of re-synchronization of the SLR and ELT time scales. The reproducibility of the mean values in comparison to previous group(s) of measurements indicates the precision and stability, with which the corresponding time scales may be adjusted.

3. Calibration documentation

The entire process of calibration has to be documented in such a way, that all the information needed for calibration purposes may be retrieved from this documentation. The standard forms will be created for all the key characteristics, settings and measurement results.

4.1 SLR site key characteristics

The documentation must contain information about:

- Site name, ID, location, agency, contact person,
- Main SLR system characteristics: pulse length, repetition rate, wavelength, configuration of T/R optics,

4.2 Local time scale characteristics

- Time reference source, device type,
- "1pps" signal parameters (polarity, amplitude, slope, slew rate),
- "1pps" trigger parameters on the SLR system,
- Clock frequency reference source, device type,
- Clock frequency, shape, amplitude

4.3 Experiment setup, survey

- Schematic drawing of the Calibration Device and SLR system setup,
- photo of the setup (see Figure 1 for example),
- survey process and results (see Figure 3 for example),

4.4 Calibration partial results

- Typical histogram of epoch differences, (see Figure 2 for example),
- Sequence of results of calibration series sequences. For each series the comment defining time scales re-synchronization (yes/not) must be included.