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SLR Station Biases

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Abstract. *The review of SLR station related biases is presented. The list of biases involved and the methods for determining of these biases are described. Recently this list is extended due to the SLR stations involvement in laser time transfer experiments. The latest achievements in station hardware development are presented along with the resulting SLR system ranging stability and reproducibility results.*

Introduction

Satellite Laser Ranging (SLR) is a space measuring technique which provides unique feature of direct range and time measurement. Its role is inevitable in International Terrestrial Reference Frame (ITRF), definition and calibration of numerous other space based measuring techniques: GNSS, laser altimetry and many others. The requirements of Global Geodetic Observing System (GGOS) for a near future will be the coordinate accuracy on the level of 1 mm and rate of 0.1 mm/year. One of the serious consequences of these requirements is a need to calibrate all the SLR hardware chain components for their absolute delays with (sub) mm accuracies. In addition to ITRF several emerging space related techniques and measurements require high accuracy calibration of various SLR station biases – laser time transfer ground to space, one way laser ranging, laser transponder and multi-static space debris laser tracking – to name just few of them.

The general technique to determine the biases is to use an independent and more accurate (bias free) measurement technique and to compare the results. However, such an alternative measurement technique is not existing for SLR. The only solution is to characterize all the individual error budget contributors, their precision and biases (Pearlman 1984). Although this solution is available there are still two key questions existing:

- How to calibrate each contributor?
- Is our contributors list complete?

The next text is trying to answer several key questions issued before the Workshop:

1. "Which biases should be seen at the stations?"

The biases seen at the station consist of two main contributors: hardware contributors and environmental contributors.

The calibration hardware key contributors are:

- *Calibration & target setup*: the transmit/receive optics configuration and its possible influence on calibration reading,
- *Calibration target distance*: target depth, geometrical range accuracy, definition of reference points both on a target and of the SLR system

- *Laser wavefront influence*: the calibration is completed in a near field, however SLR measurements are completed in far field of the transmitted beam
- *Echo signal strength*: echo signal strength fluctuations (for multiphoton systems)
- *RF interference*: mostly caused by laser transmitter (it influences calibration readings)
- *Detector setup*: range gating, echo signal strength (for SPAD based systems)
- *Timing system linearity*

The calibration hardware related to epoch and frequency key contributors are:

- *Time scale:* its frequency and epoch source and distribution
- *Clock frequency:* its source, stability, phase purity, and its relation to "1pps" epoch signal
- *SLR Epoch reference:* source, "1pps" signal shape, trigger levels, etc.
- *Epoch calibration constant:* Time interval between laser fire epoch reading and a moment, when the laser pulse is crossing the system invariant point

These issues are of low importance for SLR, but they are becoming critical for emerging applications – one way ranging, bi- and multi-static space debris laser tracking and laser time transfer.

The key contributors due to environment are:

- *Meteo sensors*: their calibration, stability, location versus SLR
- *"Local atmosphere"*: the atmospheric pollution and / or local in-homogenities might cause ranging biases up to the order of several mm
- *Local ties*: relation of SLR ref. point versus geodetic coordinates

2. "What changes in procedures and processes would give the stations greater ability to detect biases?"

Probably the best technique to detect and identify station biases related to ranging hardware is the calibration to a set of multiple ground targets. This technique (sometimes called "mini collocation") is routinely used by number of SLR sites.

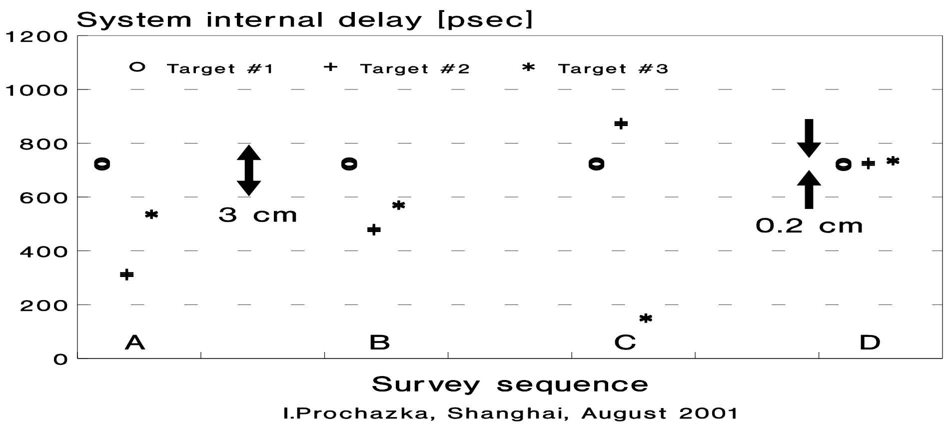

Figure 1. Example of mini-collocation results, completed in Shanghai SLR, August 2001.

The capability of this technique may be illustrated in Figure 1. The calibration results of four calibration sequences *A, B, C* and *D* are plotted for 3 different ground targets. Completing each sequence the calibration setup has been tuned, the problems have been identified and corrected. As a result the system internal delay consistency between individual targets improved significantly from series to series. From initial value of ±35 mm in *A* series down to ±2 mm in *D* series. Two millimeters was a limit of the system in 2001.

Timing system linearity can be tested by comparison to an independent timing system. The results are illustrated in Figure 2, where the results of such a comparison are plotted. The experiment was completed and published by P. Gibs, Herstmonceux, 2002. As a reference timing system the Portable Pico Event Timer (P-PET) was used. The different colors indicate different devices from various SLR sites (Borowiec, San Fernando, Herstmonceux, Potsdam, Zimmerwald,…).

From Figure 2 one can note a significant non-linearity reaching 100 ps peak-peak in a range of 0 to 150 ms. Most of the timing systems under tests exhibited biggest non-linearity in a range of 0 to 5 ms time intervals. In another words – the calibration value will be biased versus satellite laser ranging results. The "mini collocation" will not identify this problem.

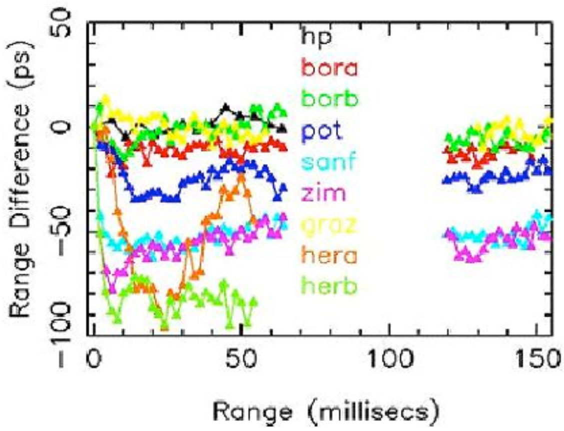

Figure 2. Timing systems linearity tests, comparison to P-PET, completed and published by P. Gibs, Herstmonceux, 2002.

In general single photon approach to SLR is a way to reduce a number of biases. In connection to very short laser pulses single photon approach is eliminating the time walk effects, most of the problems of a near field in ground target calibration. It is also significantly reducing the target spread problems associated with GNSS laser ranging.

3. "How do we stabilize calibration? What station hardware, equipment, software, etc. would give the stations greater ability to detect biases?"

In general – greater stability is a prerequisite for smaller biases. A great progress has been done in construction and development of SLR chain components, which provide (sub)picosecond timing stability even in field conditions.

Electro-optical trigger circuit (J. Kodet 2012) is acting as a Start device – optical detector and discriminator in one compact unit. It provides sub picosecond stability and drift of the time tagging of the laser fire epoch. Its contribution to the overall system stability and calibration constant reproducibility may be illustrated in Figure 3.

From Figure 3 one can learn the significant improvement (2×) of calibration stability of the entire SLR chain after installation of electro-optical trigger device. The results achieved in 2013 correspond to a stability of 0.3 mm per day. In addition the single shot precision increased from 16.5 ps to 13.2 ps rms.

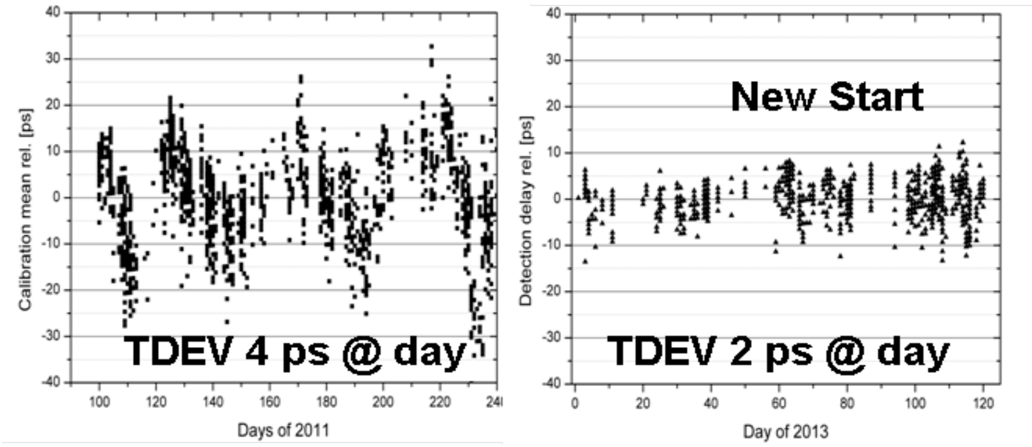

Figure 3. Effect of Electro-optical trigger circuit for SLR, calibration constant last digits, Graz SLR, standard PD and discriminator (left), new device (right). Note a significant reduction of data spread.

The new SPAD photon counting detector package optimized for extreme timing stability has been developed (Prochazka 2013). The detector package is based on a standard 200 µm diameter SPAD chip thermoelectrically cooled down to −60 °C. New control electronics has been developed, it generates the output timing pulses NIM compatible with <100 ps fall times. Fully passive temperature control is used for electronic circuit. The timing jitter of the detector itself is well below 15 ps rms, the temperature drift is as low as 280 fs/K. The continuous calibration experiment has been completed within one week in laboratory conditions ±2 K. It was based on an electro--optical trigger circuit, new SPAD detector package and NPET timing device. The results: calibration means are plotted in Figure 4. Please note the calibration constant (relative) value was stable within ±900 fs over a week.

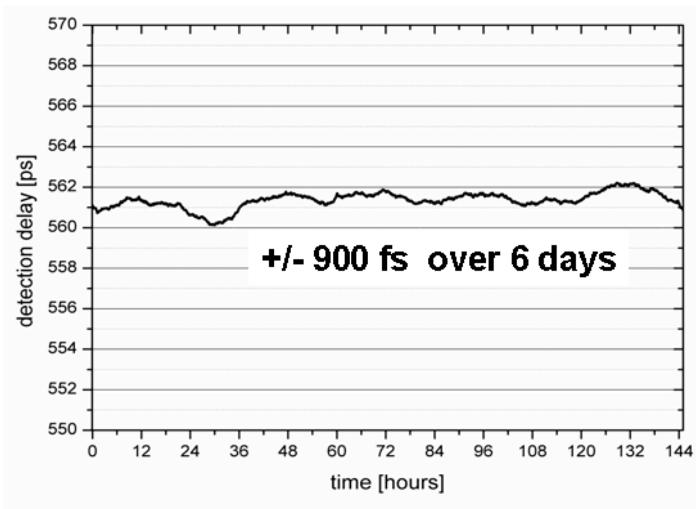

Figure 4. Calibration experiment based on new components: electro-optical trigger circuit, new SPAD detector package and NPET timing device. Note the stability over a week: ±2 K.

Conclusion

One can conclude that a "hunt for SLR station biases" is a never ending story. Although the technology is improving significantly the principle and requirements are still the same. Combining the experience of the SLR community one can formulate several recommendations:

General recommendations:

- Operate the SLR on 1 photon level only (once meaning full and available).
- Higher system stability is a prerequisite for smaller biases, thus maintain maximum system delay stability (selection of components, environment control, procedures, …).
- Repeatedly check all the individual contributors using more accurate references.
- Permanently try to identify new possible bias sources, just "…Suspect everything…".

System calibration setup recommendations:

- Use optically correct calibration targets, 2D hollow retro recommended for separate T/R.
- Use efficient spatial filtering, small FoV suppresses spurious reflections.
- Ensure perfect alignment of the receiver optics (star tracking / scanning is a good check).
- Use multiple targets at different az and range, check the system delay consistency.
- Re-survey the targets geometry regularly, use various scales, techniques, surveyors, …
- Keep detailed record of all system modifications, report any modification to ILRS.

Acknowledgment

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