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Geometry bias in a short baseline ground calibration

J. Eckl (1), I. Prochazka (2), Josef Blazej (2), J. Kodet (3), K. U. Schreiber (3)
(1) Geodetic Observatory Wettzell, BKG, Germany
(2) Czech Technical University in Prague, Czech Republic
(3) Geodetic Observatory Wettzell, TUM, Germany
johann.eckl@bkg.bund.de

Abstract. *We are reporting on a bias identified in a process of ground calibrations of station delays for the European Laser Timing project. The test target was located within one meter from the output aperture of a 0.75 meter diameter transmitting telescope. The local survey determined the mutual distance of a target from the system invariant point with 1 mm accuracy. A significant calibration constant dependence on the telescope pointing has been noticed. The dependence had a range exceeding +/- 10 mm for various pointing angles (!). The consecutive modeling of the experiment geometry identified the bias origin and determined the correct calibration value. The correct value is obtained for calibration "on axis" of the system only. However, the reflector configuration of the transmitting telescope of the WLRS does not enable such a measurement. The calibration constant was determined by fitting of values recorded for various angles, taking into account the known angular dependence. The calibration description, the geometrical model and calibration results will be reported in detail.*

Introduction

In the first quarter of 2014 calibration measurements for the European Laser Timing project where performed at the Wettzell Laser Ranging System in Germany. For this project, it is intended to reach a sychronisation of ground and space clocks at a level of 50 ps [Schlicht, 2011]. This leads to very challenging determination of any systematic delay of the ground and space segments. In the following we want to present our experience with respect to calibration measurements for time-transfer applications gathered during a calibration campaign at the WLRS, which is intended to being used as a ground segment for the ELT project.
Usually, in Satellite Laser Ranging the distance to far away objects is measured at high accuracy. However, for ELT calibration the target, which is an exact copy to the space segment, is located at short distances. For example at a distance of about 2.3 m from the invariant point in case of the WLRS. Theoretically, the laser beam propagation follows Huygens' principle, which suggests that every point which a luminous disturbance reaches becomes a source of spherical wave. Therefore, the sum of these secondary waves determines the form of the wave at any subsequent time [Huygens, 1690]. This leads to a spherical shape of the wavefront, with the transmitting telescope as the center of the sphere, in the far field, which is valid for SLR. However, at distances close to the telescope, plane wavefronts occur. This has to be regarded in measurements for the ELT calibration campaign and also in calibration measurements of SLR systems to ground targets.

Theoretical background

Figure 1 shows the 2D-Situation for a monostatic and bistatic telescope setup during ELT calibration. In both cases it can be seen, that there is no way to illuminate the detector when the telescope is directly pointing towards the direction of the detectors reference point. Considering a monostatic system, the laser light is blocked by the secondary mirror of the telescope and in a bistatic case, the transmitting telescope is usually not mounted at the position of the invariant point of the SLR-system. It follows that there is the need of offset-pointing to illuminate the detector package and as a result this leads to a detection delay caused by the geometry of the setup, keeping the presence of a plane wavefront at the location of the target in mind. During the calibration campaign in Wettzell it was found that the dependence of the measured time-interval on the offset-angle can be written as:

$$D = L \cdot \cos(\alpha) + D_0 \qquad (1)$$

Where L is the true time-interval from the invariant point of the telescope to the reference point of the detector, D_0 is the constant part of the time-interval measurement and α is the above introduced angle offset. Since there holds a linear relation between distance and time with the constant speed of light being the slope in time-of-flight measurements, equation 1 is also valid for treating distances. An extension to a 3D-Situation from the 2D-case in Figure 1 can easily be realized, calculating the 3D offset angle between azimuth/elevation-position of the telescope and the vector pointing from the invariant point to the reference point of the detector in a horizontal coordinate system.

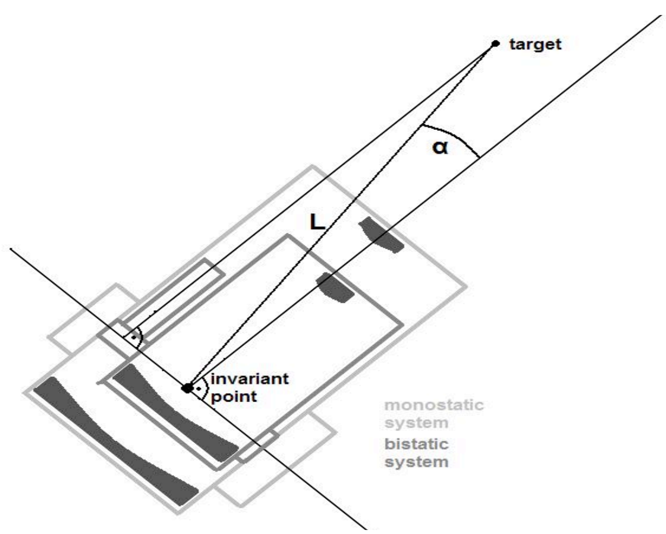

Figure 1. 2-D schematic of an SLR-system tracking in the near field of beam propagation

Assuming a maximum allowed error of 1 mm in the calibration measurement, the above equation can be used to find the maximum allowed angle offset as a function of the distance from the invariant point to the detector package (Figure 2). It shall be mentioned that for measurements to a ground target, e. g. a corner cube reflector, the same procedure is valid (Figure 4).

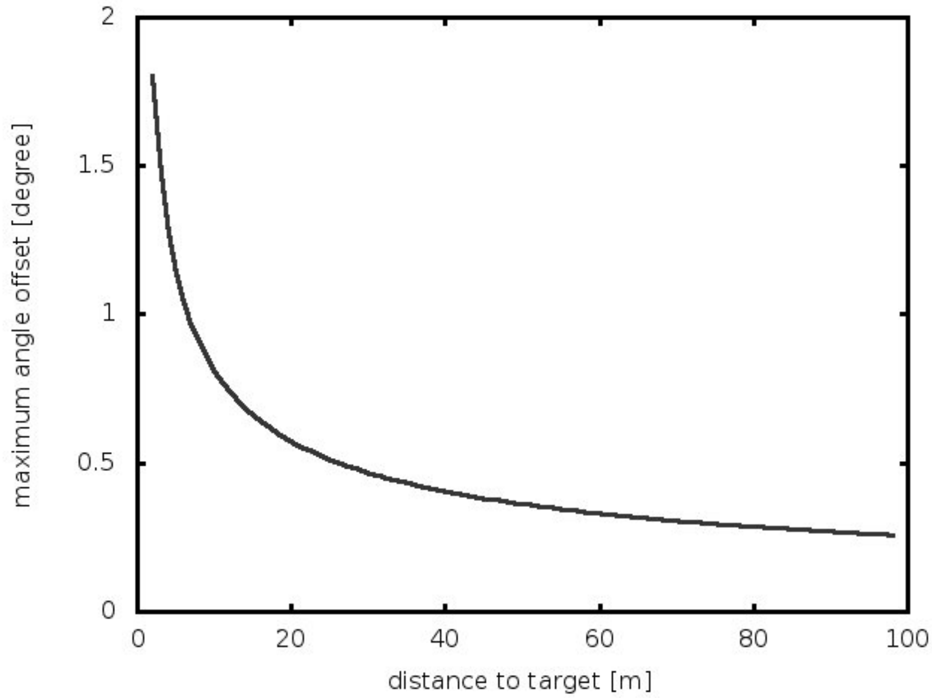

Figure 2. Maximum allowed offset angle as a function to the distance to the target to reach 1 mm accuracy.

Experimental results

To verify the above results, the time delay from the start diode of the WLRS to the ELT detector package at different azimuth angles was recorded. Thereby, this detector package was mounted at a distance of about 1 meter to the output window of the telescope and the mean values for 200 stop events each were calculated. These values, including an adjustment of equation (1) to the observed data, can be seen in Figure 3. The different colors of the data points indicate a varying return rate, which is caused by the lateral laser beam profile of the WLRS laser. Properly meaning that, the system settings, except for the azimuth angle, were not changed during the whole measurement. At low offset angles, in azimuth around 0 to 6 degree, some of the data points were rejected, because they seemed to arise from internal telescope reflections, caused by the secondary mirror. For the remaining data overall detection delay changes of more than 80 ps can be found. Furthermore, an adjustment of our model (equation 1) is in good agreement with the measurement.

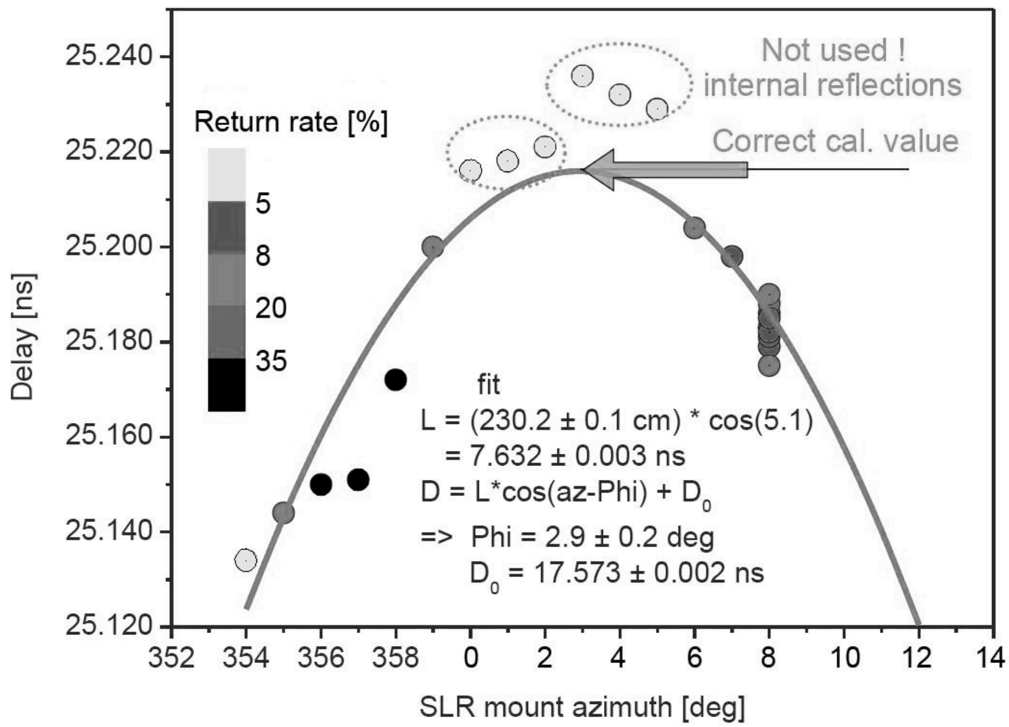

Figure 3. Mean values of time-interval measurements to the ELT-detector as a function of the SLR mount azimuth angle.

Since the WLRS uses a real-time internal calibration procedure for SLR, which prohibits an easy verification of the system delay, an external calibration target was installed recently. To also prove the validity of equation 1 for calibration ground targets, a measurement similar to the above was performed to the external calibration target of the WLRS. This target consists of a single corner cube reflector, which is located next to the ELT-detector package. Together with the system delay constant and an internal calibration measurement, the distance to the external target can be obtained. This is in general similar to an SLR measurement, except for the target being in the near field of beam propagation. The mean values of this distance measurement at various offset angles can be seen in Figure 4. Unfortunately, the available offset-angles, recorded at varying elevation and fixed azimuth, are restricted to a small region around 6 degree. However, a trend with a magnitude of about 14 mm to shorter distances is clearly visible. Here, the trend function (equation 1) was not adjusted to the data. Instead, it was calculated based on local tie surveys, thus with given distance L and angle α. Since the data used is already converted to a true distance, the constant D_0 can be set to zero. Using this approach, good agreement of trend function and the recorded data could be found as well.

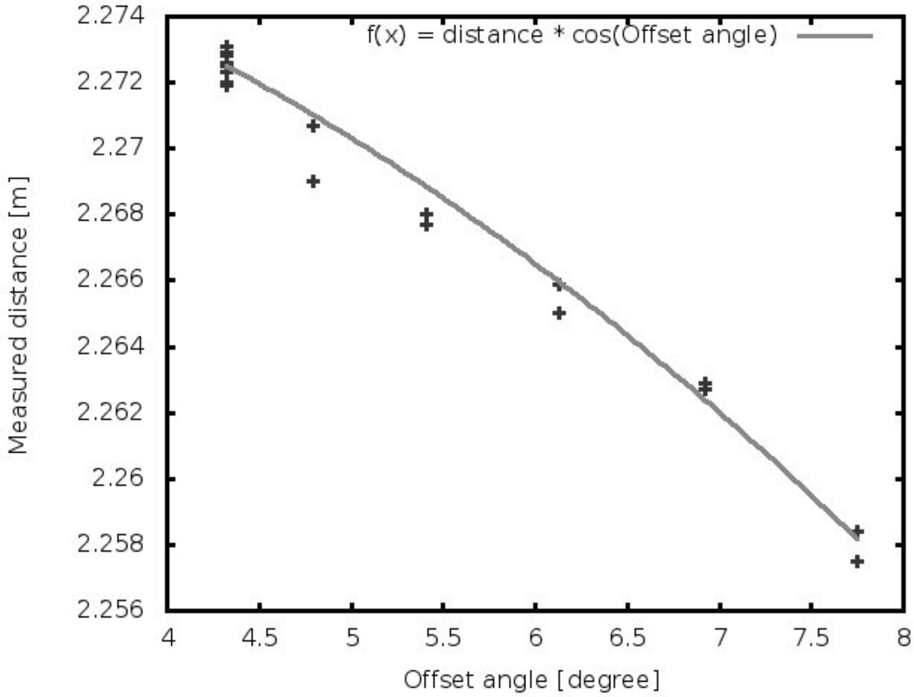

Figure 4. Distance of the external calibration target of the WLRS to the invariant point as a function of the offset angle.

Generally speaking, either ELT-project calibration or ground target calibration measurements, the offset angle of the telescope to the respective target has to be treated properly. Good practice would be to perform the measurements at several different offset-angles and adjust equation 1 to the acquired data to find the true distance to the target. However, this is not always possible. For example the aperture of a bistatic transmitting telescope is quite small and therefore, ranging to the target is just feasible in a small range of offset-angles. Therefore, a more sophisticated way would be to determine the unknown parameters of equation 1 (α and L) to find the true delay by means of local ties surveys. Especially, since an independent verification of the distance L is needed anyway, for the ELT calibration procedure, to refer the calibration data to the invariant point of the SLR-system and in case of a ground target calibration to determine the system calibration constant.

Conclusion

During ground segment calibration measurements for the ELT-project at the WLRS an offset-angle dependent delay in the time-interval measurement was detected. To account for this delay, a theoretical model for laser range finding to targets in the near field was developed. This model shows good agreement to the experimental data. Furthermore, it was validated for its applicability in ground target calibration measurements. The remaining task is to check if it has to be applied for any existing ground target and to take it into account in time-transfer calibration campaigns.

References

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