



Properties of an optical event timer for satellite laser ranging

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Received: 27 March 2024 / Accepted: 29 June 2024 / Published online: 7 August 2024
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Abstract

The resolution and above all the stability of the geodetic reference frames is crucially important when global change, such as the sea level rise is observed. In this context systematic errors are still presenting a significant challenge to the measurement techniques of space geodesy. In order to overcome this unfortunate situation for the satellite laser ranging technique, we have utilized the injection of a mode-locked laser to provide a stable low-noise link between the optical domain, where the measurements are carried out, and the microwave regime in which the station clock is defined. We obtained a considerably enhanced measurement delay stability by 10–20 ps over several days, albeit with some experimental challenges. The implementation of waveform scans required us to revisit the issue of target structure and intensity variation in satellite laser ranging.

Keywords Satellite laser ranging · Optical event timing · Mode-locked lasers · Target signature

1 Introduction

Geodesy provides the basic foundation for all observations in the system Earth, covering an enormous range in the spatial as well as in the temporal domain. Today, any two points on the surface of the earth can be related to each other with a resolution of about one centimeter and their variation over time is observable in timescales shorter than a second during co-seismic activities up to many decades for continental plate motion (Towards an Integrated Global Geodetic Observing System (IGGOS) 2000). The reference frames also play an important role for the understanding of global mass transport phenomena and most prominently for the dynamics of the increasing sea level rise (Technical summary in climate change 2021). For example, the determination of the orbits of Earth-observing altimetry satellites critically depends on the

stability of the reference markers of the observing stations. So systematic errors from variable system delays present a serious limitation to the reference frames of the techniques in space geodesy, namely Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), the Global Navigation Satellite Systems (GNSS), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). One problem is the correct determination of the system reference point. As a consequence, the local geometric ties between the instrumentation at a collocated site are not where they are expected. Worse than these stable offsets are time-variable delays in the electronic measurement devices. As these errors accumulate, they quickly reach a point where they cause drift effects and degrades the measurement such that the GGOS goal requiring a resolution of 1 part in 10^9 cannot be reached. Thus, they do not provide the necessary stability and resolution for the monitoring of global change (Towards an Integrated Global Geodetic Observing System (IGGOS) 2000; System Global Geodetic Observing 2009). Variable systematic biases affect the quality of the scale in space geodesy when the optical domain is compared to the microwave techniques (Altamimi et al. 2023). This is a worry, but not surprising. The cause for the variable delays is residing inside the electronic components of the measurement hardware. All the techniques of space geodesy are based on the estimation of geometric quantities, utilizing the transfer time of either optical or microwave signals. Although not desired, the measurement process also includes the transfer of signals through the cables, receivers,

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amplifiers, timers and other electronic devices. All of these system components add extra delay to the measurement signal and this delay is not constant. There is a considerable dependence on the input impedance of the connectors and the temperature of the elements in the electronic circuitry. The former causes signal reflections that alter signal levels, while the latter changes the internal transfer time within the electronic circuit.

Therefore, SLR and VLBI systems employ elaborate calibration schemes to eliminate these variable system delays as good as possible. Unfortunately, there are limitations to these calibration processes, and the result is that most, but not all, variations of the system delay are captured. In particular, small local temperature variations at the level of less than one degree of some electronic signal processing component inside the timing device are hard to suppress. The signal transfer time is highly temperature-dependent. We have seen effects well in excess of 50 ps on occasion. Even worse than that, there are also persisting errors remaining, which cannot be captured by the calibration process at all because the system configuration differs very slightly at the circuit board level between the measurement and the calibration process (Schreiber and Kodet 2017). A way out of this dilemma is an in situ determination of the instantaneous internal system delay during the measurement process of the VLBI and SLR systems. For VLBI, we are independently probing and timing the signal path through the entire receiver chain up to the digitizer (Kodet et al. 2018), while we are shifting the entire measurement process into the optical domain for SLR (Kodet and Schreiber 2019).

2 Event timing in the optical domain

Figure 1 illustrates the basic laser ranging concept. Short pulses from a pulse laser with a width of $10 \text{ ps} \leq \delta t \leq 200 \text{ ps}$ are used to obtain the time of flight between a ground station and a satellite target. A small part of this probe signal is split off by a semi-transparent beam splitter, and the signal is detected by a sensitive high bandwidth photodetector and time tagged on an event timer unit. The main signal propagates toward the satellite, where it is reflected back to the measurement system. When it returns to the ground station, the returning echo is time tagged again in the same way.

From the elapsed time, the range can be determined with high resolution, when the measured time interval is multiplied by the speed of light. Since the signal crosses the distance twice, the time interval has to be divided by 2. Performing the same type of measurement process to a local ground reflector at a precisely known short distance provides the necessary calibration to account for the delays accrued by the path of the laser pulse in the laboratory and the signal transfer time in the electronic timing devices. This process

assumes that the ranges and the calibrations are subject to the same internal system delays, but this is not fully the case. Obtaining high long-term stability is particularly difficult and requires excellent temperature control of every component that is part of the timing process.

2.1 Mode-locked lasers and active delay compensation

Mode-locked lasers have excellent low-noise properties both in the optical and the microwave domain. The driving Q-switch frequency of 100 MHz from a frequency standard, such as a hydrogen maser, results in an optical pulse train with an exact pulse spacing of 10 ns. A two-way feedback system actively keeps the round-trip time of the pulses constant at a fixed delay (Schreiber and Kodet 2017). Even when temperature changes occur, they will not change the propagation delay of the pulse train through the fiber. In practice, this means that the relationship of the phase of the electronic input frequency is rigidly tied to the sequence of the femtosecond laser pulses of the laser.

This corresponds to a high-resolution optical ruler, against which the satellite laser ranging pulses can be timed with high long-term stability. Variable time delays detune the overlap of the outgoing and returning clock laser pulses, which is detected and corrected by the distribution system. This error signal from the delay line adjustment provides a sensitive indication of the compensated delay variation. Figure 2 illustrates the effect as a function of time. The length variation inside an air-conditioned rack a) is within $\pm 20 \text{ ps}$ over 8 h but exceeds 150 ps over 2 months in a cable trench between buildings b). It needs to be kept in mind that these are only visualizations of the temperature related effects on the optical fiber line, which are very conservative. So far, the graph does not contain the variable delays of any electronic device or impedance mismatch of cable connections. These delays can be much larger, more variable and include significant jumps in the delays.

2.2 Long-term stable optical timing utilizing a mode-locked laser for SLR

In a rough simplification, one could say that SLR performs the time of flight measurement process in the optical domain and then switches to the electronic domain to obtain the numerical values for the time of flight at each measurement epoch. The latter is prone to be contaminated with unwanted measurement delays that cause systematic errors and are hard to contain. In order to circumvent this problem, we have shifted the time-critical part of the timing process also into the optical domain.

Technically, this is realized by injecting the “optical ruler” of equidistant laser pulses into the detector of the SLR system

Fig. 1 Schematic outline of the time-of-flight measurement process in an SLR system. The pulses of a pulse laser are divided in two signal paths. The split off signal triggers an event timer to get a start signal. The main signal is reflected off the satellite target and triggers the event timer again

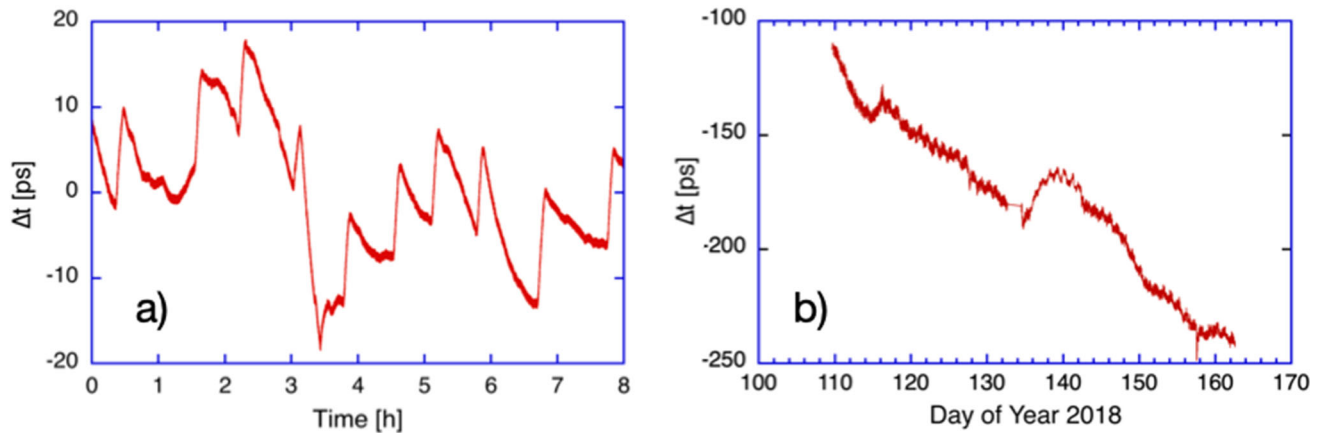
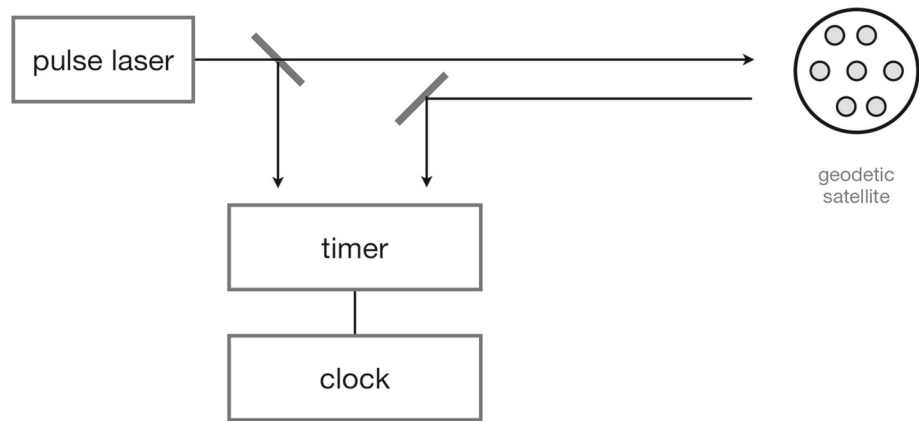
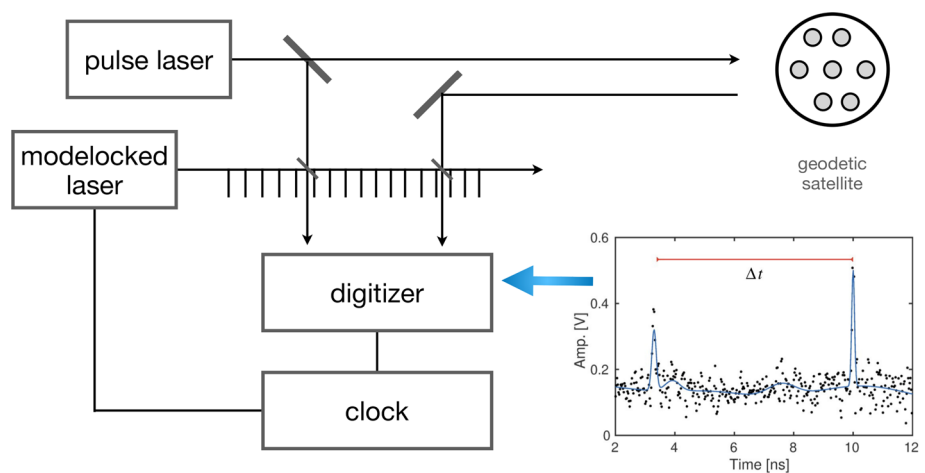


Fig. 2 Error signal of the delay-compensated time and frequency distribution system. In the short-term, over several hours, the effect of the cooling cycles of the air-conditioning system in the laboratory prints

through (a). Over a period of several months, the seasonal variations caused a significant trend of over 150 ps (b), underpinning the effectiveness of the delay compensation

Fig. 3 Schematic outline of the modified time-of-flight measurement process. In addition to a classical SLR measurement, the optical pulses from the timing system are injected into the transmit and receive path. Unlike for classical SLR, which utilizes threshold detection, the detector response is digitized over a sufficiently wide window



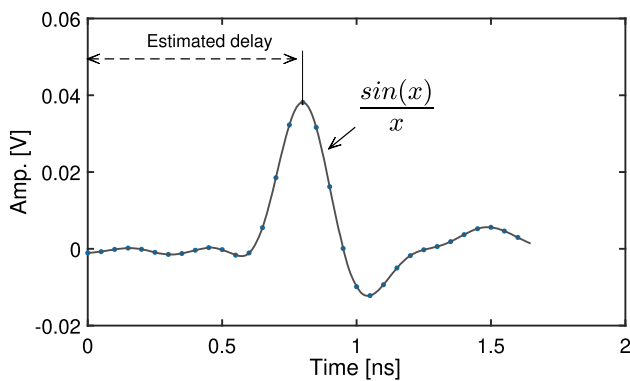


Fig. 4 Example of a reconstructed laser pulse detected by MCP. The blue points are the raw samples, which are interpolated with a resolution of 1 ps

so that both the ranging pulses and the optical time markers from the mode-locked laser are detected. This means that the frequency reference against which the ranging pulses are timed is moved to the optical domain. A similar approach has independently been utilized by the Apache Point Lunar Laser Operation (APOLLO) (Adelberger et al. 2017), albeit without the active delay compensation. The relevant section of the range gate is then sampled with a high-speed oscilloscope, and the offset Δt between the satellite or calibration return and the nearest timer pulse is determined in the post-processing. This concept is illustrated in Fig. 3. The injected timer pulses are spaced exactly 10 ns apart, defined by the frequency of hydrogen masers. The actual range is obtained by counting the number of these timer pulses between the start and stop event and subtracting Δt . We used a 2.5 GHz bandwidth oscilloscope with a sampling rate of 20 Gs/s for our setup. This allows the reconstruction of the detected satellite echoes with a good compromise between processing speed and residual timing error. The echo signal is the convolution of a short laser pulse and the detector response. The samples can be interpolated by a slit function $f(x) = A \sin(x)/x$. In this way, we can reconstruct the entire signal with a resolution of 1 ps. A typical example is shown in Fig. 4. With respect to processing speed and accuracy of reconstruction, this method was more successful than utilizing Gaussian approximations or the frequency domain distance measurement (FDDM) method (Eder 2017).

The result is a good approximation of the centroid of the ranging laser pulse. In practice, we recorded several clock pulses after the echo returned.

2.3 Comparison between classical SLR operation and optical event timing

Most of the important SLR stations today operate on high repetition rate lasers with a data rate of $500 \text{ Hz} \leq \text{shots per second} \leq 2 \text{ kHz}$ and utilize silicon avalanche photo diodes

(APD) operated in the Geiger mode for high detection sensitivity (Prochazka et al. 2011). Technically, these systems perform a leading edge pulse detection process, where the event timing is triggered when a preset threshold value has been reached. The Geiger mode operation activates the photodiode by reverse biasing it above the electrical breakdown voltage (Cova et al. 1996; Dautet et al. 1993). The steepness of the slope depends on the detected pulse intensity, which causes delay fluctuations on top of temperature-related electronic delays.

An alternative detection approach uses micro-channel-plate photomultipliers (MCP) and a constant fraction timing scheme, where the trigger voltage threshold corresponds to half of the maximum voltage generated from the detected laser pulse. Since the signal amplitude is proportional to the detected echo intensity, the actual trigger level is evaluated on a shot-by-shot basis. MCPs typically have a comparable detection bandwidth but are less sensitive than APDs. However, they are also less sensitive to delay variations as a result of signal intensity fluctuations.

Both concepts have advantages and disadvantages. While the Geiger mode operation provides a faster rise time and higher sensitivity, it is more sensitive to systematic detection delays when the intensity of the detected signals is variable. There are efforts in the SLR community to remove this effect by utilizing a C-SPAD, which offers some delay compensation. It estimates the time-walk effect by the evaluation of the avalanche rise time. However, this technique is laser pulse width and intensity dependent and does not correct for effects of target structure. Therefore, it only provides approximate empirical corrections. MCPs on the other side have no dead time but less detection sensitivity, and the dynamic range of the constant fraction trigger threshold adjustment is limited to amplitudes within less than a factor of 10. The internal temperature-related signal delay of the timer itself is independent of the detection technique.

MCP operation in optical timing In comparison with the routine operation, our novel concept provides two significant advantages. It samples the entire return signal. This allows us to perform a proper centroid detection of the detector response of the return laser pulse, by analyzing the shape of each individual return pulse. The result is a very small residual error of 18 ps single shot rms. Furthermore, we avoid additional variable delays from the electronic boards of the timer, because the applied timing pulses propagate through exactly the same electronic signal path as ranging pulses in very close succession. Most of the SLR targets do not use single cube corner reflectors or flat panels, orthogonal to the direction of the ranging laser beam. Cube corners at different target depths deform the laser pulse to become asymmetric. While this is not detectable with APDs on individual range measurements, it can be adequately recognized and deconvoluted from the digitized return pulse shape.

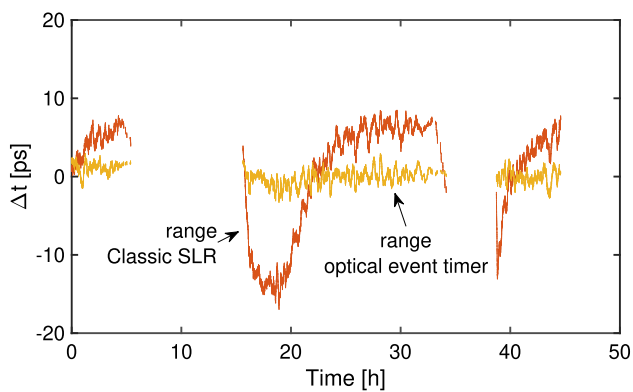


Fig. 5 Comparison between the edge detection technique and the optical timing concept. There is a considerable improvement in stability over a test run of several days

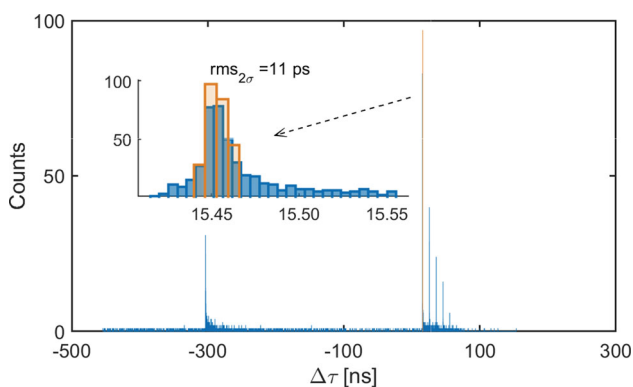


Fig. 6 Statistical APD edge detection scheme for the echo return and the delay-compensated timer signal. The histogram represents 5 min of data accumulation

In an indoor test setup, we compared both timing techniques in a side-by-side experiment over a duration of 45 h. The laser pulse width from the probe laser is 45 ps, while the pulse width from the optical ruler is 0.15 ps before the frequency doubling crystal. The result is shown in Fig. 5. The delay-compensated timing pulses and the edge-detected probe laser signal responses are jointly recorded and digitized within a time interval of less than 500 ns. Therefore, there are no additional variable delays involved. The timing is based exclusively on the bandwidth of the digitizer and the stability of the optical delay compensation. There is no detectable drift of the recorded round-trip times (yellow curve) over the entire test period of 45 h. The leading edge detection, however, shows some significant systematic variation with deviations reaching levels of 20 ps for this particular test period.

APD operation in optical timing Once a voltage breakdown has occurred, the APD detector undergoes a considerable dead time of several μs before all carriers have left the PN-junction region, and the reverse bias voltage can be applied again. This has the consequence that only one signal

can be timed per gate. In general, the analog diode output is detected by a high-speed comparator, and the output signal is in digital form. In this particular case, we utilized an oscilloscope and measured the delay between the SPAD digital edge and a well-defined auxiliary pulse. By keeping the light level on the detector at the single photon level, the detector randomly senses either the ranging signal or the timing pulses later in the gate in a statistical manner. When a sufficient number of measurements are detected, a histogram for both signal types can be established and referenced to each other. An example of such a histogram of optical pulses and how they appear on the SPAD detector is depicted in Fig. 6. The first pulse is accumulated from the ranging laser pulses. The pulse train toward the right side belongs to the pulses from the optical ruler against which the time of arrival is established. The approach corresponds to the procedure discussed in Adelberger et al. (2017). This method requires a sufficient number of valid detections in order to build meaningful histograms that allow the determination of the offset. For this experiment, we built a histogram every 5 min and applied the mean calibration, which provided a good compromise in order to keep the noise contribution from the histogram accumulation low.

3 All optical satellite ranging

We have applied the differential timing concept to satellite observations, utilizing the MCP configuration. Since we used a digital oscilloscope, we could only time-tag satellite echoes with this new setup. The start detector epoch was taken from the SLR event timer. In our experiment, we were required to obtain an epoch reading against the pulse train of the optical ruler. Therefore, a raw counter triggered by the optical ruler repetition rate of 100 MHz was used to provide a coarse epoch reading with a resolution of 10 ns. The high-resolution part of the epoch was established by centroid detection and delay estimation (Δt) between the satellite echoes and timing pulses, as schematically outlined in Fig. 3. To avoid detector overload by constantly injecting the timing pulses, we used an electro-optical modulator as a pulse picker to inject a short segment of the optical ruler into the MCP well behind the satellite echo. The entire range acquisition was triggered by the opening edge of the range gate. Therefore, this signal must be more accurate than the optical ruler repetition rate, which was required for removing 10 ns ambiguity.

Figure 7 shows an example of a passage of the satellite AJISAI, obtained by differential timing. The actual measurement rate for the Wettzell Laser Ranging System (WLRS) is 500 Hz, which is currently well outside the processing capacity of the available data recorder LeCroy WaveRunner 9254. Scanning a range gate with this digitizer currently offers a data rate of 20 scans per second at best. As a conse-

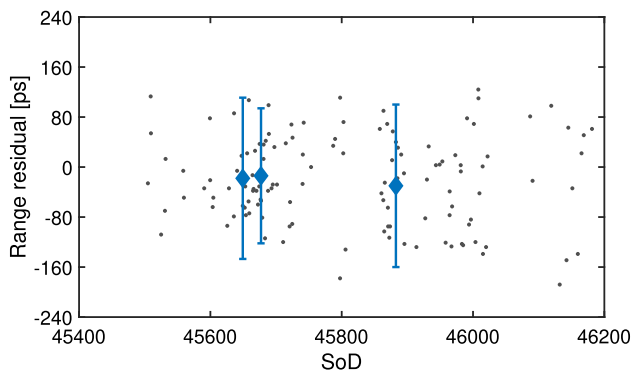


Fig. 7 An example of a residual plot of an AJISAI satellite passage, obtained by the differential timing concept. The actual ranges are obtained from the offset of the detected echo pulse and the injected pulses from the time and frequency distribution system, together with the estimated number of clock ticks. SoD is seconds of day

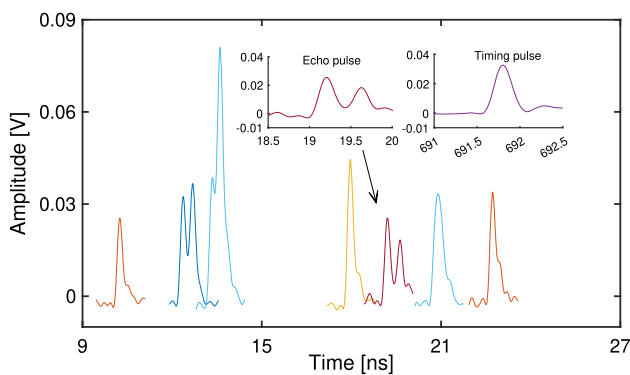


Fig. 8 Display of some recorded satellite echo waveforms. A strong target structure effect is apparent in some of the echo examples. A timing pulse shape is added for comparison purposes

quence, only 10% of all satellite returns could be captured. This data rate is not enough to allow for a meaningful comparison. Figure 8, however, shows an important feature, namely the effect of the return pulse shape from a few examples of the recorded satellite echo waveforms from AJISAI. We note a considerable asymmetry in the shape of most of the detected echo pulses as well as the presence of some double pulses. The double pulses are caused by the target structure. The instantaneous position of the illuminated cube corner retro-reflectors (CCR) on the satellite surface with a slightly different distance superimposed to the recorded echo envelope. An example of the clock pulses is also added as an inset to the right side of Fig. 8 for illustration purposes. They have very little intensity variations and exhibit a constant waveform.

A strong target structure, if not handled adequately, causes a variable bias from the true range. We have compared the widely used edge detection technique based on a constant detection threshold against the centroid detection approach as outlined above. Since the complete waveforms of the echo

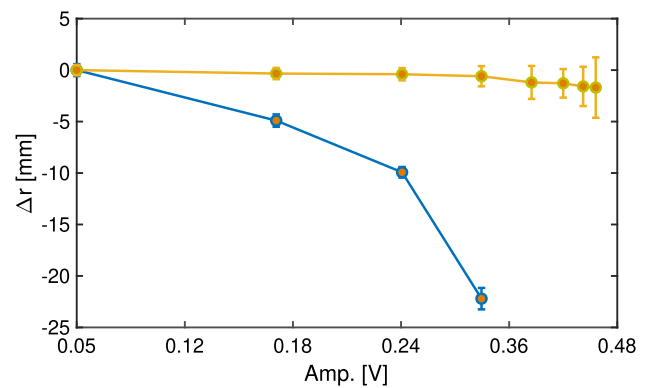


Fig. 9 Depiction of the time-walk effect measured against pulse amplitude. The blue line represents edge detection technique, while the yellow line was obtained by centroid detection of the reconstructed pulse

returns are available, this can be done on the same dataset. Figure 9 displays the result.

While the centroid detection scheme can handle the non-normal waveform distribution well, the edge detection scheme shows a significant bias sensitivity as a result of variable intensity. In extreme cases, this can exceed a value of 20 mm in the round-trip range. The differential timing technique has been investigated to explore the long-term stability of the ranging system with the goal of eliminating systematic measurement errors.

4 Discussion

Recognizing the fact that the stability of the measurement systems is pivotal for the long-term stability of the geodetic reference frames, we have explored a novel approach. By taking the timing process into the optical domain, it was possible to eliminate variable system delays from the measurements. At the WLRS laser ranging station on the Geodetic Observatory Wettzell, we have tested the combination of an optically distributed delay-compensated clock signal and a differential optical ranging concept. By recording both, the satellite return and the optically injected fs-timing pulses in a single scan of a high-speed digitizer, the entire waveform is available for each recorded laser shot. A local optical time-of-flight measurement test setup has clearly demonstrated the superior delay stability of the actively delay-compensated approach, where variations of 10–20 ps have been found in a measurement sequence over several days. Furthermore, taking advantage of the full recorded waveform, it became also possible to compare the typical edge detection technique, which is widely used in the SLR community against a trigger based on the centroid of the leading cube corner return pulse. This improved the bias stability from the intensity dependent signal delay in the detector significantly. It also allowed us to

remove target signature effects from the measurements. Due to the fact that the clock ticks are actively delay-compensated at the level of 1 ps, the system delays remained constant as expected. The improvement in the ranging system stability varies between a few ps and in the case where the timing hardware is not tightly temperature controlled, by almost 20 ps. The experiments also highlighted a known problem, which is related to the variable return signal intensity and the detection threshold. In the laboratory, we obtained biases exceeding 20 ps. Under typical observation conditions, an intensity dependent variable bias of less than 10 ps is a realistic expectation, due to a reduced dynamic range.

Despite all this, there are also some disadvantages that need to be addressed. Current high-speed digitizers are not fast enough to provide a highly resolved waveform scan for each measurement. At this point in time, we were able to obtain up to 20 scans per second. The data rate of our SLR system for comparison is 500 Hz, which is twenty times higher. We have utilized a MCP for the range measurement. This detector has no dead time, so that the satellite echo could be recorded together with the timing pulses. Avalanche photo diodes today are much more sensitive than MCPs, but feature a considerable dead time. This does not allow to record both signals in one scan. It does not preclude that the high stability can be exploited, since we have shown that a statistical treatment is applicable as a compromise. However, the evaluation of the appropriate trigger point is not so obvious. Due to the quenching process of the APDs in the Geiger mode, the centroid detection does not appear to be an option.

Acknowledgements This work has been carried out in the framework of the research program of the *Research Group Satellite Geodesy*. We acknowledge funding from the German Research Foundation (DFG) grant number: SCHR645/8-1

Author contributions All authors contributed in a meaningful way to the development of the sensor setup over an extended period of time. JK and KUS developed the basic concept, and JK and JE set up the ranging experiment, performed the measurements and provided the analysis. KUS, JK and JE co-wrote the manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL.

Data availability The authors will make the data available upon reasonable request.

Declarations

Conflict of interest There are no conflict of interest in this work.

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