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A NEW WAY FOR REDUCING BIASES IN SLR TIMING

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Abstract

A self-calibrated SLR system with an optimum range receiver is presented. Self-calibration of a common transmit / receive system is achieved by superimposing a highly accurate optical clock signal onto the photodetector. Transmitted and received laser ranging pulses are digitized in separate oscilloscope records along with a set of optical clock pulses in each record. The two time frames are synchronized in a post-processing step owing to the clock signal. All the pulses (clock and laser) are timed with a cross-correlation technique which has been proved to be very efficient in previous work where, using a 10 ns detection stage response time and a 1 Gs/s sampling rate, a ranging accuracy as high as 3 mm was obtained in single shot for a SNR of ~100. Extrapolation of the technique to two-color SLR measurements is also described. A single shot accuracy of < 5 ps is predicted with a 8 Gs/s sampling rate.

1. Introduction

The main goals of SLR, as an operational orbitographic or as a scientific tool, derive from its capability to determine artificial satellite orbits with centimeter-accuracy. From the orbit, one may deduce information of very high importance concerning earth rotation parameters, earth gravity field and its temporal variations, and a very high-quality absolute positioning. In this area, SLR could be a very good candidate, if not the best on a long term basis, to provide absolute millimeter altimetry for studies concerning minute altitude variations (mountains formation, tectonic subsidence and surrection, post-glacial rebound, oceanic loading over continental margins, etc.).

The main limitations of SLR in terms of accuracy, by descending order of importance, are probably : (i) the quite inhomogeneous repartition of SLR stations in the world, (ii) the technology of SLR that leaves some important biases uncorrected, (iii) target temporal signatures, and (iv) tropospheric delay uncertainties.

Concerning (i), we observe regular improvements, but there will always be some basic limitations (due to semi-permanent cloud coverage in some parts of the world, for example). Our input has been to develop a highly mobile SLR unit, the FTLRS whose status is reported by F. Pierron. Concerning (iii), the models have considerably improved and some technological possibilities not yet used exist [1]. And concerning (iv), the correction to look for is quite low if the pressure is correctly measured at the station [2], and in any case it is expected soon that two-color ranging [3] will achieve automatic corrections at the millimeter level. Derived from our work on the Wide-Angle Airborne Laser Ranging System (WA-ALRS) for geophysical applications [4, 5, 6] and from previous NASA publications [7, 8], we propose a new approach for the point (ii), i.e. how to limit any sort of instrumental bias.

This approach is based upon two aspects :

- use of a self-calibrated transmit / receive system,
- use of a fast digitizing of the response of the detector to laser pulses and a cross-correlation timing procedure.

2. A self-calibrated SLR system

The instability of instrumental biases are a quite basic problem in time of flight (TOF) measurements. They are mainly due to the thermal short-term evolution of the electronic circuitry behind the detector up to the classical timing unit, and the time-walk of the photodetector, which is a function of the temperature, the polarization voltage, and the energy of the echo. One solution for reducing timing biases in SLR is to use an optical Time Interval Unit (TIU), as first proposed by Degnan, [7, 8]. In this concept, a highly accurate optical clock measures the coarse TOF, with the help of classical constant fraction discriminator (CFD) and TIU setup, and a streak camera is used to measure differential times, possibly for two wavelengths. The advantage of the optical clock is to yield common time frames for the two independent time windows in which the transmitted and received pulses are measured.

This concept had previously proven its high efficiency in VLBI, since the Mark III receivers at the early 80's, for calibrating delays from cables and antenna in radio-astronomical observatories. VLBI is basically, by comparison with SLR, a completely passive device, and its calibration system is based upon the emission of ultra-short electronic pulses (a few picoseconds) derived from the atomic clock (a H maser) using a Step Recovery Diode at a frequency of 1 MHz. These pulses are observed at any frequency being an integer figure of MHz, and will be observed twice in any 2 MHz recorded band (Mark III observes generally 14 of such bands) and as they are emitted at known instants, the reception of these ticks superimposed on the radio signal provides a complete calibration of the receiving electronics, including cables and preamplifiers.

Based on this concept, we propose here an optically auto-calibrated SLR system (see Figure 1) where we additionally take advantage of the possibility of measuring two independent time windows for implementing an optimum receiver [4-6]. Actually, instead of performing an analogical processing of measured laser pulses in order to trig the timing unit, we have tested the remarkable efficiency of the digital signal processing of the pulse digitized at a high sample rate such as 1-2 Gs/s. Sub-centimeter single shot accuracy is there achieved provided the pulse is long enough to be present in a large number of samples (10 samples for a 10-ns FWHM pulse sampled at 1 Gs/s). As a first consequence, such a methodology does not require a very short response-time detector. As a second consequence, only a moderate-pulsewidth laser is required, such as 50-100 ps. Longer pulses are, however, to be avoided in order to minimize wavefront distortion. Relatively high energy lasers can thus be used (100-200 mJ @ 1064 nm).

The proposed system layout is presented in Figure 1. The highly accurate clock (H maser or GPS frequency reference receiver) of the SLR station is used to generate a train of very short optical pulses at a rate of 10 MHz. For this purpose a laser diode (e.g., C861235E by EG&G emitting at 1064 nm) is driven by a short (5-10 ns) electrical pulse generator, for example an Avtech AVO-9 unit which exhibits a typical jitter of 15 ps. The emitted optical clock pulses (OCPs) are directed towards the photodetector, where they are superimposed on the ranging pulses from the main mode-locked laser. Note that both transmitted and received ranging pulses are detected by the same photodetector in order to further reduce the detector-biases. In that configuration, these regularly spaced pulses provide two different information :

- they allow to put the two oscilloscope traces in the same time reference, provided the ambiguity due to the drifts is far below the 100 ns level, which is not a difficulty,

- they fully calibrate nearly all delay instabilities within the detection, allowing probably to limit at a very low level the requirements for external classical calibration.

The photodetector can be either a photomultiplier tube (PMT), a microchannel-plate photomultiplier (MCP/PMT) or an avalanche photodiode (APD). Devices of the latter type are preferred, since they today achieve similar quantum efficiencies and jitters than the former two ones [9]. Moreover, they allow use of Nd:YAG lasers on their fundamental wavelength (1064 nm), increasing therefore the link bugdet. The APD would be operated in linear mode and would then require an amplifier for detecting the weak echo from the satellite. However, an alternative would be to use the APD in linear mode only for detection of the transmit pulse and OCPs, and in Geiger mode for detection of the receive pulse. This would be possible with slight modification of the active quenching technique to include a third state. Time-walk compensation of the detector in both modes would be included in the post processing [10].

A start diode inside the laser is used to trigger the oscilloscope on channel 2 and give the control to the computer. A range-gate is then generated by the computer, which inhibits the optical clock and triggers the oscilloscope. During the low-state of the range gate signal, the transmit pulse is measured, while at the end of the gate the clock is enabled and a set of OCPs are measured. Both signals are thus recorded in the same waveform, i.e. in a common oscilloscope time frame (see Figure 2). The time interval between the transmit and receive range gates, $t'_0 - t_0$, is assumed to be approximately known a priori by the computer within one optical clock period. This requirement is easy to satisfy (15 m for a 100-ns period) with current satellite tracking systems. As the receive pulse arrives it triggers then the oscilloscope, with a proper trigger delay. It is then recorded along with another set of OCPs.

Owing to the double triggering of the oscilloscope, the recorded waveforms can thus be much smaller than the round-trip duration for the laser pulse (which is up to 100 ms). They may last for example 10 µs, so that about 100 calibration pulses are recorded. In the processing of such a waveform, the error due to the jitter of the laser diode driver will then vanish compared to the single shot timing precision of ranging pulses (see below). Additionally, the drift of the sampling clock might be overcome by using the reference clock as a master oscillator for the oscilloscope.

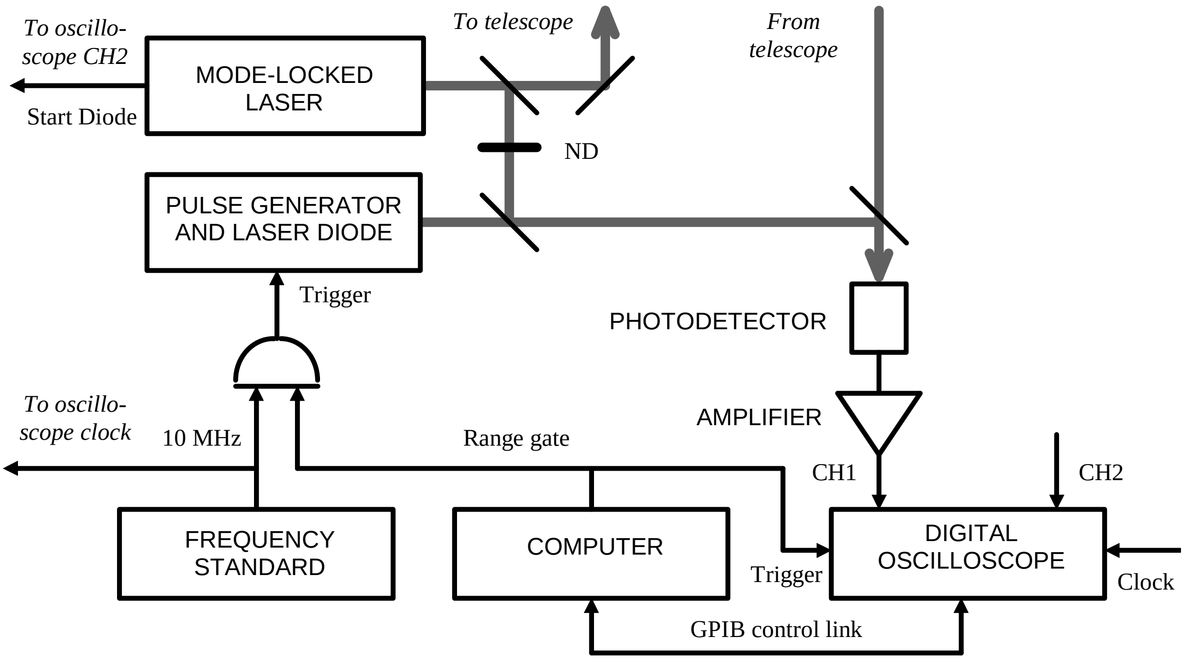

Figure 1 : Block-diagram of the optically auto-calibrated SLR system with optimum range receiver potential.

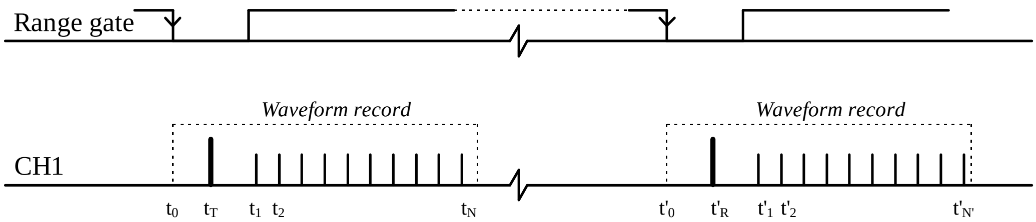

Figure 2 : Timing diagram of the optically auto-calibrated SLR system of fig. 1.

After each acquisition, the waveforms are transferred to the computer via a GPIB link. With a 10-µs record, sampled at 1Gs/s, 10 Kb of data are to be transferred per waveform, i.e. 200 Kb/s should be achieved with a 10 Hz laser PRF which is currently made. However, lower transfer rate might be achieved when the reducing the record length which is not critical.

Waveforms can be either processed in real time or a posteriori, as described in the following section. A fundamental characteristic of the proposed system is that only differential timing is required, i.e. a precise pulse location in its waveform, since time frames to different waveforms are connected owing to the optical. The integer ambiguity is resolved since the trigger times t_0 and t'_0 are known within a clock period. The TOF is thus computed according to the following method. Consider the transmit observables : $t_T - t_0, t_1 - t_0, \ldots, t_N - t_0$ and the receive observables : $t'_R - t'_0$, $t'_1 - t'_0, \ldots,$ $t'_N - t'_0$, where the primes indicate the times measured in the receive time frame. By differentiation, one can thus compute two further variables :

$$\alpha = \frac{1}{N} \sum_i \left(t'_i - t_i\right) - \left(t'_0 - t_0\right) \tag{1.a}$$

$$\beta = \left(t'_R - t_T\right) - \left(t'_0 - t_0\right) \tag{1.b}$$

where it is assumed that the same number of optical clock pulses are measured in both records, i.e. $N \approx N'$. Those variables are then combined to yield the estimate of TOF :

$$\tau = n \times T + \beta - \alpha \tag{2}$$

Variables α and β are random variables which have a common component $t'_0 - t_0$, representing a bias for a given set of transmit and receive records. On a shot to shot basis, the fluctuating parts of t_0 and t'_0 are uniformly distributed over a sampling interval, i.e. they exhibit each a 7.5 cm standard deviation for a 1 Gs/s sampling rate. The first term of equation (1.a) has a mean value equal to the integer number of clock periods, i.e. $n \times T$. The standard deviation of the fluctuating term is roughly equal to the time jitter of the optical clock pulse generator divided by $\sqrt{N}$, i.e. 15 ps / 10 = 1.5 ps for N =100. Hence, in the above definition of the time of flight, the ultimate uncertainty is with the estimates of t_T and t'_R. The uncertainty in estimates of t_T is usually very small since the SNR of the transmit pulse can be chosen arbitrarily high. On the other hand, the uncertainty in estimates of t'_R is limited by the well-known error sources (link budget, target signature, atmosphere, etc.). However, a significant improvement might be achieved when using an optimum receiver.

3. An optimum range receiver

Currently, TOF measurements are achieved by CFDs which start and stop an electronic TIU. Such receiver configurations belong to the sub-optimum class, based on leading-edge detection, and their timing accuracy is proportional to the rise-time of the measured pulses. For this reason, many attempts have been made in the last two decades to develop more rapid detectors and amplifiers [11]. However, one should remember that early range receivers were rather based on digitization of the pulses and a post-processing in which the time of emission and time of arrival for the pulses are estimated [12], [13]. In this latter configuration, optimum receivers can be implemented such as cross-correlation peak detectors. Based on previous theoretical analyses [14], Abshire has compared the performance of such receivers for their use in SLR systems in photon counting mode [15]. He concluded to the higher performance of matched-filter (or cross-correlation) peak detectors. However, it seems that digitizers available at those times did not provide sufficient timing performance to achieve centimeter ranging accuracy.

Today, the situation is quite different, as we have demonstrated since the early results obtained with the WA-ALRS [4]. Our system is composed of a short-pulse mode-locked laser (100 ps, 100 mJ @ 1064 nm), a large-area PIN photodiode (YAG 444, by EG&G) of slow rise-time (~5 ns) followed by a transimpedance amplifier[1]. The measured signal is thus proportional to the overall impulse response of the detection stage and is typically of 13 ns at FWHM with a leading edge of 4 ns. Hence, signal sampling is performed with good accuracy when using a LeCroy 7200 oscilloscope with a 1-Gs/s rate and 500 MHz signal bandwidth (the latter could be reduced without damage to ~100 MHz). The clock stability of this oscilloscope has proven to be very efficient (at the ps-level) for record traces of 10-µs in duration. In our system we have implemented two equivalent ranging procedures : 1) a cross-correlation peak detector (including a parabolic interpolation of the peak time), 2) a least-square adjustment for estimating pulse amplitude and time of arrival [6]. Using either of these methods requires a reference pulse waveform which is obtained in a laboratory calibration (pulse averaging).

[1] In our system a large-area photodiode is required for maintaining a high link budget when using a strongly diverging laser beam. The use of telescope at the receiver is not possible because of the wide-angle incident beams.

In this system the errors are mainly due to signal aliasing and electronic noise [5]. Time-walk and other receiver biases can be properly removed in the post-processing with models validated in laboratory. Electronic noise leads to a ranging error whose standard deviation is inversely proportional to the signal/noise ratio (SNR) by a formula given in the following. At the lower voltage settings amplifier noise is predominant, while at the higher settings it is oscilloscope noise that is predominant. In the latter case, assuming a signal of $1/4^{th}$ of the full scale, the highest achievable SNR is of ~100 (accounting for both electronic noise and quantization).

The precision in estimates of time of arrival of laser pulses, measured in the presence of additive electronic noise, has been reported for the case of a cross-correlation peak detector [6]. The standard deviation is written

$$\sigma_\theta = \frac{K}{SNR} \tag{3}$$

with K a pulse-shape dependent constant given by

$$K^2 = \frac{\int C_n(\tau) C_s(\tau) d\tau}{C_n(0) C_s(0)^2} \tag{4}$$

where $C_s(\tau) = \int s(t)s(t+\tau)dt$ is the auto-correlation function for $s(t)$, the derivative of the normalized signal pulse shape, and $C_n(\tau) = \mathrm{E}\left[n(t)n(t+\tau)\right]$ the noise covariance, with $C_n(0) = \sigma_n{}^2$ the variance and $SNR = a/\sigma_n$ the ratio of signal amplitude (V) and RMS noise (V). For the simple case of white noise of bandwidth B_n and a raised-cosine (i.e. symmetrical) pulse shape of duration T at FWHM, K becomes

$$K = \frac{2}{\pi}\sqrt{\frac{T}{B_n}} \tag{5}$$

Consider a sampling interval of Δt=1 ns and a noise bandwidth of $B_n = 1/\Delta t$, it follows that K=2 ns (0.30 m) for T =10 ns. When combined with a *SNR* of 100, one can predict a ranging precision of 3 mm in single-shot. However, equation (5) is the most unfavorable case because of the symmetrical pulse-shape. In practice there is usually a shorter leading edge than falling edge. As a consequence, K is slightly smaller than predicted with the help of (5). This has been verified with the WA-ALRS in which the relatively short leading edge (4 ns) when compared to the FWHM duration (13 ns) yields values for K as small as 0.22 m [6]. In practice, RMS scatters over 100 measurements as low as 1.8 mm have been observed with this system.

Such a system could thus be implemented for SLR, provided similar SNRs are achievable. Link budgets for ranging to LAGEOS between 0.05 and 612 photoelectrons have been reported for MOBLAS stations, using high-speed PMTs [8]. There, the single-shot ranging accuracy is at the centimeter level. Conversely to the WA-ALRS, in SLR systems another error source is to be taken into account: photon detection statistics. Thus, assuming a photocounting detector is used, a cross-correlation peak detector would yield a single-shot accuracy between 3 mm and 0.3 mm for an average number of photoelectrons per pulse between 1 and 100 for a 100-ps duration laser pulse [15]. In order to yield a sufficient signal level at the input of the oscilloscope, it would therefore be necessary to use an APD and amplifier, or possibly a SPAD. However, a fundamental requirement for such a detector would be that its impulse-response is strongly repetitive in order to avoid a further source of bias. Additionally, its response time should ideally not be lower than ~10 times the oscilloscope sampling interval, i.e. 1.25-10 ns for 8-1 Gs/s commercially available digital oscilloscopes, e.g. LeCroy or HP (see next section).

4. Extension of the technique to two-color measurements

The main challenge of two-color systems is the measurement of differential times of arrival for two pulses at different wavelength with a few picoseconds precision [13]. Recently, measurements at different satellites have been reported with a streak-camera based system [16]. The authors emphasize the great disparity of measured pulse shapes during the course of the satellite pass, both for a given wavelength and between the two colors. They conclude that a cross-correlation technique may for this reason not be applied. Nevertheless, we believe that in this case too, the technique would apply, by simply adjusting the reference waveform to the satellite's response, i.e. performing a kind of auto-correlation. Actually, it should not be forgotten that in the same spirit, satellite signature corrections are usually made, depending on the actual satellite, SLR instrument, and satellite attitude [17].

For the purpose of two-color measurements, the system of Figure 1 should be slightly modified. Namely, an optical delay line should be included, in order to separate sufficiently (by ~50 ns) the two wavelengths in the oscilloscope record. Another alternative would be to use another channel for digitizing the second wavelength signal, without any delay line.

With the range receiver proposed above, the single shot precision in differential times of arrival is unfortunately to high for direct application to two-color measurements. An extrapolation of the system is therefore reported in Table 1, for higher sampling-rate oscilloscopes, different SNRs and shorter system impulse responses. There we have either assumed that a) an SNR of 100 is achieved whether the sampling rate and pulse duration, or b) that pulse duration and sampling are matched such that $T/\Delta t=10$, whether the SNR. In the latter case, formula (5) becomes $K=2\times\Delta t$.

Error source	1 Gs/s*	2 Gs/s*	4 Gs/s†	8 Gs/s‡
Sampling (*SNR*=100)				
T=10 ns	< 20 ps	< 10 ps	< 5 ps	< 2.5 ps
T=1 ns	—			
Electronic Noise ($T/\Delta t=10$)				
SNR=100	20 ps	10 ps	5 ps	2.5 ps
SNR=10	200 ps	100 ps	50 ps	25 ps

Table 1 : Single-shot timing accuracy as a function of sampling rate ; *observed with the LeCroy 7200, † predicted for LeCroy LC 574 AL, ‡ predicted for LeCroy LC 584 AL

Note that the higher sampling rates are usually obtained by coupling the inputs of the oscilloscope. Hence, a 8 Gs/s rate requires the four 2Gs/s inputs to operate as a single channel. For this reason, CH2 on Figure 1 should be replaced by the Trigger input, and the operational software should control the oscilloscope's trigger via GPIB.

5. Conclusion

Derived from our experiments with the WA-ALRS and from devices already tested in VLBI and proposed for SLR since long times, we propose a new way to detect transmitted and received laser pulses. We expect from this :

- a much more easy access to a wide range of post-processing computations, as it will be easy to look very carefully at the raw data even long time after the acquisition.

- a step towards a technique with a very low level of biases, at least for the ones concerning the detection and timing, as the whole detection and datation will be permanently calibrated as it is now the case for VLBI since two decades.

The corresponding modifications of a classical SLR station in order to incorporate such a measuring system seem to be very easy to implement. They include the installation of a laser diode pulse driver, a fast sampling oscilloscope and the necessary software to store and process raw data. Allowing for much longer laser pulses, it would also permit much more energetic pulses, thus improving the echo energy. We have already tested all the part corresponding to the sampling oscilloscope and the optimal data process, and we expect to test soon the other part of the device, the one corresponding to the emission and qualification of the optical calibration laser diode pulses. For this part, the time walk corresponding to the various detection modes (Geiger mode or linear mode) must be carefully checked and the possibility of a systematic correction between them has to be evaluated.

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