Verification of ELT Performance by Monte Carlo Simulations

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To study stochastic and systematic influences on the single-photon optical time transfer experiment ELT (European Laser Timing), a full-scale simulation tool was developed. In addition to the full simulation capability of the experiment's geometrical and relativistic properties, stochastic variability in detection and time keeping as well as variability in cloud coverage can be selected. Moreover, we consider the complication of reflections from multiple retroreflectors mounted on the ISS, which also affects the stochastic variability of detection. Eventually, systematics are implemented that are due to orbit and attitude errors as well as desynchronization of clocks. This study addresses errors in final time transfer products as well as the challenge of real-time time bias detection at the SLR stations.

Introduction

The European Laser Timing (ELT) (Schreiber et al. 2009) is an optical time transfer experiment that will be part of the ESA mission ACES (Atomic Clock Ensemble in Space) (Cacciapuotti et al. 2009). This fundamental physics mission will bring two high performance clocks on board of the international space station (ISS). The combination of both clocks will provide a timescale of unprecedented accuracy and precision in space. The optical time transfer between ground clocks and the ACES timescale will be carried out by SLR stations equipped with hydrogen masers. Time transfer is a combination of one-way and two-way ranging and is explained in Exertier et al. 2018. Like the LTT (Fumin et al. 2006), and in contrast to T2L2 (Samain et al. 2014), the one-way measurements will be performed in single-photon mode. The ELT data center (Schlicht et al. 2012 and 2016) is responsible for computing and providing the time transfer products.

Simulation software

To study the capability of time-transfer to Earth orbiting satellites a full-scale simulator is build up. The features integrated in the simulation as listed in Table 1 are of both, stochastic and systematic nature. Systematic errors in orbit, attitude and clock can be considered. Stochastic variability enters due to background noise, laser pulse width and jitter, detector jitter, clock noise and cloud coverage. The ISS orbits are provided as an input from a TLE propagator, but the simulation software also allows reading CPF orbits.

Table 1: Integrated components of the one-way and two-way simulation.

Geometric components and systematic effects	Earth orientation (IERS 2010 conventions) Station movement (IERS 2010 conventions) ISS orbit errors (3rd order tracking loop) ISS attitude error (3 axes, offset and oscillation) Detector and reflector positions Multiple reflectors Visibility constraints
Signal delays	Troposphere (Mendes and Pavlis) Sagnac effect Shapiro delay Reflector delays
Relativistic effects on clocks	Special relativistic effect General relativistic effects (sun, moon, Earth)
Stochastic components	Background noise Laser pulse width and jitter Detector jitter Colored clock noise Cloud coverage (frequency and duration)

Simulation of attitude and other errors

We use this simulation tool to study different influences on time transfer. These include multiple corner cubes in combination with the increased orbit and attitude errors of a cantilevered construction like the ISS as well as high stochastic variability due to single-photon detection. The single-photon mode for the detection of laser pulses in space ensures a reduction of systematic errors in time transfer as the time-walk effect of avalanche diodes is suppressed. As is typical for classical SLR in single-photon mode, only about 1% of the laser pulses will yield time transfer triplets. In combination with the limited repetition rate of 100 Hz for the gating of the on-board detector, this implies limited data points for analysis. To partly overcome these limitations, a reconstruction of triplets will be performed. This assumes a precise two-way range interpolation. A short-arc orbit adjustment is performed to prevent that orbit and attitude errors as well as modelling errors of the station movement enter into the time transfer products. The knowledge of the attitude of the space station is very poor with an estimated worst-case precision (3 sigma) of about 0.5° per axis. Unfortunately, not in all cases an orbit adjustment can compensate for an attitude error; a constant attitude offset will not affect time transfer as it is largely absorbed by the orbit adjustment, but a variable error will surely do. As the ISS is an extended structure, we expect the most intensive attitude variations – and therefore the attitude errors – to appear at multiples of the orbital period. We simulated three cases of attitude error variations with 4x, 2x and 1x per orbit in roll, pitch and yaw. Figure 1 shows the residuals of a short-arc orbit adjustment to simulated two-way measurements for the three cases and a rotation about the roll axis. A residual effect of the attitude error that varies with 4x or 2x the orbital frequency is clearly visible in all three plots. Only in the case of period that is equal to the orbital frequency the orbit adjustment can compensate for the attitude error.

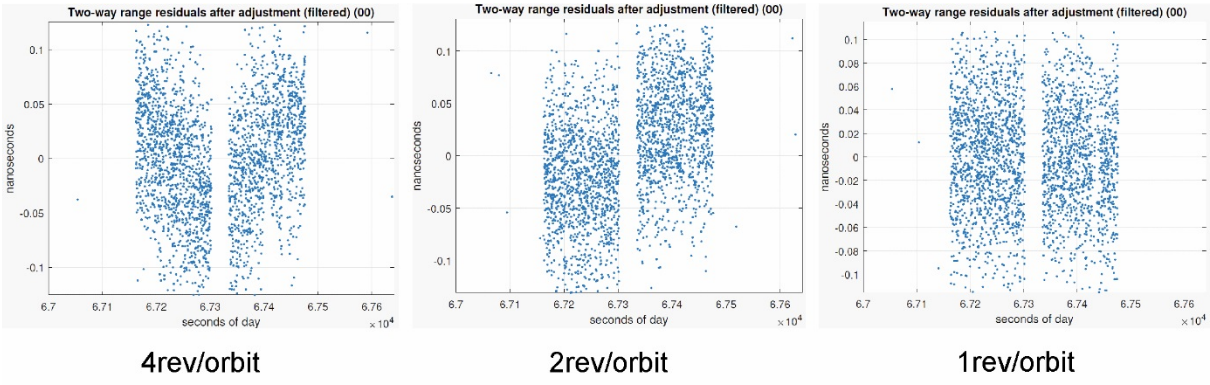

Figure 1: Variable attitude error (per revolution) leaves a signature in the two-way range residuals. This causes a systematic offset of the time-transfer in the range of some picoseconds.

Multiple CCRs

The ISS carries many corner cube reflectors (CCR) that are primarily dedicated for docking maneuvers. These reflectors produce additional returns as first experiments show. The analysis needs to take care of this by identifying the right (ELT) CCR. In addition, the SLR stations must be aware of multiple reflections as they have to guarantee ranging in single photon mode and need to adjust the time bias of the ISS. Therefore, real-time time bias detection is needed in case of day time tracking, where the range gate is about 100 ns and the orbit prediction error may be as large as 100 m. For these two purposes we implemented a new filtering method. First, a binomial filter (based on binomial statistics of the number of generated photo electrons) divides the time-vs.-range-gate space into 2D blocks, where data points in these blocks are counted and registered as returns, whenever the number exceeds a statistically derived limit. This limit is calculated based on the return rate, the background noise level and the desired probabilities for missing returns and selecting noise as returns. That followed, the two-way measurements are transformed into time bias domain. Every return is treated as it would belong to any reflector that could be seen from the station at that time. The time bias having most representatives is the time bias of the ISS; and only the right assignment of returns to reflectors contributes positively to this peak. Our tests show that this procedure works sufficiently well under the conditions of an attitude accuracy of 0.5° and an along-track orbit accuracy of 100 m to determine the real-time time bias within 50 ns. For the final time transfer product (with the knowledge of the final orbit) a selection of the ELT reflector returns can be achieved as long as the range to other reflectors is as close as about twice the reflector signature (filter criterion 2.2 sigma). The real-time time bias detection algorithm will be offered to each station contributing to the ELT experiment.

Monte Carlo Simulations

To test the influence of stochastic errors on the time-transfer experiment, we performed Monte-Carlo simulations. Each result was achieved by 80 individual simulations for the station Wettzell. Different background noise levels and analysis strategies were investigated with some results given by Table 2. A background noise rate of 5.00E+05/s is typical for a night time pass, whereas the higher value can be expected for day-time passes. The two analysis methods with and without the new filtering technique lead to different results, with the new filtering method giving the better results. This is remarkable and shall be further analyzed. We expect that this is related to the fact that noise events, which are recorded before the first and after the last signal of a pass as well as during cloud obstruction, are largely removed by the new filtering strategy. Day-time passes have less data points and therefore less precision. The predicted precision of 3 ps for one pass cannot be achieved under day-time conditions without noise reduction.

Table 2: Monte Carlo simulations of different background noise and different analysis strategies.

Background noise rate [1/s]	Binomial noise filtering	Time transfer σ $[ps]$
5.00E+05 (night)	no	1.6979
5.00E+05 (night)	yes	0.4541
5.00E+06 (day)	no	4.7743
5.00E+06 (day)	yes	1.8626

Conclusions

We developed a full-scale simulation program for one-way and two-way ranging to Earth-orbiting satellites. It can handle many stochastic and systematic errors influencing SLR measurements as well as optical one-way ranging. With the help of these simulations it is possible to study the constraints in orbit and attitude determination of an extended structure like the ISS for the purpose of time transfer. We showed that the high error in attitude will limit the accuracy and precision of the method of optical time transfer in single-photon mode. Hence, a new strategy for the two-way orbit interpolation must be developed. We therefore recommend tracking the ISS with the highest possible repetition rate, even though the one-way range gate is limited to 100 Hz or 1 kHz. Without attitude error the specified precision of 3 ps per pass can be achieved under the best possible conditions: night time and no clouds.

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