Detector Data Simulation and Filtering for the European Laser Timing (ELT) Experiment On-board ACES

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1. BACKGROUND

- Accuracy requirements on frequency and time transfer are continuously increasing.
- Most present satellite based clock comparison systems work in the microwave domain and are based on GPS and TWSTFT (Two-Way Satellite Time and Frequency Transfer).
- Recently, systems such as LASSO (LAser Synchronization from a Stationary Orbit) and T2L2 (Time Transfer by Laser Link) promised even better performance in the optical domain.
- In 2017 the ESA mission ACES (Atomic Clock Ensemble in Space) will bring a new generation of atomic clocks into the microgravity environment of the ISS, which will distribute a stable and accurate time base. In the frame of this mission the European Laser Timing Experiment (ELT) will be conducted.

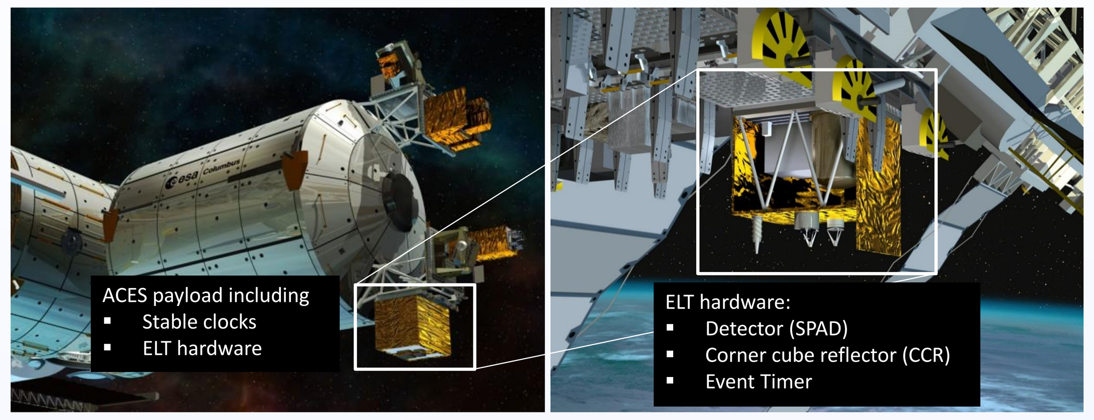


Figure 1: ACES payload with the ELT hardware as it will be mounted onto the ISS. (Courtesy of ESA)

- Clock comparisons and time transfer with picosecond accuracy
- Space-to-ground and ground-to-ground clock synchronization
- Common-view and non-common view modes

2. TIME TRANSFER PRINCIPLE & SIGNIFICANCE OF DATA FILTERING

- In the ELT scenario **temporal information is carried by ultra-short laser pulses**: The SPAD detects laser pulses fired from a satellite laser ranging (SLR) station towards ACES and the CCR reflects these pulses back to the ground station. The detection dates of the SPAD are recorded in the ACES time scale, while the two-way time-of-flight is used for precise ranging.
- **Time transfer and clock analysis is performed based on data triplets** comprising the time of transmission t_{start} of a laser pulse, its time of reception $t_{detector}$ at the ELT detector and its time of reception t_{return} back at the station detector. Accordingly, the synchronization χ_{AS} between the ground clock A and the satellite clock S is

$$\chi_{AS} = \frac{t_{start} + t_{return}}{2} - t_{detector} + \tau_{relativity} + \tau_{atmosphere} + \tau_{geometry},$$

where $\tau_{relativity}$, $\tau_{atmosphere}$, and $\tau_{geometry}$ are correction terms for relativistic effects, atmosphere and the geometrical offset between the CCR and the SPAD, which depends on the position and attitude of the ISS.

- In common-view configuration (figure 2, top) the ISS visibility times at two SLR sites A and B overlap so that time transfer χ_{AB} between the clocks of A and B is given by $\chi_{AB} = \chi_{AS} - \chi_{BS}$. In non-common view mode (figure 2, bottom) temporal information is carried by the ACES oscillator over the distance where the ISS is neither visible for station A nor for station B, i.e. clock stability becomes relevant.
- Apart from the actual signal detection times $t_{detector}$ and t_{return}, which are triggered by the laser photons, **a large amount of noise data is recorded.** This data primarily results from other sources of illumination and detector dark counts.
- Filtering the actual signal detection events is one of the main data processing challenges of the ELT data center, which is hosted by our institution. **The present work focusses on ELT detector data filtering**, as filtering two-way data is a standard task in SLR.

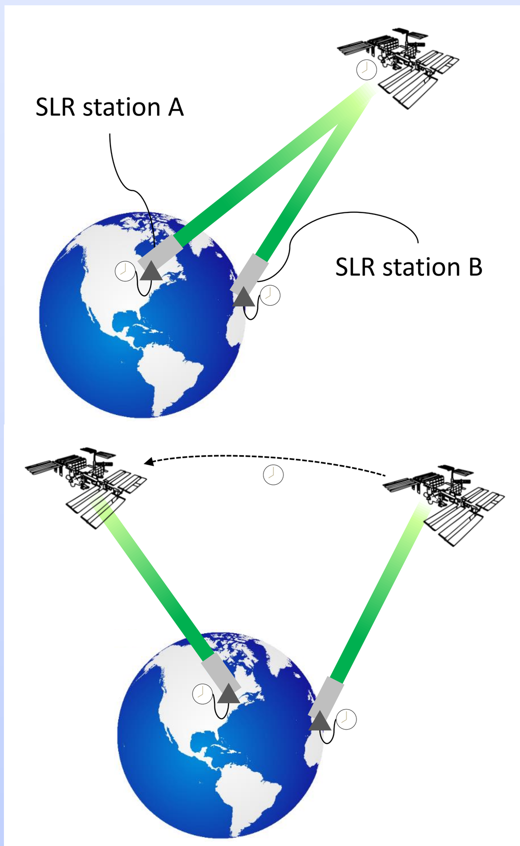
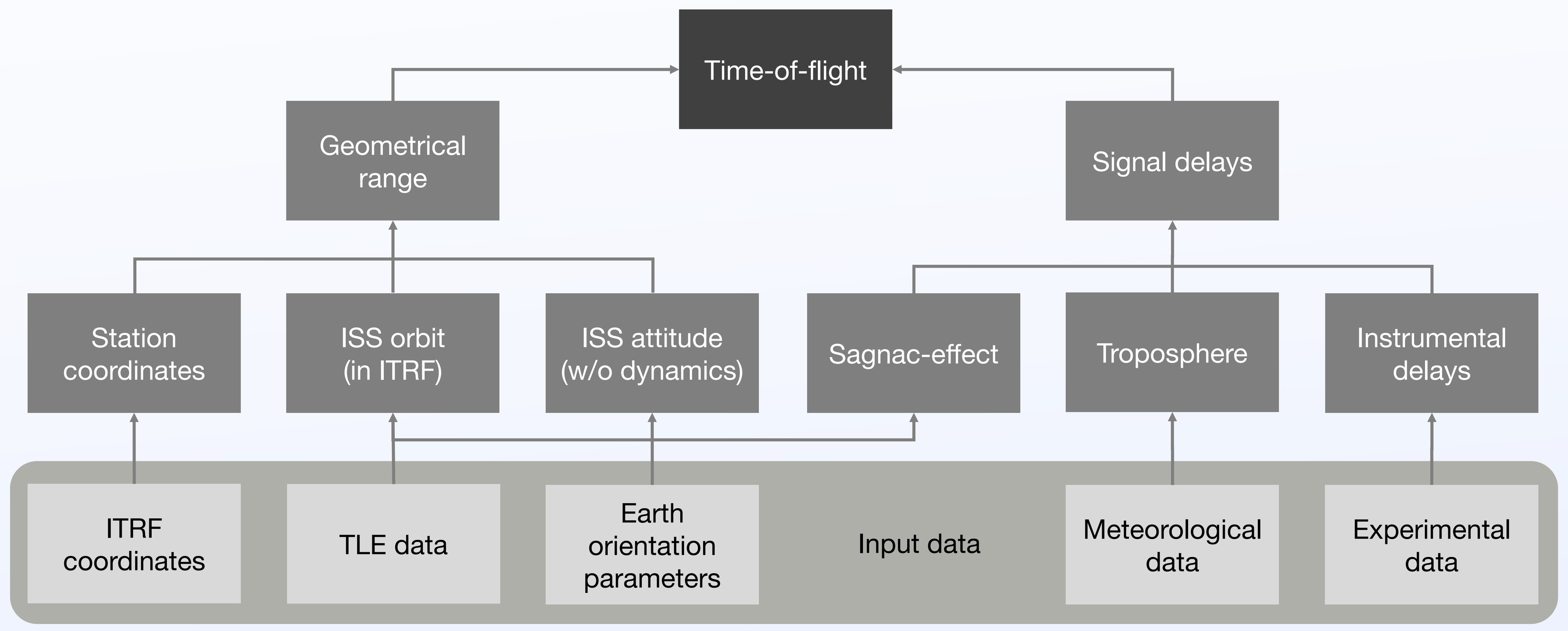


Figure 2: Time transfer principle in common-view (top) and non-common view mode (bottom).

3. DETECTOR GATING & LASER PULSE ARRIVAL TIMES

- To allow for high precision time transfer the ELT detector works in **single photon mode**. This mitigates detector time-walk effects facilitating higher timing precision.
- **Gating the detector and applying a suitable data processing strategy** is necessary to cope with the high noise levels in single photon mode. The ELT detector is periodically activated (gate open) w.r.t. the local ACES time scale. The gates are opened shortly before periodic time events to account for detector dead time and too early arriving laser pulses.
- SLR stations must adjust the transmission times of the laser pulses so that they arrive at the detector when the gate is open. Initially, **pulse propagation times are computed using comparatively inaccurate orbit predictions.** These predictions will be available as CPF files with errors of less than one hundred meters.
- During an ISS pass the imprecise orbit predictions can be improved in real-time using the precise two-way ranging data. We model the time-of-flight of a laser pulse as follows:



4. DETECTOR DATA SIMULATION

- The **detector noise statistics are derived from external data of an indoor experiment**, which used one of the ELT detector package breadboard versions to precisely measure the time delays between detector activation and registration of signal or noise photons.
- We fit exponential functions to the histograms of the noise delay data to obtain **analytical noise probability densities.** These are used to simulate the random noise events of the ELT detector. The decision whether a **signal or a noise detection is simulated** is made randomly according to a Bernoulli distribution.
- Ideally, the laser pulses should arrive exactly at the periodic time events about which the detector gates are centered. **Deviations of the actual from the ideal pulse transmission times** (e.g. due to inaccurate knowledge of the ISS orbit) **and the pulse width itself cause deviations from these ideal times of arrival**, which are also considered in our simulations.
- Figures 3 and 4 show simulated detector data for different background noise levels and orbit prediction errors (time and range bias) broadening and shifting the signal peak.

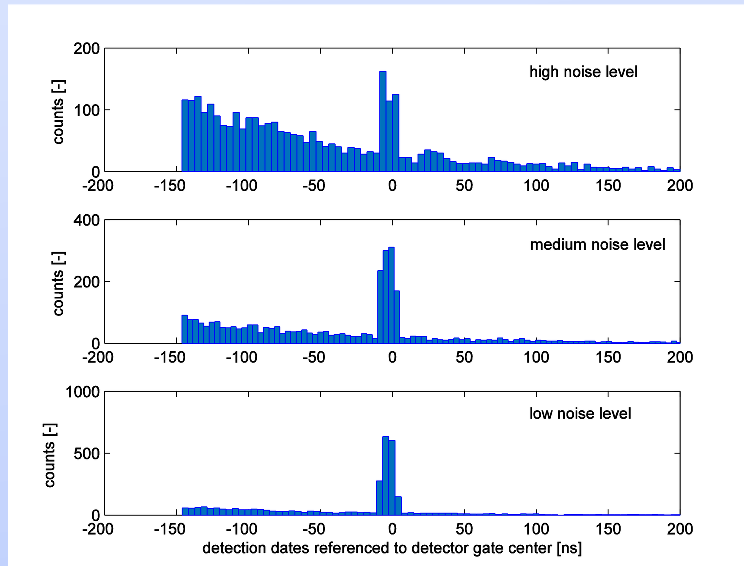


Figure 3: Simulated detection dates of one ISS pass for a small orbit error and different noise levels.

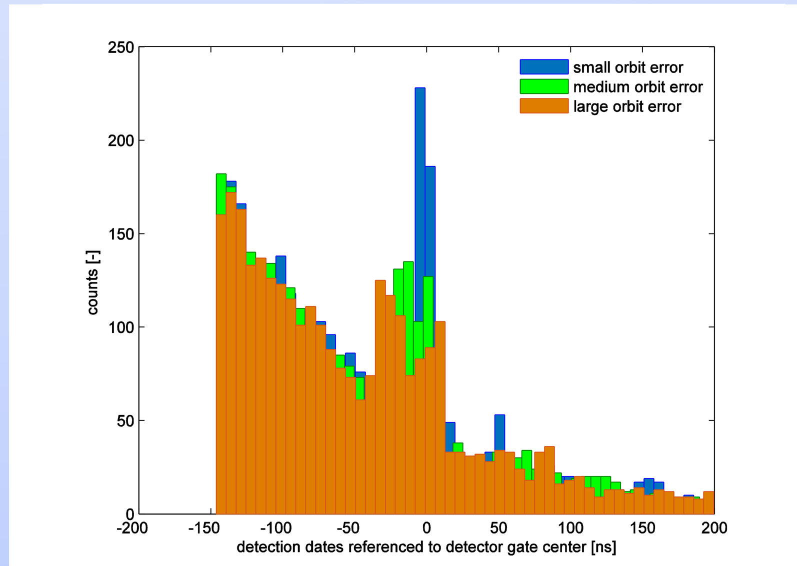


Figure 4: Simulated detection dates of one ISS pass for a high noise level and different orbit errors.

5. DETECTOR DATA FILTERING STRATEGY

- Detector data filtering refers to identifying the ELT detection dates, which originate from laser photons, among extensive noise. In a first step, we reference the recorded ELT detection dates to UTC.
- The **detection date residuals** (observed detection date minus computed detection date) serve as the basis upon which we decide whether a detection date belongs to a signal or noise detection event. To compute the detection date of a laser pulse its time-of-flight must be determined. Therefore, **we improve the orbit data by fitting corrections** that are quadratic in time in the along-track and radial directions based on the precise two-way ranging data (see figure 5). The association of transmit times and signal generated detection times is unambiguous.
- To remove most of the noise we **fit an exponential curve to the histogram of the residuals.** Prior to that, we "dilute" the histogram using wider bins and rescale it to reduce the impact of the signal peak on the fit. We only keep residuals with original histogram bars that are above that curve, as the rest is most likely noise data.
- Finally, we **iteratively remove residuals that deviate more than 2.3 times the standard deviation from the histogram mean value.** After each iteration we remove the linear trend from the remaining residuals to keep the resulting histograms Gaussian-like.

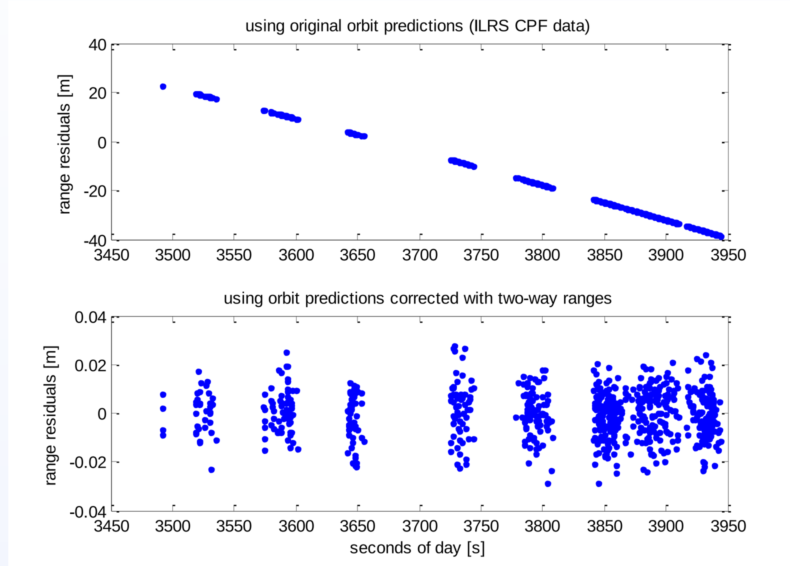


Figure 5: Two-way range residuals before (top) and after (bottom) correcting the orbit predictions based on real two-way ranging data from T2L2.

6. VALIDATION OF THE FILTERING STRATEGY

- The presented filtering strategy worked well for our simulated data.
- For validation we tested our algorithms with real T2L2 data.
- Orbit predictions were used to see how our strategy performs in quick-look analyses.
- Figure 6 shows the filtered one-way residuals.

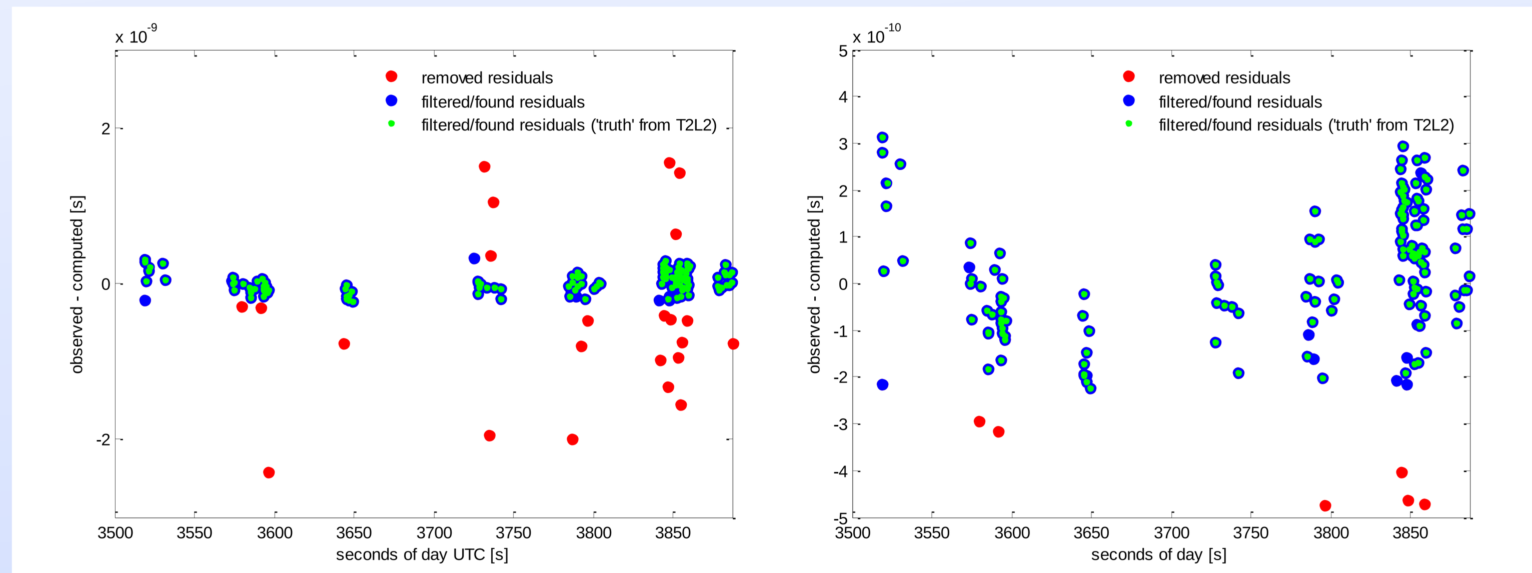


Figure 6: Results of filtering T2L2 detector residuals using the presented filtering scheme. The right plot shows details of the results indicating how well our strategy works.

7. CONCLUSION

Identifying the time triplets "ground-transmission", "space-detection", and "ground-reception" is crucial for time transfer based on ultra-short laser pulses. The identification of two-way time stamps among extensive noise is a standard task in SLR as opposed to identifying one-way time stamps of the new ELT space detector. Working in single photon mode in presence of strong background illumination is challenging. Hence, we simulated data for the ELT space detector based on experimentally derived noise statistics and TLE orbits. We presented a strategy for ELT detector data filtering, which can cope with our simulated detector data as well as real data from the T2L2 experiment.