

## Considerations for an optical link for the ACES mission

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### Abstract

*The design of an atomic clock ensemble to be operated on the International Space Station (ISS) is currently under development in Europe. This experiment constitutes a high precision timescale in space and offers the great opportunity to study the behavior of “state of the art” atomic clocks in a micro-gravity environment. A key element for this project is a microwave link between one or several ground stations and the ISS clock ensemble. Due to systematic delays on the propagation path of the microwave link (insufficient knowledge of the dielectric number as a function of time in the troposphere and ionosphere and phase center variations) there remains an uncertainty in the time comparison (ie. the time difference of a specific epoch on the ground and in space) of up to several nanoseconds. Optical technologies, based on time of flight measurements of ultra short laser pulses, offer the prospect to reduce this uncertainty in time comparison to approximately 25 ps one way. The successful LTT (Laser Time Transfer) project on the Chinese Compass M1 satellite is based on an earlier version of the proposed experiment below. Furthermore we note, that a similar system, T2L2 (Time Transfer by Laser Link) was initially part of the ESA selection in 1997 for ACES, but shifted to the Jason 2 satellite mission following a re-arrangement of the project in 2000.*

### Scientific Objectives

Timescale comparisons by GPS and TWSTFT (microwave) techniques are in routine operation for many time laboratories around the world. The comparison of timescales by means of cw optical frequency transfer is the most advanced technique in this respect and has been used to compare optical clocks over distances of several kilometers [1,2]. While this approach essentially works on a narrow bandwidth transmission line, it fails to provide a direct link to an exact epoch (point in time) for the two timescales under investigation with an accuracy of better than several ns. In order to compare the epochs of two widely separated timescales at high precision, one has to apply a broadband technique such as the time of flight measurement of ultra-short laser pulses. Such an approach is characterized by several critical aspects, which are:

- Geometrically well defined start point of optical range measurement
- A well defined propagation path with clearly modeled path delays (given in the visible)
- Geometrically well defined end point of optical range measurement
- 2- way ranging to establish a precise distance and to derive the epoch of arrival at the ISS
- Low jitter conversion of laser pulse to time (epoch)

The ACES mission provides a unique opportunity for the evaluation of the limits in precise clock comparison investigation. The existing microwave link serves as a reference against

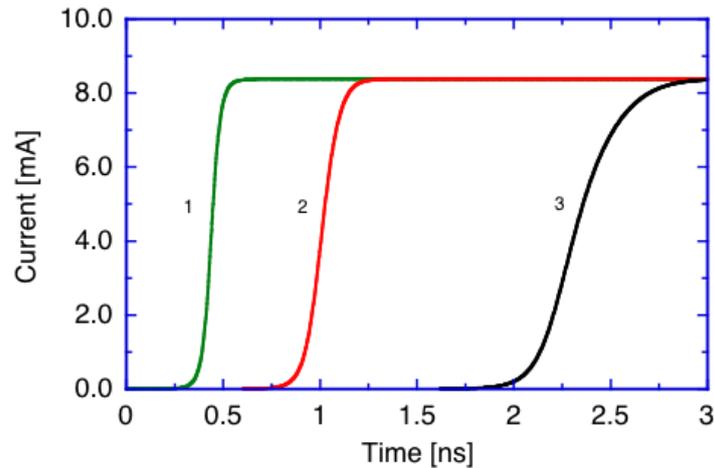
which the optical technique can be compared. Apart from improving the atmospheric propagation models by comparing the refractive index to the microwave propagation delay (including phase center stability of the microwave antenna), SLR will provide independent precise optically derived orbits of the ISS as well as a link between a timescale on the ground and the ACES timescale with an accuracy of about 100 ps.

## Method

Satellite laser ranging (SLR) provides a viable technique to achieve these objectives. However some detailed considerations are required to utilize the full potential. When the time of arrival of a laser pulse is determined, the corresponding epoch is not obtained instantaneously. The conversion process of an optical pulse to an electrical signal causes a delay and the mapping of this electrical pulse on the timescale of a clock is subject to further delays. These delays are usually not constant and among other effects they vary as a function of operating temperature and signal strength. In order to minimize these influences, SLR adopts frequent system calibration procedures, where the time of flight of laser pulses over an a priori known distance are used to establish the currently valid value of this unavoidable system delay. In order to do a time comparison between a precise clock on the ground and the atomic clock ensemble in space SLR operations to a corner cube on the satellite are an essential ingredient. From SLR ranges one can precisely compute the time of arrival of the laser pulse at the location of the corner cube of the satellite with respect to the timescale of the SLR system on the ground, in turn can be used to relate the timescale on the ground to the timescale of the atomic clock ensemble. The corresponding epoch  $t_{rec}$  of the time of arrival of the laser pulse at the spacecraft with respect to the timescale established by the atomic clock ensemble is

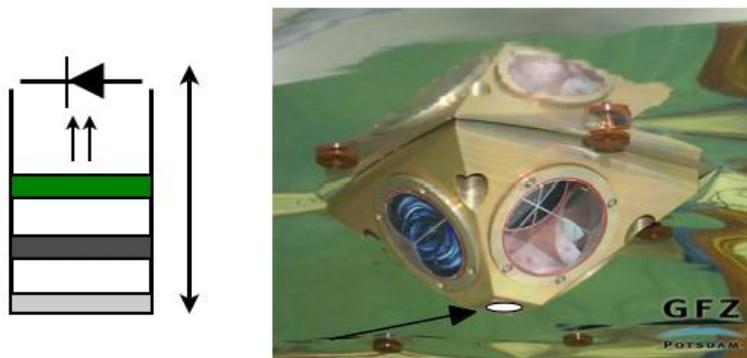
$$t_{rec} = t_{start} + \frac{r}{c} + \tau_{sat} + \tau_{off} ,$$

where  $t_{start}$  is the epoch when the laser pulse passes the reference point of the SLR system on the ground.  $\tau_{sat}$  is the internal timing delay on board of the satellite and  $\tau_{off}$  is the offset between the timescale on the satellite and the timescale on the ground. It is important to note that the quantity  $r/c$  can be determined very well with SLR and that this is the particular strength of the ranging technique. (For simplicity this discussion does not look at relativistic effects or clock drifts.) In order to determine the best available value for  $\tau_{off}$  as the prime quantity of interest,  $\tau_{sat}$  must be both established well and be kept as constant as possible. This is where the ultimate challenge of the clock comparison sits. Apart from electronic delays the conversion of light into an electrical signal represent the most critical components in the ranging link. The delay associated with the generation of photo-electrons from an incidence light pulse (photoelectric effect) depends very much on the input signal strength, which in turn is hard to control because of the speckle nature of the SLR pulse as a result of passing through the turbulent atmosphere. Figure 1 shows the modeled delay for the generation of an electrical output pulse from 3 different levels of optical input intensity for a silicon solid state detector [3] with thick absorption layer.



**Figure 1.** Output signal response to an input light pulse at  $t = 0$ , for a strong signal of 100 photo-electrons (1), a moderate signal of 10 photo-electrons (2) and a single photo-electron (3).

For the model 3 different levels of signal strength have been investigated ie. 100 photo-electrons (1), 10 photo-electrons (2) and 1 photo-electron. As one can see from fig. 1, one obtains the shortest delay for the strongest input signal. This reduction in response time comes from a shortcut of the electron multiplication process in the avalanche region of the semiconductor. Intensity variations therefore lead to a varying delay and are extremely hard to quantify. However, if the input light level is reduced so much, that the detector strictly operates in the single photo-electron regime, the corresponding timing-jitter is minimized. Thin layer photo-detectors, such as the K14-SPAD [4] reduce the unavoidable jitter approximately by a factor of 5. This comes at the expense of sensor sensitivity, but for the ranging to the ISS this drawback is not an issue.



**Figure 2.** Retro-reflector as used on the Satellite Champ. Only one corner cube contributes to the echo at each incoming laser pulse. The arrow marks the location, where the wide-angle detector should be located. The left side illustrates the detection scheme (see text for details).

Figure 2 shows the proposed reflector element for the ACES project. It mainly uses the GFZ design, which has been successfully applied to the Champ satellite. At the location indicated on the lower part of the photo in Fig. 2 the wide acceptance angle photo-detector arrangement is located. The basic principle of the detector arrangement is sketched on the left

side of fig. 2. The light enters at the lower part of the sketch. An optional diffusor plate sits at the beginning of a small 1 – 2 cm long duct in order to scatter the incoming light evenly around the duct. This is followed by a spectral filter (bandwidth 0.3 to 10 nm, the exact value to be yet determined) around the frequency doubled Nd:YAG laser line (532 nm). A K14-SPAD is located at the bottom of the duct. This avalanche diode is operated in the Geiger mode with a gate pulse derived at equidistant time intervals from the onboard timing system. As a consequence of this, the ranging procedure requires all participating laser stations to fire laser pulses such that the arrival time at the satellite is pre-determined to within  $\sim < 1 \mu\text{s}$ . This procedure has been successfully tested on the Chinese Compass-M1 satellite [5]. The detected laser pulses are timed on the satellite with respect to the local timescale. The length of the receiver duct along with the diffusor and the input aperture determines the total attenuation of the incoming laser beam in order to operate the photodiode in the single photo-electron regime for low jitter detection.

### Principle of Operation

The principle of operation is based on low light flux time coherent detection of laser pulses and aims at synchronizing transmitter and receiver such, that the laser pulse arrives at the receiver shortly after the activation of the gate-pulse required for Geiger mode operation [6,7]. Since only the first photo-electron after gate-on can be detected and timed, the signal of interest has to arrive earlier than a statistically probable noise event. If the laser pulse arrives at the detector on the satellite within the first 100 ns, the probability of obtaining a valid datation on board of the satellite is very high. For the ACES mission the following cases of illumination and a constant flux-rate of the sun as parameterized below have been used:

Solar induced average photon flux is:  $0.2 \text{ watts/m}^2/0.1 \text{ nm}$  (wavelength window). This corresponds to  $10^{18} \text{ photons/s/m}^2/0.1 \text{ nm}$ . The Earth albedo is assumed to be 10%. The field of view of the detector on the satellite is approx. 1 radian at about 400 km altitude.

**Case 1** – Detector illuminated by direct sunlight:  $> 10^{10}$  photons per second

photon-counting impossible, however there is no damage on the photodiode and the recovery of the photodiode takes place within a few seconds after the full illumination.

**Case 2** – Daylight operation, the entire footprint on the Earth illuminated by sunlight

$3 \cdot 10^{12}$  photons/s/10 nm on detector active area diameter of 1 mm  
 $1 \cdot 10^{11}$  photons/s/10 nm on detector active area diameter of 200  $\mu\text{m}$   
 $2 \cdot 10^9$  photons/s/10 nm on detector active area diameter of 25  $\mu\text{m}$

**Case 3** – Night time on entire footprint with a reduction on photon flux of a factor of 1000, which is a pessimistic estimate.

$3 \cdot 10^9$  photons/s/10 nm on detector active area diameter of 1 mm  
 $1 \cdot 10^8$  photons/s/10 nm on detector active area diameter of 200  $\mu\text{m}$   
 $2 \cdot 10^6$  photons/s/10 nm on detector active area diameter of 25  $\mu\text{m}$

The above listed values correspond to a worst case scenario estimates. The back-ground photon flux depends, among others, on the optical receiver filter bandwidth. A 10 nm

bandwidth is used for the calculations above. With a narrower filter bandwidth the background photon flux is decreased linearly, e.g. 30 times less for 0.3 nm filter. However this must be balanced against the desired operational robustness of the receiver unit, which improves with wider filters.

## System Requirements

There are essentially 3 relevant subsystems to consider. These are a) the retro-reflector assembly, b) the optical receiver and c) the event timing unit. All of these subsystems are discussed individually below:

**a) Retro-reflector Assembly:** As indicated in figure 2, a modified version of the Champ or Grace reflector array design is proposed. The metal part of the assembly is with 10 cm length on a side slightly larger than for the mission Champ and Grace, since it will also house the active optical receiver element. Approximately 1 cm increase in length and width of the baseplate is required for that purpose. The corner cubes have already demonstrated their suitability for a low Earth orbiter application. There are no ambiguities for SLR applications since only one corner cube is contributing to the signal at any laser shot from any direction and with a theoretical cross section of ca. 1 million square meter it is an easy SLR target. At the same time the optical receiver can be reached from any directions with the exception of low elevation angles of the satellite relative to the observing SLR station. The eccentricity between the CCR-Array and the geometric point of reference of the atomic clock ensemble has to be determined with millimeter accuracy prior to the launch of the payload. The weight of the CCR-Array is below 0.5 kg.

**b) Optical Receiver:** The basic design of the optical receiver contains 3 parts. These are the detector optics, the photo-detector itself and the necessary electronic circuits. The latter in particular consists of a gating circuit, a break-down quenching circuit, the detector chip temperature control, the gate voltage biasing circuit and the power supply, which generates all required voltages out of the +/- 5 Volt supply voltage from the general supply line. Depending on the general design of the ACES package, it has to be determined whether the electronic circuit will be located inside the CCR-Assembly or inside the ACES package. The power requirement for the entire detector package is typically below 3 watts at maximum. The detector optics, consisting of the diffusor plate, the spectral filter, something between blocking glass with 10 nm of bandwidth or an interference filter of 0.3 nm bandwidth and maybe an iris or baffle for the reduction of unwanted background light result in a unit with a volume of about 3 square centimeters, no requirement for power and about 25 grams of weight. This includes also the K-14 SPAD (photo-detector). In particular we propose:

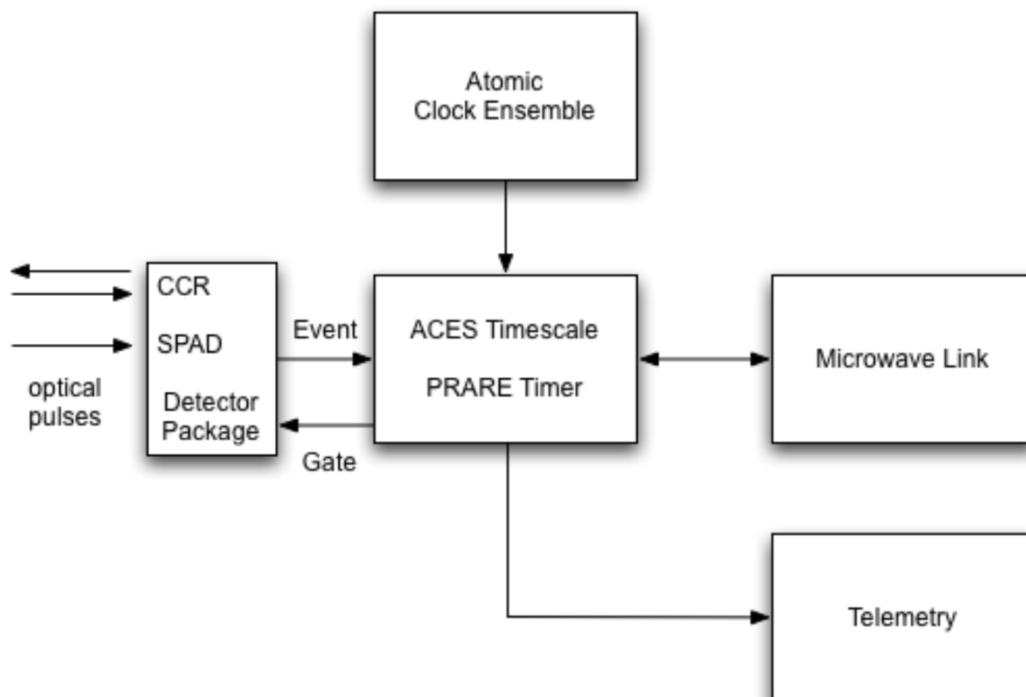
200  $\mu\text{m}$  detection chip K14 SPAD, vacuum housing, TE temperature stabilization  
 timing resolution: 30 ps (rms)  
 timing stability:  $\approx 10$  ps  
 power consumption: 3 Watts  
 weight: optics and detector electronics:  $\approx 500\text{g}$   
 temperature range:  $-30\dots +30$  C  
 For stabilized temperature ( $\pm 2$  K), higher timing stability (1ps) is obtained  
 Gate time before event:  $> 0.1 \mu\text{s}$  (fully illuminated FOV)  
 $>20 \mu\text{s}$  (full darkness)

**c) Timing Electronics:** The epoch of the arrival of the laser pulse at the spacecraft has to be recorded on the onboard timing system. This function is obtained from the PRARE microwave system, which provides a synchronized timescale between a suitable microwave transmitter/receiver station on the ground and the ACES payload. The output of the optical detector package is a NIM-pulse with very sharp rise time, which is passed on to the PRARE system. Figure 3 shows the FPGA hardware dedicated for the timing of the optical signals as provided by TimeTech GmbH.



**Figure 3.** Prototype of the event timing hardware on the microwave link electronics.

The PRARE package determines the corresponding epoch of the leading edge of the pulse and also handles coarse filtering functions, the telemetry of the recorded events to the PRARE ground stations and generates the required Geiger mode gates for the K-14 SPAD. Appropriate repetition rates have to be defined by the science team. They may cover a range from 10 Hz up to 10 kHz. The limiting factor will be the allocated bandwidth of the telemetry down link rather than technical reasons on the detector package or at the PRARE control system. Figure 4 gives a block diagram of the general concept of the optical link with respect to the entire ACES payload.



**Figure 4.** Simplified block diagram of the ACES payload and the interfacing to the optical timing package.

It can be seen, that the required modifications to the ACES payload are minimal. Furthermore, both weight and power consumption of the optical package are low.

**d) Operating Modes:** All participating SLR stations have to have the ability to fire the laser at a predefined epoch with a required accuracy of about  $0.1 \mu\text{s}$  in order to contribute significantly to the data yield for a fully illuminated Earth in the field of view. This condition relaxes by 1 – 2 orders of magnitude for an entirely dark footprint of the detector on the ground. Furthermore they have to time the start epoch of laser fire preferably to much better than 100 ps of resolution. Finally the stations must be capable of generating fullrate SLR observation data, in order to allow the time comparison between the timescale on the ground and at the atomic clock ensemble in a post-processing analysis step independent from the ranging network. Therefore the impact of this mission on the tracking network in terms of hardware requirements is minimal. Furthermore the operation follows standard ILRS ranging procedures. In order to guarantee eye-safety at the ISS (if applicable) the ILRS has a number of established procedures such as elevation or time restricted tracking as well as laser output power control (both by increased beam divergence and reduction of transmit energy).

**e) Laser Tracking Calibration:** As shown in the range equation in the introductory part of this proposal, there are several extra delays to be dealt with. While  $\tau_{\text{off}}$  is the offset between the timescale on the ground and the timescale of ACES and hence the quantity of interest,  $\tau_{\text{sat}}$  describes the internal signal delay at the satellite. This delay is caused by cables, the transfer time of the signal in the detector unit and by varying signal levels at the photodiode. Cable, detector and electronic delays have to be calibrated preflight. They are constant over the mission, if the detector and subsequent electronics are temperature controlled and the optical signal level is kept at or below the single photo-electron level, corresponding to state 3 in fig. 1. Using a second channel for event timing would provide the possibility to also evaluate characteristics of the rise-time of the signal and classify them with respect to the optical signal strength. So signal levels corresponding to the states 2 and 3 can be identified, tagged and removed from the time comparison process. This mode of operation has to be implemented by preflight laboratory calibrations. Standard ILRS network calibration procedures are removing ground station biases from the round trip ranging to the ACES optical detector package. Laser ranging stations with a good timing system like the H maser timescale in the Wettzell observatory will provide the most significant input to the optical tracking to the ACES package.

## Conclusion

The Chinese Compass M1 mission as well as T2L2 have demonstrated that time transfer via an optical laser link is a viable application for comparing the timescale between ground and satellite as well as between to remote locations on the ground (common view and non-common view). From that point of view it is a challenging task to extend the time transfer to a precise clock ensemble in a microgravity environment, which is tied to the ground with a two way microwave satellite time and frequency transfer unit, one of these components providing the necessary event timing capabilities. Apart from linking two distinctly different high precision time transfer techniques together, such an experiment will allow a study of residual refraction uncertainties between the optical and the microwave regime. We hope that this time transfer experiment can be eventually accommodated on the ACES space segment.

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