The European Laser Timing (ELT) experiment on-board ACES

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Abstract— **The development of techniques for the comparison of distant clocks and for the distribution of stable and accurate time scales has important applications in metrology and fundamental physics studies. Additionally, the rapid progress of frequency standards in the optical domain is presently demanding additional efforts for improving the performances of existing time and frequency transfer links. Present clock comparison systems in the microwave domain are based on GPS and TWSTFT (Two-Way Satellite Time and Frequency Transfer). ELT (European Laser Timing) is an optical link presently under study in the frame of the ESA mission "Atomic Clock Ensemble in Space". The on-board hardware consists of a corner cube retro-reflector (CCR), a single-photon avalanche diode (SPAD), and an event timer board connected to the ACES time scale. Light pulses fired towards ACES by a laser ranging station will be detected by the SPAD diode and time tagged in the ACES time scale. At the same time, the CCR will re-direct the laser pulse towards the ground station providing precise ranging information. This paper will present the ELT scientific objectives, the recent studies performed on the ELT hardware, and the dedicated test campaign carried out at the Wettzell laser ranging station to demonstrate the experiment feasibility. Recent test results will be also discussed.**

I. INTRODUCTION

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 of the order of a nanosecond. 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 uses an earlier version of the proposal below [5]. 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.

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)
- High temporal stability

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), Satellite Laser Ranging (SLR) will provide independent precise op-

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tically 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.

II. TIME TRANSFER BY LASER LINK

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 perform 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 contributes essential information. 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, which immediately provides the relation between the timescale on the ground and 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

$$t_{rec} = t_{start} + \frac{r}{c} + \tau_{sat} + \tau_{off} \ , \tag{1}$$

where t_{start} is the epoch when the laser pulse passes the reference point of the SLR system on the ground. τ_{sat} is the internal timing delay on board of the satellite and τ_{off} is the offset between the timescale on the satellite and the timescale on the ground. It is important to note that the light travel time r/c (including delays introduced by the atmosphere) can be determined very well with SLR and that this is the particular strength of the ranging technique. In order to determine the best available value for τ_{off} as the prime quantity of interest, τ_{sat} must be both established well and be kept as constant as possible. This is where the ultimate challenge of the clock comparison resides. 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. 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 (3). As one can see from fig. 1, the shortest delay is obtained 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 reduction is gained at the expense of sensor sensitivity, but for the ranging to the ISS this drawback is not an issue.

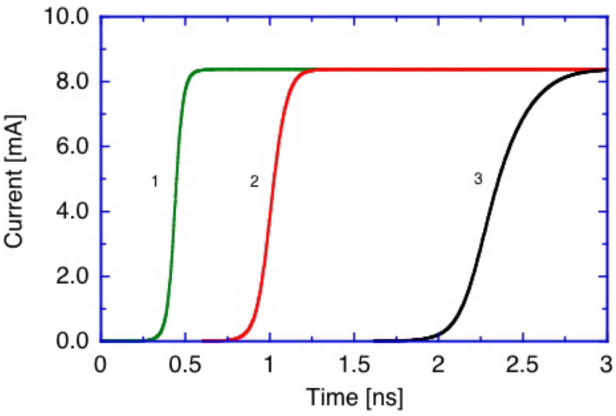

Fig. 1. Output signal response to an input light pulse at t = 0, for a strong signal of 100 photo-electrons (1), a moderate signal of 10 photo-electrons (2) and a single photo-electron (3).

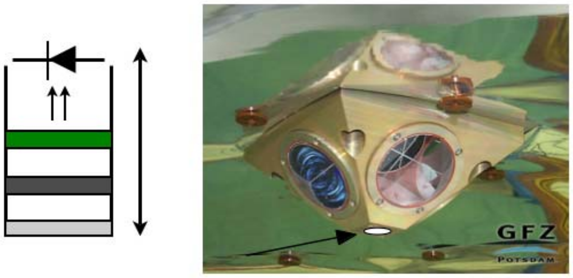

Fig. 2. Retro-reflector as used on the Satellite CHAMP. Only one corner cube contributes to the echo at each incoming laser pulse. The arrow marks the location, where the wide-angle detector should be located. The left side illustrates the detection scheme (see text for details, foto courtesy of GFZ).

Figure 2 shows the proposed reflector element for the ACES project. It is based on the GFZ design, which has been successfully implemented on the CHAMP satellite. At the location indicated with the arrow in the right hand side of fig. 2 the wide acceptance angle photo-detector arrangement is located. The basic principle of the detector arrangement is sketched on the left hand side of fig. 2. The light enters at the lower part of the detector assembly. An optional diffusor plate at the entrance of a small 1 – 2 cm long tube scatters the incoming light evenly around the duct. A spectral filter behind the diffusor (bandwidth 0.3 to 10 nm, the exact value to be yet determined) selects photons close to 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 , 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 1μs. This procedure of operation 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 diffuser and the input aperture determine the total attenuation of the incoming laser beam in order to operate the photodiode in the single photo-electron regime allowing low jitter measurements.

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-opening 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 performance evaluation for the ACES mission three different cases of illumination and a constant flux-rate of the sun have been used: The average solar photon flux is 0.2 watts/m^2/0.1 nm (wavelength window) which corresponds to 10^{18} photons/s/m^2/0.1 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. Three basic scenarios are relevant:

- The detector is illuminated by direct sunlight corresponding to a flux exceeding 10^{10} photons per second which renders photon-counting impossible. However, the photodiode suffers no damage and recovers within a few seconds after the end of full illumination.
- In daylight operation with the entire footprint on the Earth illuminated by sunlight, but no direct exposure of the detector to the sun results on average in 2×10^9 photons/s/10 nm hitting detector (with an active area of 25 μm). Laser Ranging is possible, but requires that the laser pulse arrives at the detector within some 100 ns after the gate is armed (time coherent ranging).
- Night time on the entire footprint will reduce the photon flux by at least three orders of magnitude as a conservative estimate. This corresponds to a convenient ranging situation of 2×10^6 photons/s/10 nm on a detector with an active area diameter of 25 μm

The above listed flux values correspond to a worst case scenario estimates. The background 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.

III. WETTZELL GROUND BASED DEMONSTRATION EXPERIMENT

In order to demonstrate all the required functions of the laser link to ACES we have designed an experiment where the proposed hardware for the space segment has been integrated into the measurement setup of the SLR observatory on the ground. In this way the entire laser link between a ground station and a satellite equiped with an active detector could be fully tested. The only difference between this evaluation experiment and a real application is the fact that the laser pulse is bounced back from the satellite and detected at the ground station, rather than being detected on the satellite. This results in a double passage through the atmosphere and some loss of signal intensity due to the longer propagation path. Since the signal on the SPAD needs to be attenuated to the single photon detection regime anyway, the longer path length is of no concern for the experiment.

Figure 3 shows a block diagram illustration of the experiment. The upper part of the block diagram shows the typical SLR functions. A pulse laser emits short laser pulses, which are fired at a satellite by an afocal telescope tracking the target. Corner Cube Reflectors (CCR) onboard the satellite are bouncing a small portion of the laser light back to the observing station, where the arrival is detected by photodetector (Micro-Channel Plate, MPC) and timed on the local timing system. By subtracting the time of arrival from the time of emission and correcting for the extra delay of the Earth atmosphere, the range to the particular satellite is measured at the epoch of the laser fire event with a precision of 2 mm – 1.2 cm, depending on the structure (apparent optical depth) of the CCR assembly.

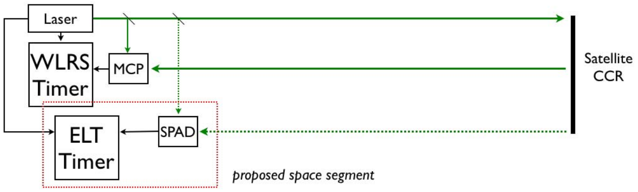

Fig. 3. Block diagram of the Wettzell Ground Based Demonstration Experiment. An arbitrary SLR satellite with a suitable Corner Cube Reflector (CCR) is used as a passive space segment. The laser echos are received by the usual SLR system and in parallel by the proposed satellite receiver hardware.

The proposed space segment hardware as described in section II has been integrated into the optical setup of the Wettzell Laser Ranging System (WLRS) in a way that matches the testable functions as closely as possible. A K14-SPAD along with the timing hardware from the TWSTFT package (TimeTech GmbH) according to the current ACES design were added to the WLRS ranging hardware as a selfcontained measurement package. A beam splitter with a 9:1 intensity distribution ratio was inserted such that the SPAD package was reliably operated in the required single photon regime. This ensures the absence of a detector dependent bias as outlined in the paragraph related to fig. 1. Figure 4 shows the setup at the receiver section of the WLRS. In order to obtain comparable ranges for both detector arrangements during the tracking of a satellite pass, the laser fire epochs were also fed to the "space segment" hardware. When the hardware eventually is operated on the ISS, this information has to be matched after the recorded echo registrations are transfered to ground by telemetry. However, since this part is a straight forward function it is not required to test that in our ground based experiment.

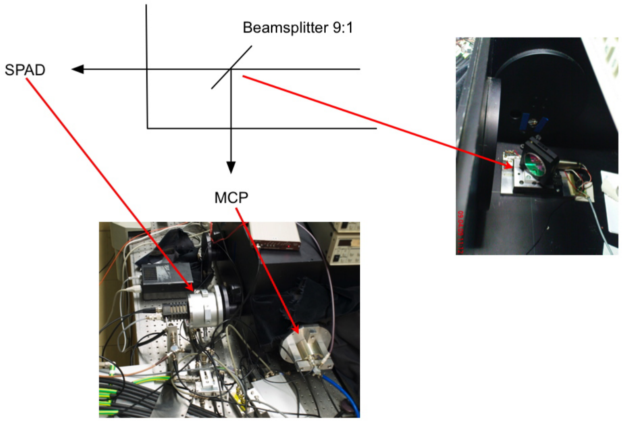

Fig. 4. Experimental setup at the WLRS. The MCP detector and the SPAD share the same receive beam via a 9:1 beam splitter. The low transmission reduces the return signal level to the single photon regime in which the SPAD is operated in order to avoid intensity related system biases.

IV. RESULTS

A. Stability Test of the WLRS

Before integrating the additional timer and detector we have performed stability tests of the WLRS timing system. At first the system was run for several hours, calibrating the ranging to a local laboratory target at constant distance with a fire rate of 10 Hz. From these measurements the Allan deviation shown in fig. 5 was derived. After about 100 seconds a minimum well below 1 ps has been obtained. However, this test only shows the intrinsic stability of the measurement system. Additional influence factors have to be considered for satellite measurement. First of all the signal level of the detected laser pulse is very stable in the laboratory while satellite ranging measurements are affected by strong shot by shot intensity fluctuations due to widely variable speckle patterns caused by atmospheric turbulences. In addition the microchannel plate (MCP) photo-detector triggers off the leading edge of the laser pulse rather than centering on the full temporal width of the ranging signal as avalanche photodiodes at low signal levels do. Nevertheless this test demonstrates the high resolution of the measurement concept.

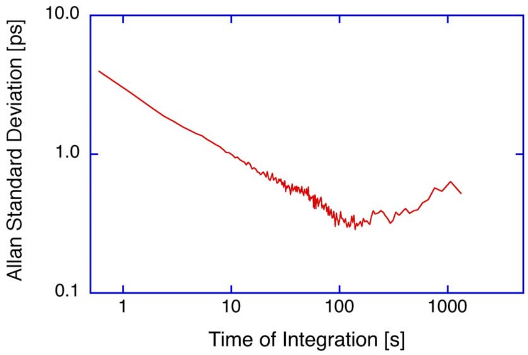

Fig. 5. Allan deviation of the WLRS ranging to a constant local target, using an MCP.

Since the ELT experiment also aims at non-common view clock comparisons, we have to characterize the long-term stability of the SLR system. Figure 6 shows the corresponding Allan deviation of a series of system calibrations taken over a timespan of more than a month. One can see that the stability of the timing system stays below 10 ps over more than 10 days. Most of this variation seems to originate from temperature variations in the ranging electronics, since the time series of the individual calibration measurements shows a small systematic trend.

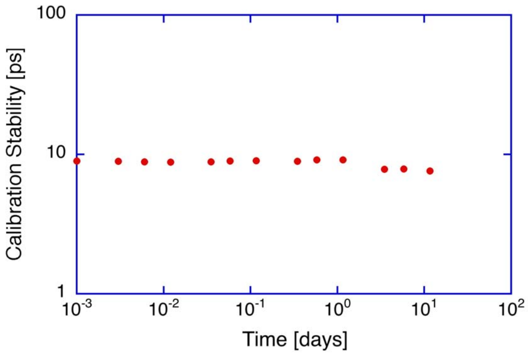

Fig. 6. Allan deviation of the WLRS ranging to a constant local target, using an MCP.

B. Detector Evaluation

The ELT detector package was provided for experiments in Wettzell. It consists of a solid state photon counter based on Single Photon Avalanche Photodiode (SPAD) pulse biased above the break voltage. The detection chip is a K14-SPAD silicon element with an active area of 200 μm diameter and thermoelectrically cooled down to -60 degrees Celsius. It is actively quenched and gated by built in electronics. The detector effective dark count rate corresponds to 25 kHz. This rather high value is well tolerable considering expected high background photon flux in the intended application.

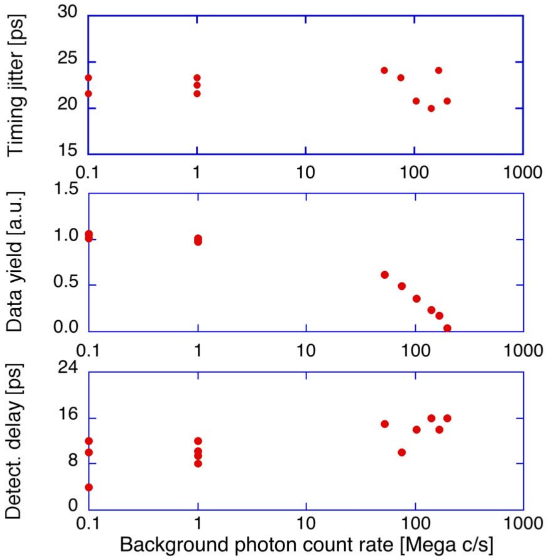

Fig. 7. The results of laboratory calibration tests of the SPAD detector package for Wettzell experiment. Time correlated photon counting experiments using 48 ps long laser pulses were performed, the average optical signal strength was ≈ 1 photon per pulse. Additionally, the detector was illuminated by a continuous thermal light source (tungsten bulb), which generated background photon flux. The resulting timing jitter (top), data yield (center) and photon detection delay (bottom) and their dependence on the background photon flux is shown.

Prior to operation in the field experiment, the detector was tested in a series of laboratory calibration tests in a classical Time Correlated Photon Counting experiment. A laser diode providing 48 ps long pulses was used as a photon source, the timing was performed by an event timing device with a resolution of about 1.2 picosecond. The detector is characterized by a detection jitter well below 25 ps rms, the detection delay stability was found to be ±5 ps per hour. This excellent photon counting stability is achieved over an enormous dynamical range of background photon flux ranging from zero up to about 200×10^6 of photons per second hitting the detector active area. Figure 7 summarizes the results.

After performing the laboratory evaluation of the detector, all hardware was installed and operated at the WLRS. After some adjustment reliable operation in single photon detection mode has been achieved as shown in fig. 8. It turned out that the measured timing jitter of 103 ps was much larger than the approximately 25 ps obtained from the pulser experiment (see fig. 7 top). Since the Nd:YAG laser of the SLR system constitutes the only major change of the experimental setup, it was concluded that the laser pulse width of this laser is well in excess of the 80 ps specified by the producer. Indeed, independent measurements revealed an anomalous laser pulse width of 185 ps. This has no effect for the MCP measurements since they trigger from the leading edge of the laser pulse, rather than the full pulse width, which is seen by the avalanche diode in single photon detection mode. This mode of operation however is mandatory for the detector on the spacecraft in order to be independent from unwanted timewalk effects and to survive the high background radiation levels.

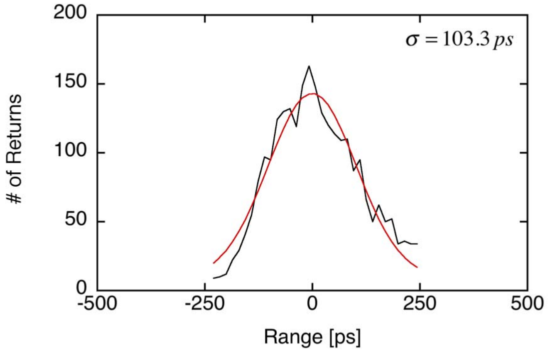

Fig. 8. Calibration histogram taken with the SPAD at the WLRS laser ranging hardware, using the event timer of "TimeTech GmbH". A jitter of 103 ps has been obtained.

C. Comparison of Satellite Observations

After the evaluation of the system calibration several satellit passes have been measured with both detectors operated simultaneously each on a specific timing systems in order to test the entire laser link between a ground station and a satellite equiped with an active detector. Apart from the satellite "Ajisai", we also observed passages from "Envisat" and "Starlette". A passage of the latter satellite was chosen for the evaluation of the system performance, because the structure of the retro reflector array on Starlette does not contribute significantly to the measurement uncertainty and because a good data coverage over the entire satellite pass has been obtained. Figure 9 and fig. 10 show the obtained histograms of the satellite returns relative to the orbit of the satellite taken by the SPAD and the MCP respectively. As one can see, there are a lot more returns for the MCP measurements as opposed to the SPAD measurements, which is caused by the vastly different signal levels received by the two different detectors. Fitting a Gaussian to the histogram and filtering recursively with a 2.2σ cut-off criterion yields a jitter of 89 ps for the MCP and 116 ps for the SPAD. Again, this

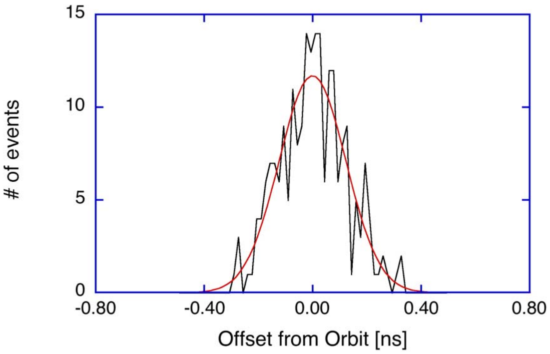

Fig. 9. Histogram over the range measurements relative to the satellite orbit of Starlette, obtained from the SPAD detector. A jitter of 116 ps has been obtained for this pass.

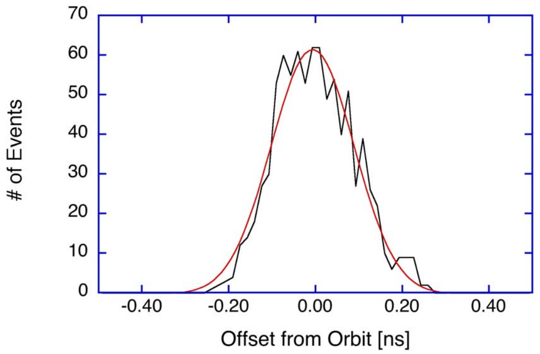

Fig. 10. Histogram over the range measurements relative to the satellite orbit of Starlette, obtained from the MCP detector. A jitter of 89 ps has been obtained for this pass.

result is worse than the expectation, but it is fully consistent with the calibration signal evaluation. Furthermore this small increase of the satellite ranging jitter over the calibration jitter demonstrates the feasibility of the one-way optical ranging approach for a time transfer experiment. However, in order to achieve the full potential of the time transfer a shorter pulse width of the laser is required.

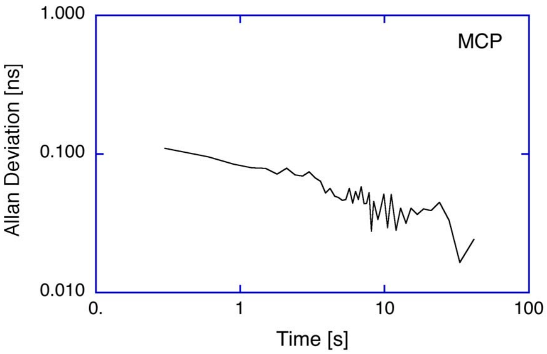

Fig. 11. Allan deviation of the WLRS ranging stability obtained from measuements of a satellite pass of Ajisai using an MCP.

In the next step we have evaluated a pass of “Ajisai” with good simultaneous coverage on both detectors. Once the satellite returns have been extracted from the measurement noise, a Allan deviation graph has been computed from the remaining timeseries of satellite echos. The results are displayed in fig. 11 for the MCP and in fig. 12 for the SPAD detector. Both detectors show similar behavior. At around 50 seconds of integration a measurements stability of 20 ps is achieved for the MCP. The timeseries for the SPAD is shorter and with fewer returns, but even in this case the stability reached after 20 seconds is of the order of 25 ps. Extrapolating the graph of fig. 12 to 100 seconds one would yield the expected measurement stability of 8 ps for the SPAD.

V. CONCLUSION

In this paper we have investigated the properties of a one-way time transfer experiment between a ground station and the projected detector and timing hardware for the European Laser Timing Experiment (ELT) proposed for the Atomic Clock Ensemble in Space (ACES) mission in preparation for the Columbus module on the ISS. In a ground based experiment the quality of a laser link between the Wettzell Laser Ranging System and several different satellites has been tested, after essential detector properties such as the operation at the single photon light level regime, successful operation at high background radiation levels and low detector jitter had been shown. The laser pulse-width of the WLRS was found to be well in excess of the specification value of 80 ps. The obtained results and independent measurements show an actual pulse width of about 180 ps. This led to satellite returns with larger jitter than expected. However, the comparison between laboratory calibrations and satellite returns are compatible with the experimental expectations. An Allan deviation analysis of the measurements of both detectors indicate a measurement stability as expected, provided the available satellite passes are sufficiently long with a high enough data yield.

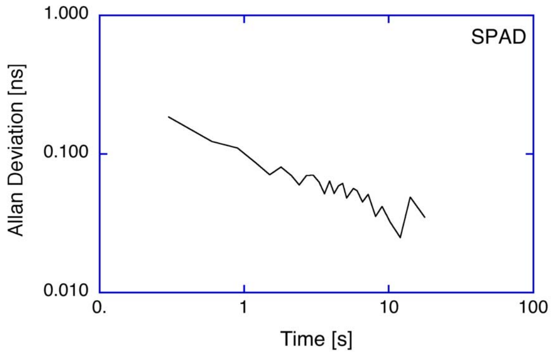

Fig. 12. Allan deviation of the WLRS ranging stability obtained from measuements of a satellite pass of Ajisai using an SPAD.

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