Development of the European Laser Timing instrumentation for the ACES time transfer using laser pulses

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ABSTRACT

We are presenting the work progress and recent results in the field of the European Laser Timing instrumentation for the ACES time transfer using laser pulses. European Laser Timing (ELT) is an optical link presently under preparation in the frame of the ESA mission "Atomic Clock Ensemble in Space" (ACES). The on-board hardware consists of a comer cube retro-reflector (CCR), an optical receiver based on a single-photon avalanche diode (SPAD) and an event timer board connected to the ACES time scale. Short laser pulses fired towards ACES by a laser ranging station will be time tagged with respect to the ground time scale. They will also be detected in space 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 procedure provides ground-to-space and ground-to-ground time transfer with a precision and accuracy outperforming the radiofrequency techniques.

Extensive work has been done on the photon counting detector. Three different versions of the photon counter for space application have been developed and tested. The main areas of interest were: minimal power consumption requirements of the optical detector package, long term stability of detection delay and a broad operational temperature range. The detector shall be capable to operate within a temperature range of − 50° to + 50° C while keeping the detection delay stability on the picosecond level for temperature variations of 6.5 K peak-to-peak. The detection delay shall be characterized and controlled – e.g. delay between the event of photon absorption and the appearance of the electrical pulse on the detector output. A configuration of the optical receiver able to maintain uniform sensitivity over a wide field of view of 120 degrees was developed. The parameters of the optical receiver obtained in the ground tests meet safely all the requirements for the ELT mission.

1. INTRODUCTION

A laser time transfer link for the European Space Agency is under construction for its application in the experiment Atomic Clock Ensemble in Space (ACES). The device is expected to be launched toward the International Space Station (ISS) in 2013. The main objective of the European Laser Timing (ELT) laser time transfer system is the precise synchronization of ground based clocks and the ACES clock on board the ISS with a precision of a few picoseconds and an accuracy of 50 picoseconds [1]. The project is a spin-off of the existing projects of laser ranging to artificial satellites around the Earth within the satellite laser ranging (SLR) community [2].

During the design process of the optical receiver several concept changes over previous realizations were necessary [1]. First of all the optical receiver was separated from the corner cube retro reflector array and was installed inside the ACES module. This configuration will maintain a much more stable operation temperature for the optical detector package. Additionally, the flat input aperture was replaced by a cylindrical construction, what has the property of maintaining a more uniform optical receiver sensitivity over a wider range of incidence angles.

2. OPTICAL RECEIVER CONCEPT AND DESIGN

The orbit altitude of the International Space Station is about 400 km. Taking into account the satellite laser ranging station transmitted energy per pulse and the laser beam divergence the signal photon flux at the satellite orbit is of the order of 10^{13} photons per square meter and per laser shot. The photon counting approach to the optical signal detection has been selected in order to reduce the systematic biases as much as possible. The advantage of a minimum of systematic errors is counter-balanced by additional requirements on the optical detection and data reduction process. Therefore the photon counting detector has to be gated synchronously with the on-board time scale, so that the laser has to be fired at pre-defined epochs. The solar light scattered in the Earth atmosphere and by the Earth surface itself will contribute to the background photon flux superimposed on the useful optical signal. The optical receiver has two key functions:

a) delivery of the laser pulses to the active area of photodetector with predefined attenuation and field of view, and
b) suppression of the background flux photons.

The photon counting detection module has been designed and is under construction in our group [3]. It is based on the Single Photon Avalanche Diode (SPAD) and an active quenching and gating circuit. The diameter of the detector active area is 100 microns.

The main optical receiver parameter requirements are as follows:

a) signal attenuation adjusted to deliver an average signal of 1 photon to the 100 µm detector aperture for the case of a signal photon flux density of 10^{13} photons per square meter,
b) field of view ± 60 degrees from nadir with the optical transmission as uniform as possible, and
c) optical band-pass filtering with 0.3 to 2 nm filter bandwidth centered at 532 nm, the actual filter bandwidth will be determined later.

The entire optical receiver must be simple, rugged and stable to operate in space at low Earth orbit for 3 years.

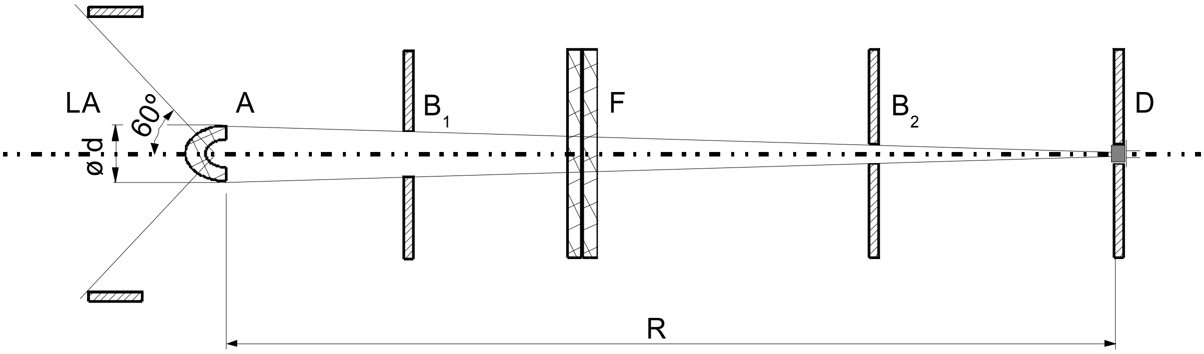

Fig. 1. Scheme of the proposed optical receiver, the diffusing entrance aperture ***A*** of diameter ***d*,** the band-pass optical filter ***F***, set of baffles ***B***, detection chip ***D*.** The total distance between the entrance aperture ***A*** and the detector ***D*** is ***R***. The field of view of the optical detector is limited by the limiting input aperture ***LA*.**

The optical scheme of the receiver is shown in Fig. 1. The photons are scattered by the entrance aperture ***A*** of diameter ***d***. The paraxial photons are passing trough the band-pass optical filter ***F*** and hit the detection chip active area ***D***. The photons scattered off-axis are blocked by a set of baffles and pinholes ***B***. The total optical attenuation is given by the properties of the input aperture, the optical filter transmission and by the geometrical relation ***(R/detector chip active area diameter)***^{2}. The distance ***R*** is expected to be around 65 mm resulting in an attenuation factor of the order of 10^6. The field of view of the optical receiver needs be ± 60 degrees. The entire optics is placed in a nadir pointing direction from the space to ground. To ensure the uniform sensitivity of the entire optical detector, the suitable shape of the input diffusing aperture ***A*** has to be selected. A rough flat glass surface was naturally the first proposal. However, such a diffusing aperture acts as a Lambert light source with scattered intensity decreasing according to the cosine of the inclination angle. For this reason different aperture shapes such as a cylinder, a cone, and a truncated cone were investigated and compared with respect to their scattering characteristics. The influence of the aperture form for the wavelength of 532 nm has also been examined. The results are summarized in Fig. 2. The relative signal intensity is plotted as a function of the incident angle of the laser beam relative to the optical axis. In the diagram the intensities are normalized to unity at 20 degrees inclination angle.

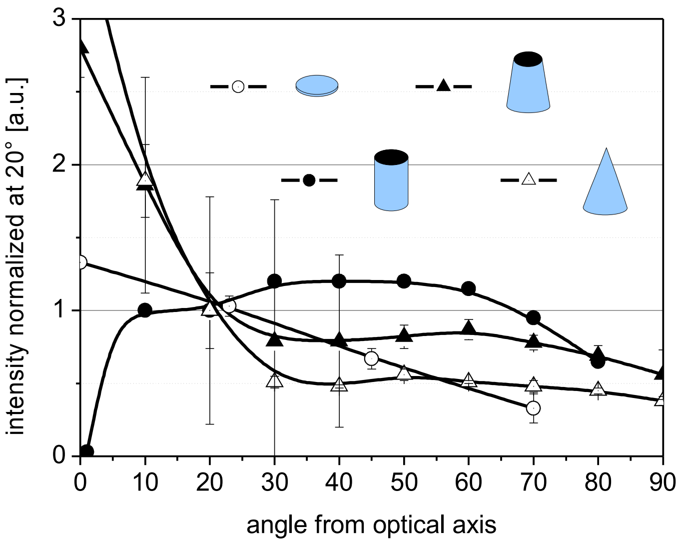

Fig. 2. Scattering properties of different profiles of fused silica input apertures at 532 nm, shown as intensities normalized at 20 degrees vs. inclination angle. Profiles symbols shown Al-coated faces in black and rough input faces in gray (light blue) color.

The combination of the rough surface of a cylinder and a blinded circular front face provide the most uniform signal intensity over a wide range of inclination angles. This will result in a flat signal to noise ratio dependence over the inclination angle, despite of received signal level decreasing with square of the range distance. The highest signal level is also obtained for the cylindrical shape with blinded input face causing a “dead zone” for signals coming from the nadir direction. This means there are is no signal for the a vertically pointing laser beam. Because this region in small, it does not represent a serious problem and will not cause a reduction of useful data. Typical SLR stations are able to precisely optically track low flying space object (ISS or similar) up to elevations only slightly above 80 degrees from the horizon. It means that the signal will arrive on the detector optics on-board the satellite at the incidence angle of 10 degrees or more.

The combination of optical blocking glasses and an interference filter is used to block the unwanted photons (e.g. background light) from entering the detector. If the ratio of the ***d/R*** is smaller than 0.1, the beam divergence at the filter entrance is within ± 2.5 degrees from the optical axis. A conventional optical filter with 0.3 to 2 nm bandwidth centered at 532 nm is also required, the exact bandwidth however will be determined later. The final selection is a trade-off between signal to noise ratio, system robustness and space qualified optical filters availability. In general – a narrow filter would provide better signal to noise ratio on the optical detector output, a broader filter would improve the device robustness over a broad temperature range.

The resulting optical receiver design is as follows: The input aperture ***A*** is formed by a fused silica cylinder, it has a diameter of 3 mm and it is 5 mm long, its input cylindrical surface is diffuse, its front circular face is Al-coated. The optical distance ***R*** between the input aperture and the detector is 65 mm. The rather moderate interference band-pass filter from 0.3 to 2.0 nm wide, centered around a wavelength of 532 nm may be used. All the components of the optical receiver are already available as space qualified version and are simple and rugged.

The optical receiver setup was tested in an indoor experiment for overall optical attenuation and field of view and for its timing properties. The continuous wave diode pumped frequency doubled Nd:YAG laser providing 2 mW at 532 nm wavelength was used as a light source for attenuation and field of view tests. The optical attenuation is tuned such, that the exposure to a photon flux of 10^{13} photons / m^2 on an average generates a signal of 1 – 1.5 photons hitting the active area of a detector with a diameter of 100 µm. This is valid for signal incidence angle in the range of 10 to 60 degrees. The optical receiver has been tested in the time domain using an Hamamatsu laser diode delivering 48 ps long pulses at 778 nm wavelengths. The photons scattered by the rough surface propagate different path lengths toward the detector. Obviously, the path lengths difference is proportional to the aperture dimensions. Selecting the input aperture size in the range of single millimeters a negligible deterioration of timing performance of the photon counting detector, both for the random and the systematic component, was achieved.

3. RECEIVER ELECTRONICS DESIGN AND TESTS

The photon counting detector is based on the Single Photon Avalanche Diode (SPAD) operated in an actively gated and quenched mode. The mature detection chip based on the K14 technology with an active area diameter of 100 µm is used.

Fig. 3. Picture of the electronics of the photon counting detector, version ELT 3.0. The detection chip is on the right. The device is thermally isolated to maintain the temperature within the operating range of +25° to +80° C.

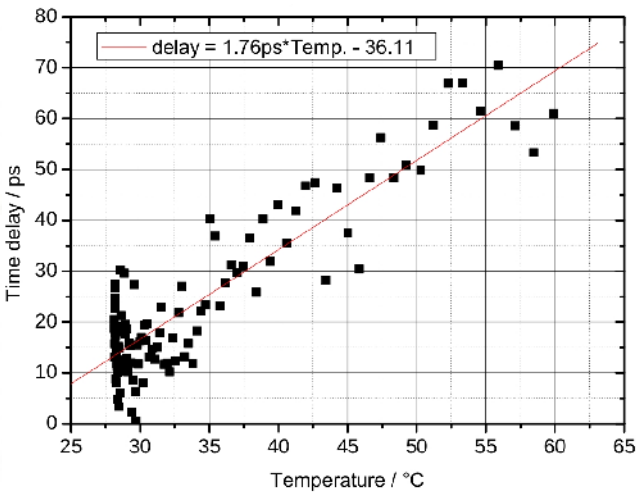

Fig. 4. The temperature dependence of the photon detection delay versus temperature. Note the slope of the dependence of + 1.76 ps / K.

Three different versions of the control electronics have been built and tested. The figure of merit were: a minimal power consumption of the optical detector package, a long term stability of detection delay and a broad operational temperature range. The detector shall be capable to operate within a temperature range of − 50° to + 50° C while keeping the detection delay stable on the picosecond level for a temperature variation of 6.5 K peak-to-peak. The latest version (ELT 3.0) of active quenching and gating electronics board is based on a combination of PECL and CMOS logical circuits. The ultrafast PECL comparator manufactured by Analog Devices ensures the high timing resolution and especially the high timing stability of the entire detector over a wide temperature range. The remaining logical components are low-power CMOS-type. for the operation the detector only needs a single power supply voltage of 5.3 ± 0.1 V, while the total power required is significantly lower than 1 W. The electronics board can be operated over the required temperature range with the SPAD detection chip biasing power supply designed to compensate the temperature dependence of the detection chip breakdown voltage.

Figure 3 shows a photo of the electronics of the photon counting detector, version ELT 3.0; the detection chip is sticking out on the right side. The entire device is placed inside a thermostat, to maintain operate the detector over a temperature range from room temperature up to + 80° C. The temperature dependence of the pure electric delay of the entire circuit board was measured to be + 0.2 ps / K. The temperature dependence of the photon to electric signal detection delay is shown in Fig. 4. The calculated slope is 1.76 ps / K resulting in < 12 ps delay difference over a temperature range of 6.5 K, corresponding to the expected temperature variations for the detector between day and night. It is expected that the temperature coefficient can be further reduced from the presently achieved value down to below 1 ps / K.

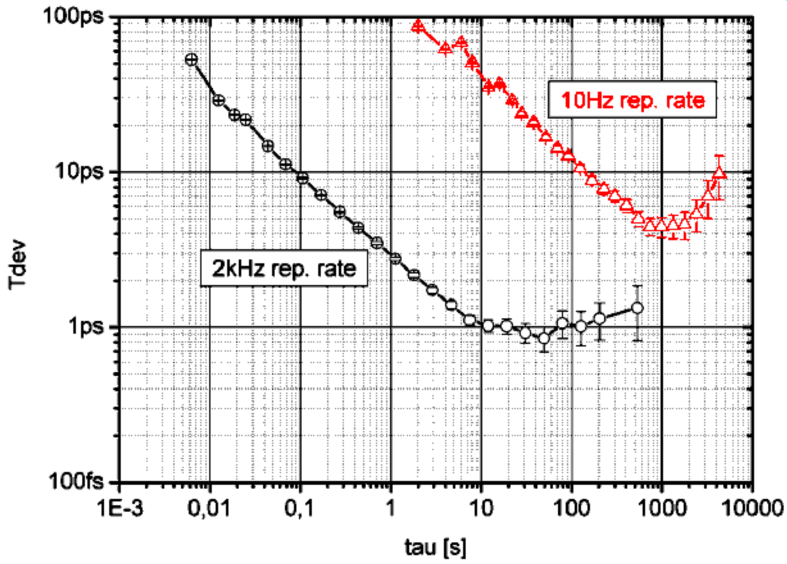

Fig. 5. The timing resolution and stability (***T_DEV***) of the ELT photon counting detectors together with the entire laser ranging signal loop. The upper curve (triangles) corresponds to the 10 Hz repetition rate operation and modest resolution timing system. The lower curve (circles) corresponds to the operation with repetition rate of 2 kHz and the top performance laser ranging system (SLR Graz, Austria).

The timing stability of the entire laser time transfer chain was measured in two configurations. The results are summarized in Fig. 5, where the T_{DEV} values are plotted. The upper curve (triangles) corresponds to the worst possible scenario: laser pulse width of 50 ps, 10 Hz laser fire rate, a laser to echo ratio of 5 %, and the a timing electronics resolution of 50 ps. From the data one can conclude, that for one measurement session – one satellite pass over the observer within a period of 200 seconds a time transfer precision of 10 ps can be obtained. The measured values are matching the ones well, which were obtained during the demonstration experiment carried out at the Wettzell Laser Ranging System early 2009 and published in [1]. In addition to this, the best possible scenario is plotted in the same figure by circles.

This data was collected at the satellite laser ranging station in Graz, Austria. The system is based on a laser generating 8 ps long pulses at the repetition rate of 2 kHz. A timing system with resolution below 8 ps was used to record the data. One can conclude, that for the best possible scenario the time transfer precision of 1 ps is achievable for measurement time intervals just above 10 seconds.

4. DETECTION DELAYS IN THE LASER TIME TRANSFER CHAIN

One of the main scientific objectives of the ELT experiment on board ACES consists in the distribution of an accurate time scale to ground users. Indeed, we require that the absolute delays in the ELT link for space-to-ground time transfer be calibrated to an uncertainty below 50 ps (25 ps as target). This includes the processes of: laser pulse emission/reception and time stamping in the ground clock time scale, laser pulse reception on ACES-board ACES and time stamping in the ACES time scale, two-way propagation of the laser pulse in the atmosphere from the reference emission point on ground to the reference reception point in space and back to the reference reception point on ground.

The individual contributions listed above may be split into two groups: the laser pulse reception on-board ACES and time stamping in the local clock time scale can be attributed to the ELT directly, while the others (propagation in the corner cube reflector, two-way propagation of the laser pulse in the atmosphere from the reference emission point on ground to the reference reception point in space and back to the reference reception point on ground) may be attributed to the SLR. Considering the fact, that SLR recently provided a precision and accuracy on the level of 2 – 3 mm [4] corresponding to 6 – 10 ps in one way signal propagation, the SLR related delays may be considered as known with required accuracy. Consequently, the ELT Package and the SLR system ground internal delays shall be determined to a resulting accuracy better than 40 ps.

The absolute detection delay of the ELT detector package consists of several contributors, their values and precision estimates are summarized in Table 1.

Table 1. Detection delay contributors.

Effect	Delay	Delay accuracy estimate
Optical signal propagation / geometry	~ 200 ps	5 ps
Photon to e^- conversion in SPAD	<< 1 ps	~ 0 ps
Carrier multiplication in SPAD	~ 1000 ps	15 ps
Electrical signal propagation	~ 200 ps	5 ps
Electronics circuit internal delay / geometry	~ 1000 ps	10 ps
Total delay	~ 2500 ps	< 20 ps (r. s. s.)

The delays of the optical and electrical signal propagation may be determined from geometrical dimensions and material constants. Considering a (sub)mm dimension measurement accuracy a resulting value of 5 ps is obtained. The carrier multiplication and the electronics circuit delays may be measured by means of a fast digitizing oscilloscope, which provides 10 ps accuracy for fast electrical signal shapes. The accuracy of the carrier multiplication measurement is additionally degraded by fluctuations in the avalanche buildup current pulse shape It resulting in an accuracy of 15 ps. The example of the avalanche buildup current pulse recoded on the 2.5 GHz bandwidth oscilloscope is shown in Fig. 6.

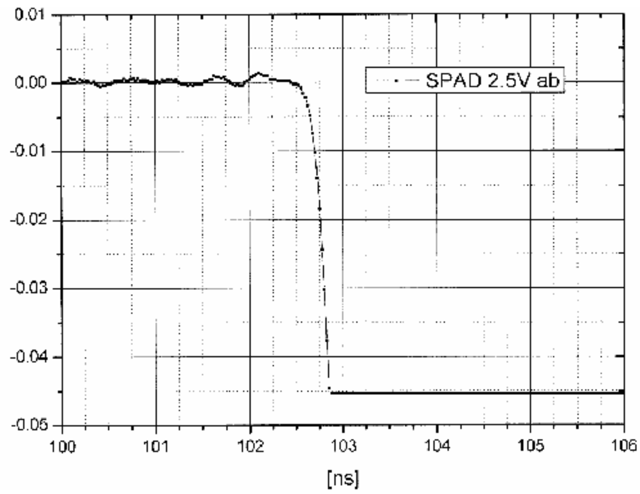

Fig. 6. Example of an avalanche build-up current pulse recoded by the 2.5 GHz bandwidth oscilloscope, vertical units are Volts on 50 Ω load, the horizontal sweep speed is 25 ps / dot.

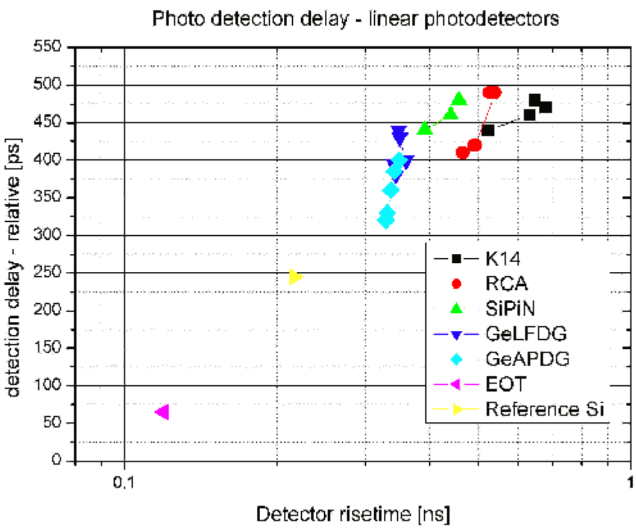

Fig. 7. Relative detection delay at 50 % of a leading edge of the linear photodiode response to a ps laser pulse, the photodiodes were biased to 4 different reverse voltages in the range of 1 to 8 V.

From Fig. 6, we can conclude, that with fixed trigger threshold of − 0.01 V, the trigger time of the next comparator may be determined with an uncertainty below 10 ps per 1 mV of trigger level. In a similar way the other electronic delays can be determined along with their uncertainty. However, some additional issues remain open – the definition of the absolute delay also depends on the bandwidth of the recording instrument. This fact can be demonstrated on the following experiment: the time of arrival of a picosecond laser pulse was monitored by various photodiodes of various instrument transfer functions – various pulse rise-times. The electrical output of these photodiodes was recorded on a digitizing oscilloscope with 2.5 GHz bandwidth. The results are summarized in Fig. 7.

From the previous experimental results one can conclude that the determination of the absolute detection delays of the ELT photon detection package is not straightforward and that the definition of the value itself is dependent on some additional parameters. It is important to note, that the same problems are there when defining the absolute delays related to the ground segment – meaning the delay between the events when the laser pulse is crossing the reference point of the ground station and the electrical pulse edge is appearing at the reference point.

Both these two effects of absolute delay determination and definition may be solved if we replace the term of "absolute" delay related to individual component and replace it by delay correction, which is involved in the entire laser time transfer chain. In fact, this technique is routinely used in SLR up to mm accuracy. The proposed calibration scheme and terms definition is shown in Fig. 8.

The ELT optical detector is located in front of the satellite laser ranging system at a distance ***L***. The epoch difference ***E2−E1*** and the distance ***L*** provide the calibration constant for the laser time transfer for this particular ground station. The SLR experience shows, that the ground calibration can be carried out with an accuracy of 5 ps or better.

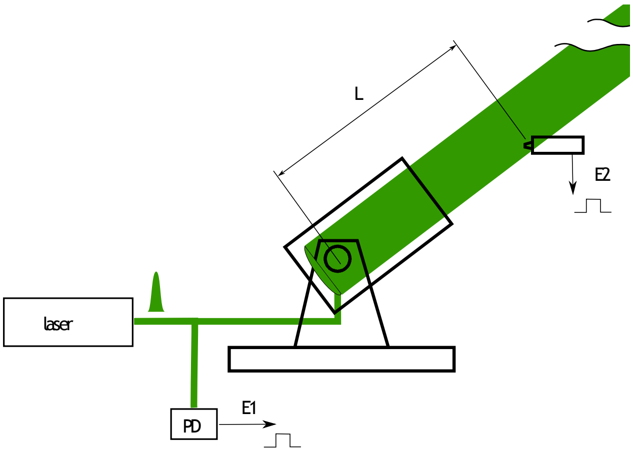

Fig. 8. The principle of the ELT differential delays calibration. Epoch ***E1*** is generated by photodiode ***PD*** and second epoch ***E2*** by ELT optical detector located at a distance ***L*** from SLR station reference mount point.

5. CONCLUSION

The optical receiver for the European Laser Timing experiment is under development and construction. The optical part of the receiver was designed and validated in indoor tests. Present design provides the required signal attenuation, field of view and an extremely flat dependence of the signal strength versus incidence angle. The electronic part of the photon counting detector was optimized for minimal power requirements and temperature stability. 12 ps peak-to-peak for a temperature variation of 6.5 K, as expected over one entire ISS pass, has been measured. The design and construction of the flight module has been started. The preliminary design shows, that the entire detector package mass will be well below 800 g and its total power consumption will be less than 0.8 W. The technique of the absolute detection delay measurement was developed and tested. The technique for calibration of the laser time transfer delay correction with the accuracy of 5 ps is in line with ELT time transfer experiments. The optical receiver parameters obtained in the ground tests meet safely all the requirements for the ELT mission.

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