Accurate Optical Time Transfer between a Clock on Ground and in Space

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Abstract

The Optical Time Transfer between a H-maser on the ground and the atomic clock ensemble in space (ACES) via the ELT interface, requires two concatenated highly stable two way laser links. While the use of satellite laser ranging provides both the range information and the reading (epoch) of the remote clock by a free space laser link relative to the geometrical reference points on the ground and the satellites, another actively stabilized fiber based ground link provides the accurate time reference between the H-maser on the ground and the ranging system. Once the local reference target at the ranging site is also equipped with similar two-way compensated timing reference, it is possible to identify and remove systematic errors to within 1 ps caused by otherwise not detectable system delays. We report on a lossless time and frequency distribution system that delivers this functionality.

1. System delays in space geodesy

Satellite Laser Ranging (SLR) is the only two-way measurement technique in the toolbox of satellite geodesy. Furthermore it operates in the optical regime. This provides several important advantages. Since the start and stop event of a time of flight measurement concept are timed on the same clock, a small clock offset is no concern, because it cancels out in the process of the time interval determination. A time offset of this clock is associated with the satellite position along the orbit and the satellite velocity is small compared to the speed of light, exploited for the range determination. The optical laser pulses have a very large bandwidth, so the probe signal for the range measurement is well defined in time. Furthermore it is much easier to establish the tropospheric delay of the ranging signal, as the refractive index of the atmosphere is well defined, unlike the dielectric number ε of the ionosphere and the wet path delay of the troposphere, which is the corresponding quantity for the range correction of the microwave techniques. For all of these reasons, SLR is the technique of choice to perform accurate time transfer between ground and space [1,2]. The timescale of a satellite in orbit is related to the respective timescale of a ground station by the epoch of the measurement at the ground station puls half of the measured roundtrip time of the laser pulse. Finally the geometrical offset between the retro-reflector on the satellite and the timer as well as the electrical delay have to be included into the correction process of the time comparison. Figure 1 depicts the time synchronization process in a range / time diagram.

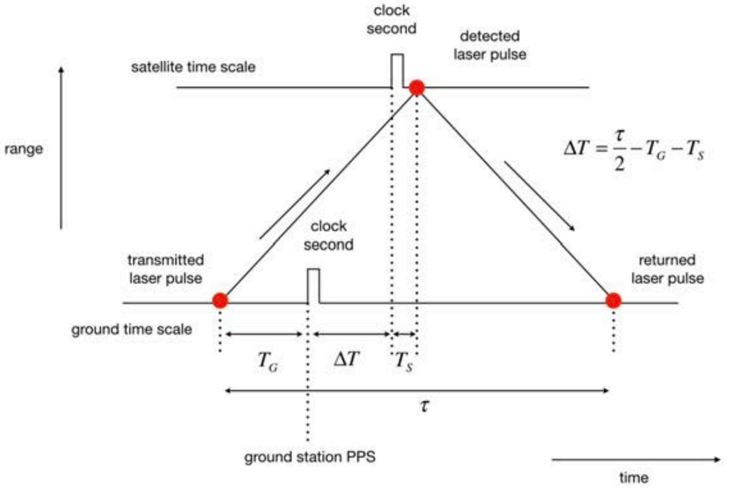

Fig. 1: Illustration of the optical time transfer process, between a timescale on the ground and in space. The horizontal axis indicates time, while the ordinate represents the distance between the timescales.

The offset ΔT between the PPS signal on the ground and the PPS in the timescale of the satellite is then given by

$$\Delta T = \frac{\tau}{2} - T_G - T_S \ ,$$

where τ is the roundtrip time of the laserpulses (corrected to the reference point of the measurement system, T_G the offset between the laser fire epoch and the leading edge of the PPS signal of the ground station and T_S the respective offset between the instance of detection, corrected for the effective time offset between the retro-reflector and the satellite center of mass, to which the timescale is synchronized. In this simplistic experiment design, we have assumed that accurate time is available at the laser ranging instrumentation, so that T_G is a well established quantity. However this is usually not the case. A few meters in an ideal situation and several hundred meters in less favorable situations separate the ranging timer and the clock. This causes additional delays, which usually are variable over time and hard to control. Figure 2 illustrates this situation.

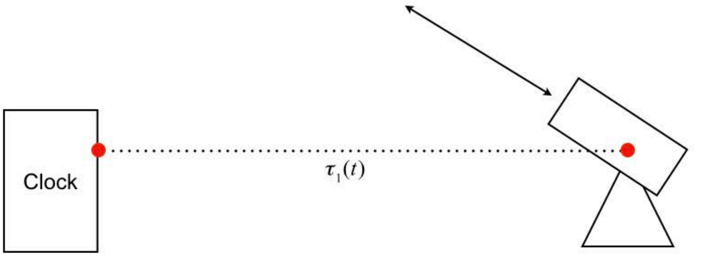

Fig. 2: Accurate time transfer requires the exact knowledge of the time delay between the point of reference at the clock and the effective reference point of the SLR system, performing the time transfer. In most cases this offset will vary in time, due to the electronic systems and cable runs involved in the transport of the timing signals.

Although we used a straight line to indicate the time offset between the reference clock and the reference point of the SLR system, there will never be a simple relationship in practice. The clock signals usually are transported on cables, including amplifiers, switches and distribution electronics. Each of these components adds a variable system delay, which changes with temperature, impedance and differences in the electric ground potential. Variations in the order of 1 ns are no exception and this is several orders of magnitude above the desired stability of a few picoseconds.

In [2] we describe a local two-way optical time and frequency distribution system, based on a fs mode-locked laser, which incorporates an active interferometric control, that maintains the delay of the timing signal stable to about 1 ps. Apart from the application in time transfer, this concept is also suitable for the identification and compensation of variable system delays [3], when applied in a closure measurement process. Furthermore, it does not only work for SLR. It is applicable to the VLBI technique in a very similar fashion, calibrating VLBI antennas in situ in a way comparable to a SLR system (see ref. [3] for details).

2. Results

We have monitored the stability of the system delay between several parts of the observatory in the short- and the long-term. Each location is linked up to the clock by an actively compensated link of the novel time and frequency distribution system. In one case the source and the endpoint of the local time transfer link are separated by a fiber of about 20 m of length, running within an air-conditioned environment, specified to be stable in temperature to within 1 degree. The effect on the system delay over 8 hours is shown in fig. 3a. In another case the distance between the clock and the geodetic measurement system is about 500 m, corresponding to 2 different buildings. Figure 3b) shows the observed error signal of the delay compensation.

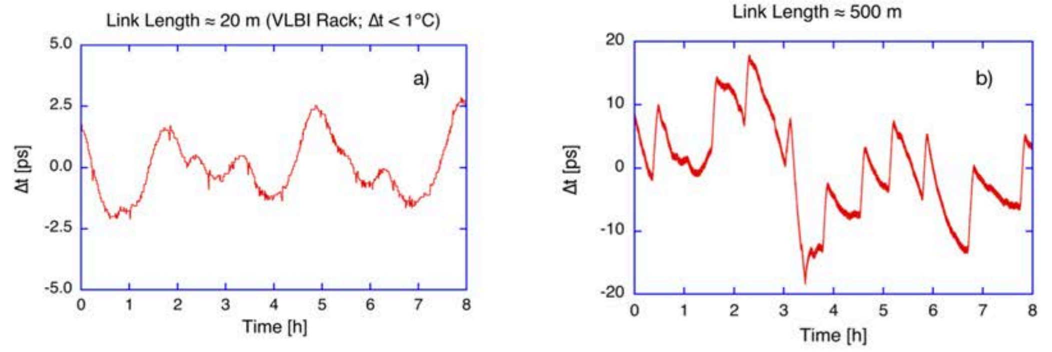

Fig. 3: Short-term stability of the local time and frequency distribution. The compensated delay variation is taken from the error signal of the closed loop delay compensation. A variation of only several picoseconds is observed for a short lead of 20 m, running inside an air conditioned room a). Considerably larger delays are found for a 500 m long run of fiber, connecting 2 different buildings b).

The signature of the delay compensation as shown in fig. 3b) strongly indicates the effect of temperature on the system delay, accounting for more than 30 ps over only 8 hours. Most of the observed saw-tooth pattern can be related to the cooling cycles of an air-conditioning unit. The variability of the clock delay becomes much more pronounced, when we monitor the long-term drift. Over more than 100 days, these short-term variations become almost negligible as we observe a compensated total variation exceeding 350 ps. Most of this will probably be due to seasonal changes. Figure 4 shows the result for the same link as presented for the short-term in fig. 3b).

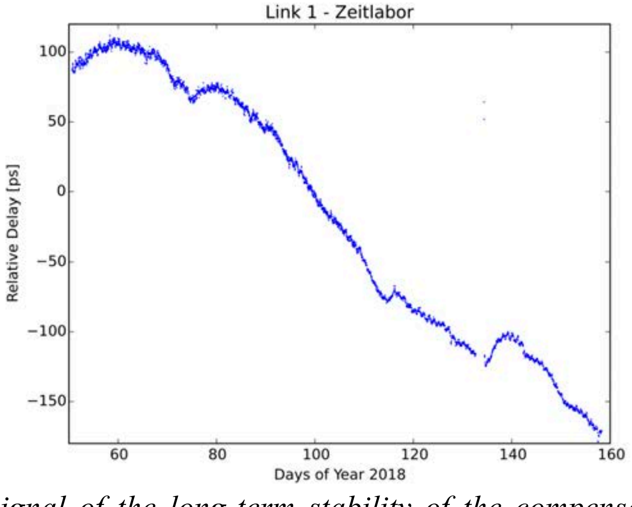

Fig. 4: Error signal of the long-term stability of the compensated time and frequency fiber link. Over a period of more than 100 days a delay variation of more than 350 ps has been taken out by the closed loop system.

Conclusion

Accurate optical time transfer between a ground station and a satellite in space is demanding as unknown systematic biases are easily acquired in the measurement process. These errors are hard to eliminate as they are small and there is no easy reference against which they can be established and removed. This situation is exacerbated when the clock is not placed right beside the ranging instrumentation. We have shown that an optical compensated local two-way time and frequency has to take variable delays of more than 350 ps out in the long-term, a delay that if not correctly identified, would add a considerable bias to the optical time transfer application. This time and frequency distribution system also has the advantage that it can be utilized to find and remove systematic errors in satellite laser ranging in a closure measurement process.

References:

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