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A direct comparison between two independently calibrated time transfer techniques: T2L2 and GPS Common-Views

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Abstract. We present a direct comparison between two satellite time transfer techniques on independently calibrated links: Time Transfer by Laser Link (T2L2) and Common-Views (CV) of satellites from the Global Positioning System (GPS) constellation. The GPS CV and T2L2 links between three European laboratories where independently calibrated against the same reference point of the local timescales. For all the links the mean values of the differences between GPS CV and T2L2 are equal or below 240 ps, with standard deviations below 500 ps, mostly due to GPS CV. Almost all deviations from 0 ns are within the combined uncertainty estimates. Despite the weak number of common points obtained, due to the fact that T2L2 is weather dependent, these results are providing an unprecedented sub-ns consistency between two independently calibrated microwave and optical satellite time transfer techniques.

1. Introduction

The most common time transfer technique used for remote time scale comparisons is based on Common-Views (CV) of satellites from the Global Positioning System (GPS) constellation, one of the Global Navigation Satellite Systems (GNSS) currently in operation. Time Transfer by Laser Link (T2L2) is an optical two-way technique developed by the laboratory Géoazur of Observatoire de la Côte d'Azur (OCA), Valbonne, France, with the support of the French Space Agency CNES.

During Autumn 2013, a mobile laser ranging station called FTLRS, developed by OCA, was implemented in Observatoire de Paris (OP), Paris, France, for tests on time and frequency transfer in parallel with GPS CV. To this aim, FTLRS was connected to the active H-maser used as local oscillator for the LNE-SYRTE Primary Frequency Standards, LNE-SYRTE being the OP laboratory designated by the French National Metrology Institute (NMI) Laboratoire National de Métrologie et d'Essais (LNE) for Time and Frequency Metrology activities. OP was then included in the regular set of T2L2 sessions, and it was possible to build a direct comparison between GPS CV and T2L2. For that purpose, a double campaign for the characterization of the link offsets was organized by LNE-SYRTE for the GPS CV, and by OCA for T2L2. An additional third station was included: NERC Space Geodetic Facility (SGF) in Herstmonceux, United Kingdom. In the three stations both time transfer techniques where using a reference time scale materialized by a 1 PPS pulse coherent with a 10 MHz signal. The time scale at OP and SGF was a free running H-maser, while in OCA the H-maser signal was steered by a micro phase stepper, in order to keep the local time scale close to Coordinated Universal Time (UTC). For the scope of this experiment all the measurements have been made by taking as common reference marker of the time scale the crossing of the 1 V level of the 1 PPS signal on a well defined connector of a 1 PPS signal distribution amplifier.

2. T2L2 link

The T2L2 principle is derived from classical satellite laser telemetry techniques, with a dedicated on-board instrumentation able to time tag the laser pulses reaching the satellite [1]. Measurement are timing triplets based on the time of transmission of a laser pulse from the ground, the time of arrival of the pulse on-board the satellite, and the time of arrival on the ground of the photons from that given pulse reflected by the satellite. The time transfer between two stations is obtained from the combination of such triplets, after computation of a fit for each satellite path producing one normal point of the time scale difference. An improvement of at least one order of magnitude in time transfer uncertainty over the existing microwave techniques is expected, the stability of this optical technique provides the capability to compare today's most accurate frequency standards.

T2L2, based on a ground network of laser ranging stations and on a dedicated space segment, is currently in its operational phase since the launch in 2008 of the dedicated payload hosted by the JASON-2 satellite [2, 3, 4].The full accuracy of a T2L2 link can only be achieved when JASON-2 is visible at the same time from both the ground station of the link. Some attempt for non common view time transfer has been made. But in this case the accuracy is strongly limited by the stability of the on-board quartz oscillator and does not present a noticeable improvement against traditional time transfer techniques.

The years 2012-2013 were especially devoted to T2L2 accuracy estimation. A first ground to ground validation was achieved by a short baseline experiment [5]. A deep analysis of the instrumental bias has also been performed [6], and a ground to ground time transfer accuracy budget was established [7]. For a typical T2L2 time transfer link the extended uncertainty ($k = 2$) is estimated at 138 ps. Although many laser ranging station participate to T2L2 experiment we only consider here the links between OCA, SGF and OP, because the GPS links have been calibrated for these three stations only. One of the goals of the T2L2 experiment, which is weather dependent, is indeed the one-off calibration of other time transfer techniques.

3. GPS CV link

In each station, a GPS receiver collects measurements of the differences between the local time scale and a satellite clock, which can be referred to GPS Time, the common satellite system time scale. Measurements can be based on P-code data broadcast on both GPS microwave carriers, allowing for the ionosphere-free combination based on the software developed at the Royal Observatory of Belgium (ROB) and made available by the Bureau International des Poids et Mesures (BIPM) that we call TAIP3 here [8].

The data processing consists in averaging outliers out [9], in order to build a time difference for each standard epoch according to the Common Generic GNSS Time Transfer Standard (CGGTTS) format [10]. Time transfer between remote time scales is obtained by computing the CV differences between similar CGGTTS data recorded at the same epochs. Another geodetic technique applied to time transfer between remote time scales, the Precise Point Positioning

(PPP), as was developed by National Resources Canada (NRCan) [11] among other groups, provides a better short term stability because measurements are based on the phase of the carrier frequencies. But the carrier does not contain any identifiable time marker, and therefore the time transfer uncertainty remains limited by the detection capability of the time tag associated with the code. In addition, the short term stability is not the issue in the comparison with another time transfer technique. This is why we disregard PPP in the following, any GPS time transfer being limited by the same uncertainty on the determination of the hardware delays.

4. Direct comparison between both techniques

During the comparison period, all GPS stations have operated almost continuously. By using the offsets between remote time scale reference points obtained from the GPS calibration campaign, the time differences between the time scales have been computed by GPS CV for the three links OCA-OP, OCA-SGF and OP-SGF. The classical GPS CV are 16 min sampled. But we also computed a filtered GPS time transfer by a moving average over 13 consecutive CV samples. This is providing 16 min sampled 3.5 h averaged points exhibiting a lower noise without smoothing out artificially physical effects included in the data. On the other hand, the T2L2 normal points are providing the time differences between two remote time scales at epochs depending on the satellite path and on the available triplets.

For each link, we have plotted both GPS CV time transfer results, together with the T2L2 results. For clarity of the figures, an additional quadratic fit was also removed, in order to take into account the H-maser differential drifts: the parameters of the fit are provided inside each figure. GPS CV are producing 16 min sampled time scale differences which are not necessarily synchronous with any T2L2 normal point epochs. For the computation of the differences between both techniques, in order to detect any potential deviation, two adjacent GPS CV points have been interpolated to produce one GPS CV result synchronous with the corresponding T2L2 normal point epoch. The combined uncertainties were computed by building a simple quadratic sum between the GPS CV link uncertainties given in [12], and the ground to ground T2L2 uncertainty given in [7]. We obtain 1.1 ns for OCA-OP and OCA-SGF, and 0.8 ns for OP-SGF.

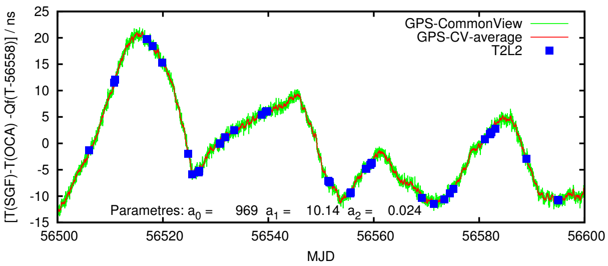

Figure 1. Time differences between SGF and OCA by GPS CV and T2L2 with a quadratic fit removed (colour online).

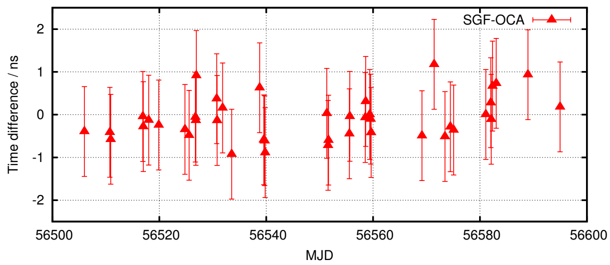

Figure 2. Difference between both techniques on the link SGF-OCA. The error bars represent the combined uncertainty (colour online).

Figure 1 shows such time scale differences issued from both techniques on the link SGF-OCA: the most noisy continuous green line shows the GPS CV 16 min sampled time transfer, the smoothed continuous red line shows the additionally 3.5 h averaged GPS CV time transfer, and the blue squares are the T2L2 time differences. The deviations between both techniques for the links SGF-OCA are reported in Figure 2.

Similarly, the time differences between the time scales and the differences between both techniques are reported in Figure 3 and 4 for the link SGF-OP and in Figure 5 and 6 for

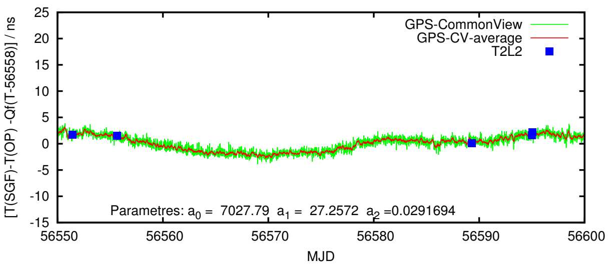

Figure 3. Time differences between SGF and OP by GPS CV and T2L2 with a quadratic fit removed (colour online).

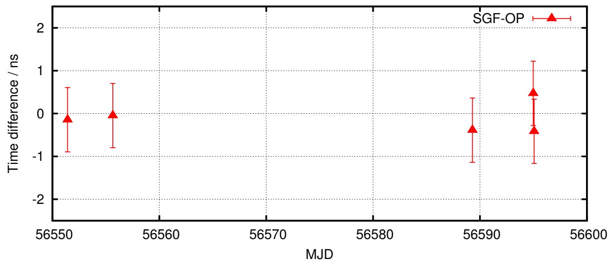

Figure 4. Difference between both techniques for the link SGF-OP. The error bars represent the combined uncertainty (colour online).

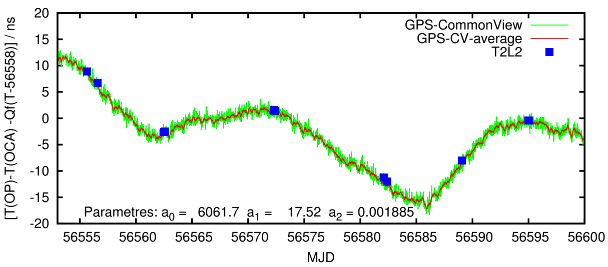

Figure 5. Time differences between OCA and OP by GPS CV and T2L2 with a quadratic fit removed (colour online).

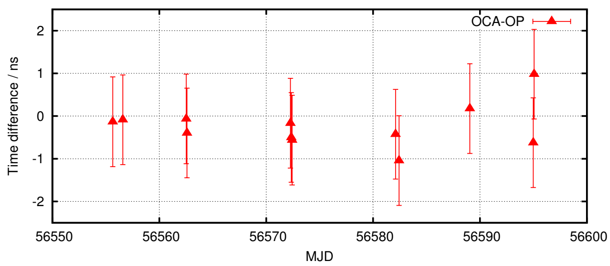

Figure 6. Difference between both techniques for the link OCA-OP. The error bars represent the combined uncertainty (colour online).

the link o OCA-OP. Note that in the plots including OCA, the shape of the curves is due to the manual steering of the H-maser in order to keep the local time scale close to UTC. One can see that there is only a weak number of T2L2 points on the plots. This is mostly due to the fact that T2L2 is weather dependent, but also to some technical issues which limited the measurements for some links. Clearly, the OCA-SGF link is exhibiting the largest number of common points compared to the two other links. But we also see in Figure 1, 3 and 5 that the discrepancy between both independently calibrated techniques remains remarkably small over the whole period of measurements for all the links.

When properly calibrated, the two techniques are measuring the same time deviations between remote time scale reference points, hence the difference is expected to be close to 0 ns. What we see in Figure 2, 4 and 6 is more accurately the remarkable consistency between both techniques.

The mean values of the three data sets are reported in Table 1, together with the standard deviations and the combined uncertainties. We consider here the standard deviations obtained from the 16 min sampled GPS CV and the ones obtained after the additional smoothing on 13 consecutive samples. We see that the average differences between GPS CV and T2L2 are equal or below 240 ps. Despite the weak number of common points obtained, this is clearly showing a largely sub-ns consistency between the two independently calibrated techniques: all deviations of the mean values from 0 ns are within the combined uncertainties. In addition, we do not detect any significant trend nor periodic term, even when considering the OCA-SGF link exhibiting the highest number of data. When considering this link only, where the number of available points seems significant enough to build a consistent mean value of the differences together with the related standard deviation, we can see that the moving average on GPS data reduces the noise

Table 1. Mean values of the time differences between GPS CV and T2L2.

Link	Number of points	Mean value (ns)	Standard Deviation (ns)		Combined Uncertainty (ns)
			Raw GPS CV	Filtered GPS CV	
OCA-OP	12	0.24	0.48	0.25	1.1
OCA-SGF	42	0.09	0.49	0.37	1.1
OP-SGF	5	0.10	0.32	0.32	0.8

significantly. But, as expected, the GPS CV are setting not only the noise level but also the uncertainty for such data.

5. Conclusion

For the two techniques GPS CV and T2L2, two independent relative calibration campaigns were achieved in Autumn 2013 between the three European stations OCA, OP and SGF. By using the corrective offsets obtained for each link between remote time scale reference points, common to both microwave and optical satellite techniques, a direct comparison provided an unprecedented consistency at a sub-ns level. The mean values of the time differences between GPS CV and T2L2 are equal or below 240 ps, with a standard deviation below 500 ps, mostly due to GPS CV. The resulting average differences are clearly negligible with respect to the combined uncertainties between both techniques, which are between 0.8 and 1.1 ns depending on the link considered. Although the estimated uncertainty of T2L2 is much lower than the estimated uncertainty of GPS CV, the good agreement between the two techniques confirms that the independent link calibrations have been carried out properly and that the uncertainty budgets have been established in a rigorous way, even when conservative. This result provides a full validation of the GPS CV link uncertainty budget computations, and a confirmation of the T2L2 performances for ground to ground time transfer . It is also a demonstration of the T2L2 capability for the sub-ns calibration of other time transfer techniques. The decommissioning of the space segment of T2L2, which was considered in 2015, has been postponed, and the operation extended at least until the end of 2016, allowing for further measurements. It should also be noted that a similar instrument called European Laser Timing (ELT) [13] will be hosted on-board the International Space Station (ISS) inside the Atomic Clock Ensemble in Space (ACES) module [14] . The launch of the ACES module is currently planned for early 2017. As was proven by this experiment, optical satellite techniques like T2L2 should be kept as possible candidates for the validation of long distance time transfer through optical fiber links, provided that the required portable stations be will be made available in the reference sites and that the required flight instruments would be implemented on-board additional space segments in the future. Unfortunately today there are no laboratories that are equipped with a T2L2 station and with a fiber time transfer link, therefore to benefit of the full accuracy of a T2L2 link for the validation of a fiber link [15] the deployment of two mobile T2L2 stations is required.

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