Synchronization of distant Laser stations thanks to Time Transfer by Laser Link : Proposal for a dedicated campaign

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1 Abstract

The hight performance of the Time Transfer by Laser Link (T2L2 on board the satellite Jason-2) experiment, at the picosecond level, has been demonstrated thanks to several campaigns, data analysis and thorough instrumental error budgets. The principle was to observe the satellite passes in Common View (CV) from a couple of Satellite Laser Ranging (SLR) stations to ensure the ground-to-ground time transfer from both ground-to-space ones. This ensures the benefit of using quasi-simultaneous on-board epochs and avoids making assumptions and hypotheses about the behavior of the on-board Ultra Stable Oscillator (USO).

The aim of the present work is to synchronize remote ground clocks that are in non Common View, i.e. between stations from America, Asia, and Europe. The main difficulty is to take into account the complex behaviour of the on-board oscillator during 1-2 satellite orbital revolutions (1 rev = 6700 s) and more. We show that, by integrating a recently published model describing the frequency responses of the Jason-2 USO to physical effects, as temperature and radiations, we are able to propagate the phase (time) between two successive passes of the satellite (2 hours) above the same station with an error of a few nanoseconds (ns) and a repeatability of 3-4 ns.

As a first test, we determined the time differences between the Grasse local clock (H-maser) and the ones used by another non European SLR stations involved in the tracking of T2L2. First results show that some SLR stations of the network are not currently synchronized with the UTC (Universal Time Coordinate) time scale at the required limit of 100 ns, as it is recommended by the International Laser Ranging Service. We are discussing the internal error budget of the non CV process.

In order to provide some accurate values to support this, we are proposing to do a campaign, of 1-2 months in 2016, between several SLR stations (i.e., Grasse and Herstmonceux on the one hand, and Changchung and Koganei on the other) in order to simultaneously compare the GPS and T2L2 time links

over an intercontinental distance. The objective is to quantify the necessary efforts to be developed for SLR's, considering time & frequency, to achieve the common GGOS (Global Geodetic Observing System) goals.

2 Introduction

Laser stations from the ILRS (International Laser Ranging Service) network track geodetic satellites, as the LAGEOS (LAser GEOdynamics Satellite) targets, by using the SLR (Satellite Laser Ranging) technique (Pearlman et al., 2002). In order to obtain an accurate solution of the underlying terrestrial reference frame from precise orbit determination, all the time systems used by laser stations should be synchronized with UTC (Universal Time Coordinate) at ± 100 nanoseconds (ns). Considering the satellite velocity, this implies position errors < 1 mm along-track. Presently, time & frequency equipments used in current SLR stations play an important role in the global error budget of the technique (Samain et al., 2015). In our efforts to improve the SLR technique and manage the ILRS service it appears important to promote not only better time references but also a fully coherent network (see the GGOS recommendations (Altamini et al., 2005)).

The Time Transfer by Laser Link (T2L2) experiment on-board the oceanographic satellite Jason-2 (launched in June 2008 at 1335 km), aims to synchronize remote ground clocks using the laser technology. The space segment was described in Samain et al. (2014). It uses a classical Laser Reflector Array (LRA) for two-way ranging and is based on the Ultra Stable Oscillator (USO) of DORIS (Doppler Orbithography and Radiopositionning on Satellite) as the on-board time & frequency reference (Auriol & Tourain, 2010). The ground-to-space time transfer stability was established at 5-7 picoseconds (ps) over 75 s when an ultra-stable clock (as hydrogen maser) is used at ground level (Exertier et al., 2010). A complete data processing was realized in order to establish the ground-to-ground time transfer between remote clocks from every ground-to-space observed passes. Performance of metrological level has been demonstrated through a series of campaigns which were essentially conducted in Europe, i.e. in Common View (CV) (Exertier et al., 2013).

Thanks to the permanent laser tracking of T2L2/Jason-2 provided by the ILRS network (around 20-22 stations), we studied a time transfer process that is dedicated to the non CV case. The goal is to achieve a time transfer between ground clocks over continental distances in spite of the DORIS USO stability. Whereas its short-term stability is of a few parts in 10^{-13} over 1,000 s for frequency, it is of several ns over one orbital revolution (around 6700 s) for phase. Due to a recent study of the frequency behavior of the quartz oscillator of DORIS/Jason-2 which led to a physical model (Belli et al., 2015), it enabled us to develop an efficient method to calculate the non CV time transfer at the ns level.

The current state of SLR stations for time & frequency is presented in Section 3, whereas the method, data and first results are presented in Section 4. Section 5 is dedicated to a proposal for a new campaign ; its aim is to urge SLR stations (in America, Asia and Europe) to make a 1-2 month tracking campaign in order to estimate ground-to-ground accurate links which could be collocated with GPS. We conclude in Section 6.

3 Time and frequency at SLR sites

3.1 Equipment and metrology

Throughout the ILRS network, stations are using different time & frequency reference systems. For the best equipment, it is based on an atomic clock (cesium, H-maser, rubidium) but more generally on a quartz oscillator which is synchronized with the UTC time scale by GPS (Global Positioning System). The realization of the local time scales can be very different in terms of stability and accuracy. The enhanced short-term stability is obtained by the use of an hydrogen maser (H-maser) at the level of 10^{-15} at 1,000 s whereas other systems are at a few 10^{-13}. Concerning accuracy, it is challenging to permanently maintain the time offset of the local clock relative to UTC under a reasonable limit (Laas-Bourez et al., 2013). In addition, number of facilities were not calibrated in time (delay in ground cables of around 100-200 ns, depending on the length of the cables), thereby providing partial degradations in the time accuracy (Samain et al., 2015).

Some geodetic sites are collocated with other space geodesy techniques such as SLR, GPS and/or DORIS. In such observatory, obviously, the time and frequency laboratory is the common time basis. Nevertheless, each technique should be separately time calibrated, the delays in ground cables and devices being strongly different (Laas-Bourez et al., 2014).

3.2 A global overview of the network

On-board Jason-2, T2L2 is linked to the GPS of the platform whose role is to provide UTC(GPS) to all on-board instruments (Cerri et al., 2010). The PPS (Pulse Per Second) which is emitted by the receiver and has a jitter of roughly 0.3 μs is regularly timed by T2L2. It gives us the opportunity to directly compare, in the same time scale, the PPS epochs and the ones coming from the optical events emitted by ground laser stations (Exertier et al., 2010).

Thanks to a local interpolation (over 0.5 s maximum) between each kind of epochs, it has been possible to compute the average time difference per pass (of around 600 s) between each SLR station and UTC(GPS). The precision of this process is no more than $\pm$ 30 ns due to the PPS jitter but it allowed us to monitor every time system of SLR stations on the long term (from day to years). The resulting series per station give information about the long-term variations of the local time scale. The Figure 1 presents the series of time offset for 6 laser stations from March 2013 to March 2015. We clearly see big differences from a station to another or, for the same station, variations of its offset can reach $\pm 1\mu$s or more.

From this global overview, it appears that : 1/ SLR stations are not synchronized at $< \pm 100$ ns with UTC, 2/ the time offsets sometimes are subject to rapid changes. We should interpret this reality in term of Time Bias (TB) per station. This TB is affecting the epoch of all laser events whatever the space targets. For some Low Earth Orbit trajectories it corresponds to an along-track orbit error of a few mm.

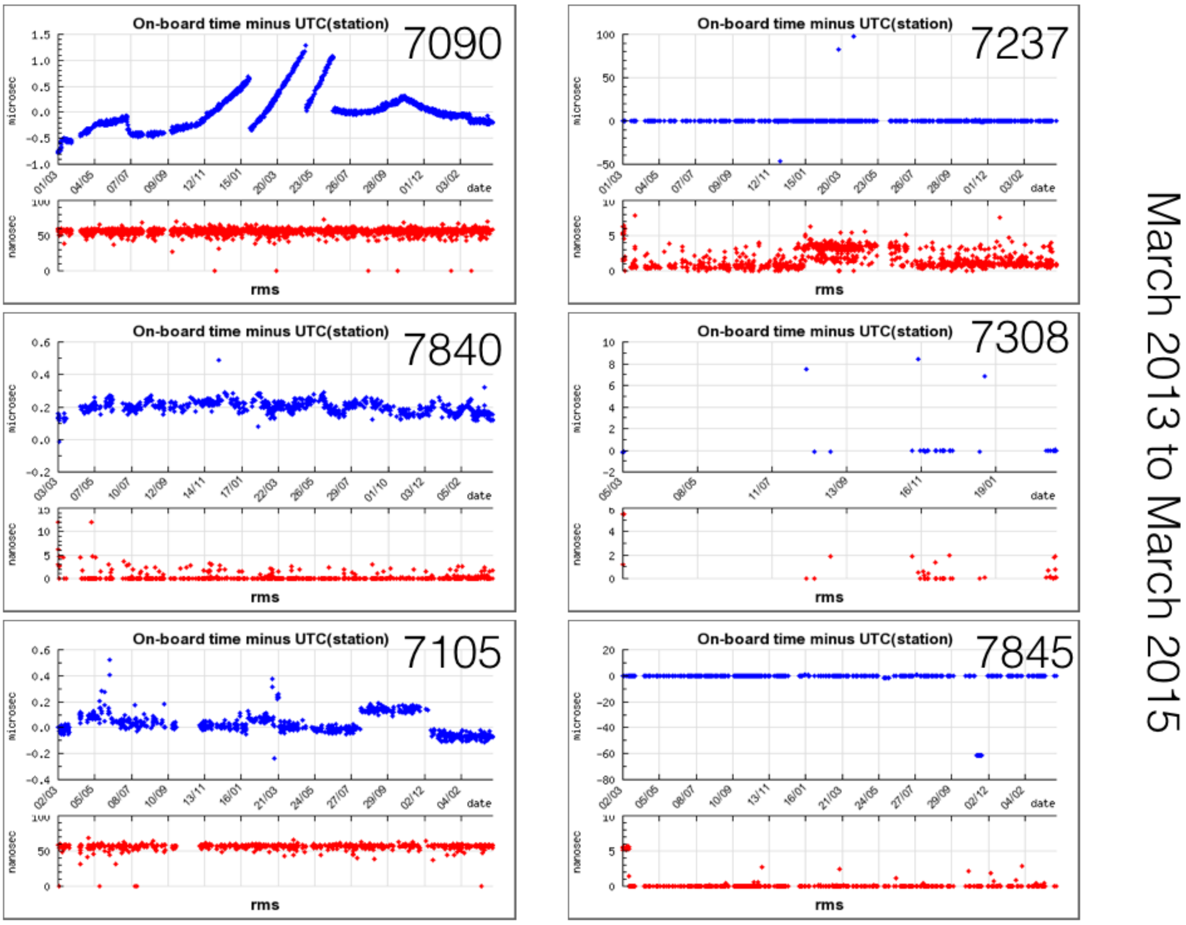

FIGURE 1 – A global overview of the long-term monitoring of clocks at six SLR stations (up and down and from left to right : Yaragadee, Herstmonceux, Greenbelt, Changchun, Koganei, Grasse). The common time scale (On-board time) is close to UTC(GPS) and is realized thanks to a local PPS which is provided to the equipment of the Jason-2 platform including T2L2

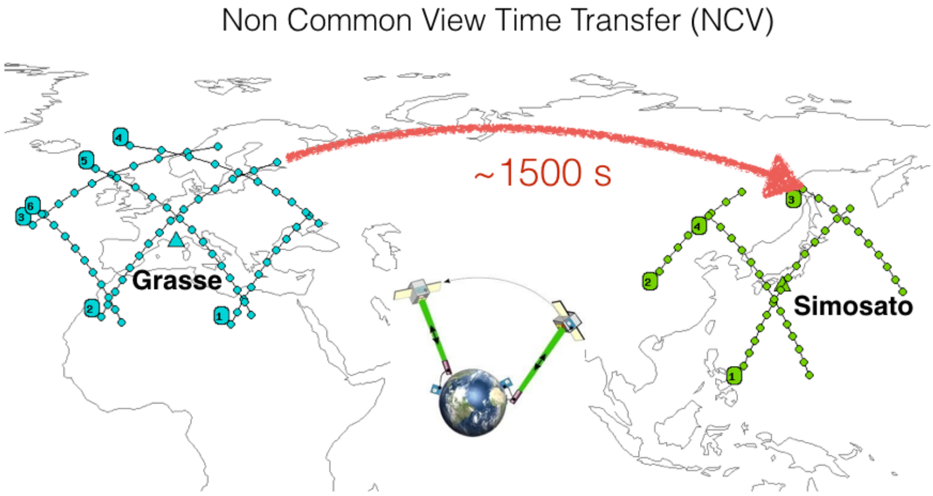

Figure 2 – Jason-2 ephemeris over one day in the non Common View case. The flying time between Grasse (7845) and Simosato (7308) in Japan is of 1,680 s as a minimum.

4 Time transfer in non Common View

4.1 Applied methodology

In order to transfer time over continental distances (in non CV) it is necessary to take into account the time of flight during which the satellite is not tracked by laser. It is between 1,500 s in the best case (for a direct flight) and more than 10,000 s in the worst (depending on the orbital configuration). See on Figure 2 one possible scenario between Grasse (France) and Simosato (Japan) SLR's stations.

In the present paper, the goal is to establish a method for calculating the non CV time transfer over several hours in order to synchronize a plurality of remote stations. This is due to the relatively poor coverage of the Jason-2 trajectory by SLR stations involved in the T2L2 tracking. As a consequence of frequency variations appearing along several orbital revolutions, a frequency model of the on-board oscillator (empirical or physical) is a key element to transfer time in non CV. We have studied the frequency variations of the DORIS USO on Jason-2, and we established a physical model based primarily on temperature and radiation effects (Belli et al., 2015). Its accuracy has been estimated at a few 10^{-13} which corresponds roughly to 4-5 ns over 10,000 s, after integration to pass in the time domain, including the effects of general relativity (Petit and Wolf,, 1994). See on Figure 3 a schematic representation. The non CV time transfer process we developed here is mainly based on the numerical integration of the modelled frequency variations. Nevertheless, we felt it necessary for this integration to be constrained by the T2L2 data itself (phase) which was obtained from successive passes above a reference station.

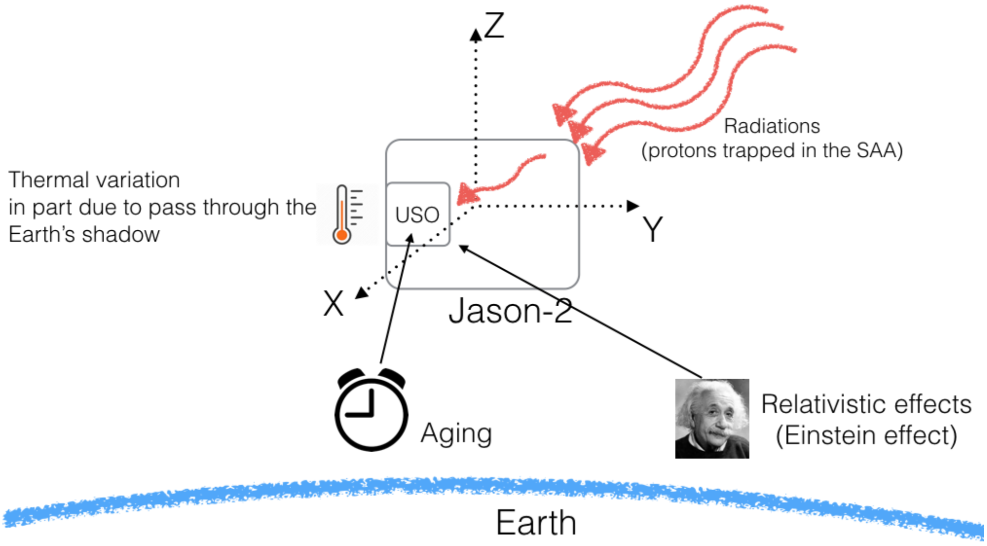

FIGURE 3 – Schematic representation of the physical effects that affect the frequency of the DORIS USO on-board Jason-2 at the level of 10^{-13} : temperature, radiations coming from the high energy protons trapped in the SAA (South Atlantic Anomaly), ageing and general relativity.

4.2 First results

From two years of T2L2 data (2013 to 2015, see above) we extracted some examples in order to illustrate the calculation and to show its benefits and limits. In parallel, we used the USO model and established its outputs (epoch and relative frequency bias) every minutes. A typical result is shown in tables 1 and 2 for the day January, 12 in 2015. The situation is as follows for Grasse (7845) and Changchun (7237) SLR's : from four possible time transfers, we have only one direct Jason-2 fly of 1765 s, but if we extend the calculation period to six hours, it is thus possible to synchronize four SLR stations (Hawaii, 7119 and Yaragadee, 7090). The different passes over the stations are shown in table 1.

The non CV process consists to integrate the frequency model from the on-board epoch observed by a selected station (as a reference) and the on-board epoch observed by the target stations (i.e. during the ground-to-space time transfer). The non CV time transfer is the difference between the computed phase and the observed one at each target station from the reference one. The result of this process can be seen in table 2. The first non CV time transfer is computed from Grasse station (used as a reference) with two successive passes ($\Delta = 7{,}032$ s) ; the frequency model is integrated over 10,000 s and is constrained to minimize the phase differences with involved stations by a weighted least squares process. The weights (see table 2) were empirically estimated considering the performance of each station. The repeatability of the time difference between both stations over two links is : -217.203 -37.743 = 254.846 ns ± 0.6 ns and 254.577 ± 0.6 ns, respectively. The second test, for the same day, is using a time integration of 21,000 s from Changchun (reference). We mainly see the same

Date MJD and day	hour	station 1	st. 2	st. 3	st. 4
57034 (20150112)	0 :00		7237		7119
57034 (20150112)	3 :20	7845			
57034 (20150112)	3 :53		7237		
57034 (20150112)	5 :17	7845			
57034 (20150112)	5 :50		7237		
57034 (20150112)	8 :21			7090	
57034 (20150112)	10 :01			7090	
57034 (20150112)	16 :08				7825
57034 (20150112)	18 :05			7090	
57034 (20150112)	20 :02		7237	7090	

Table 1 – Involved stations and passes for the MJD day 57034 ; Grasse (7845), Changchun (7237) in China, Yaragadee (7090) (AUS), Hawaii (7119) (US), and Mt Stromlo (7825) (AUS) not used here.

kind of repeatability but the time transfer value is now shifted by 1-2 ns from the previous test. Finally, the third test was extended to more than 12 hours ; the time difference between Grasse and Changchun is of -217.260 -38.675 = 255.935 ns, whereas some passes from Yaragadee are now visible. The repeatability is of the same order than before.

All these quantities or time differences were not calibrated yet, with regard to the UTC time scale. For doing that, SLR stations should be time calibrated and T2L2 versus GPS should be compared as independent space time transfer techniques, this is why we propose a new dedicated campaign for 2016.

5 A proposal for 2016

Taking into account the results of our analysis, it appears useful and even necessary to measure accurately the time difference between remote ground clocks among the SLR systems in use and to compare the resulting T2L2 non CV link with a GPS link.
Because it could be difficult to involve several SLR's together, we propose to establish a tracking campaign between two remote stations with the ultimate aim of measuring the ground-to-ground time transfer repeatedly. Taking into account the changing meteorological conditions that affect the laser tracking efficiency, we propose to involve two stations in Europe (e.g., Grasse and Herstmonceux) and two in Asia (Changchun in China and Koganei in Japan). Every stations should use a co-located GPS receiver dedicated to time & frequency ; every stations should be time calibrated by our travelling equipment. One being dedicated to SLR (Samain et al., 2011), the other for GPS (Rovera et al., 2014).

If it is well coordinated (see our T2L2 website on http ://www.geoazur.fr/t2l2/en/data/v4/ ; click on Ephemeris), a 1-month campaign should be enough to establish a first error budget.

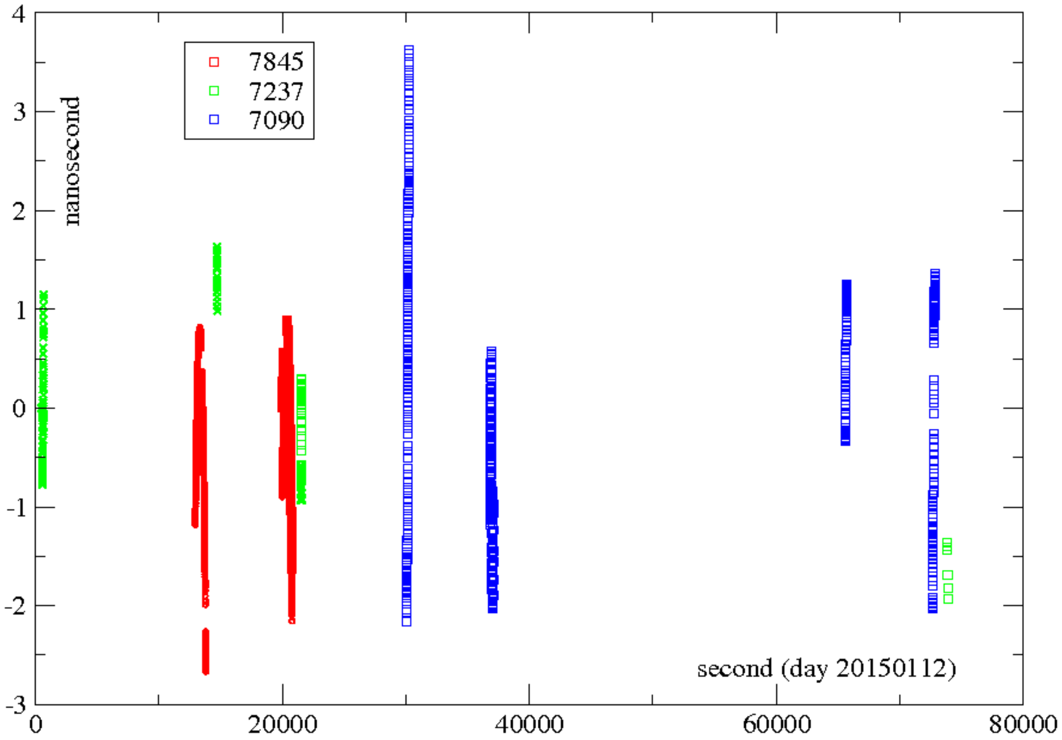

Figure 4 – Results of the non Common View time transfer between Grasse (7845), Changchun (7237) and Yaragadee (7090).

Pass nb.	station	nb data	Δsec	Time Transfer (ns)	RMS
pass 1	7845	665	0	-217.203	0.085
pass 2	id	434	7032	-217.205	
pass 2	7237	17	1765	37.743	0.575
pass 3	id	31	8544	37.372	
pass 1	7845	665	12454	-217.246	0.185
pass 2	id	434	19486	-217.249	
pass 1	7237	69	0	38.428	1.049
pass 2	id	17	14209	39.454	
pass 3	id	31	20998	38.664	
pass 2	7845	434	-1511	-217.260	0.542
pass 3	7237	31	0	38.675	0.868
pass 1	7090	150	8577	-43.211	1.082
pass 2	id	207	15298	-43.112	
pass 3	id	94	44095	-42.753	

Table 2 – Three calculations of time transfer in non Common View between Grasse (7845) and Changchun (7237) over 2 hours (up), 6 hours (middle), and 12h (down) ; we used a weighted process with $w = 0.75$, 0.40, and 0.30 for 7845, 7237, and 7090 (Yaragadee), respectively.

6 Conclusion

The T2L2 space instrument, in addition to the SLR tracking on Jason-2, is used to establish for the first time a global view of the ILRS network from the point of view of time shifted to UTC. SLR stations are realize their own time-scale which should be synchronized, *a priori*, with the common UTC one at 100 ns or less.

In order to calculate the instantaneous time differences between stations from a same time-scale, we developed a dedicated process which is mainly based on T2L2 phase data and on the integration of modelled frequency variations of the DORIS USO. The time transfer in non Common View between couples of SLR stations were calculated over some orbital revolutions due to the stability of our process of around 1-2 ns over 20,000 s. It showed that time differences are at the level of 250-300 ns (best case) and can reach up to approximately 1-2 microseconds in worst cases. Next step of this study will be to establish a dedicated campaign involving both T2L2 and GPS space time transfer techniques over a continental distance.

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