**Time Transfer by Laser Link (T2L2):**
**A way to synchronize SLR observatories to the 1 ns level**

**P. Exertier (1), C. Courde (1), A. Belli (1), E. Samain (1), J.M. Torre (1), Ph. Guillemot (2)**
*(1) Geoazur/OCA-UNS, 250 avenue Einstein, F-06560 Valbonne Sophia-Antipolis*
*(2)Centre National d'Etudes Spatiales, 18 avenue Belin, F-31455 Toulouse*

**Abstract**. *The Time Transfer by Laser Link (T2L2) experiment, a passenger of the Jason-2 satellite, was developed by both OCA and CNES to perform ground to ground time transfer between remote clocks. The principle is derived from laser telemetry technology with dedicated space equipment designed to record arrival time of very short laser pulses at the satellite. Several experiments demonstrated the capability of the T2L2 system (hardware and software) to perform time transfer between ultra-stable clocks for Common View (CV) passes. T2L2 allows realizing some links between distant clocks with time stability of a few picoseconds over 1000 s and accuracy of the order of 100 ps.*
*The non-Common View mode is limited by the stability of the on board Ultra Stable Oscillator (USO, Allan standard deviation of a part of* $10^{-13}$ *over 1000 s), which is provided by the on board DORIS instrument. We show that the modelisation of the relative frequency variations of the USO, at least over few tens of thousands of seconds, is necessary to ensure time transfer between Satellite Laser Ranging (SLR) observatories at the 1-2 ns level. In addition, a proper time calibration of SLR equipment at ground is necessary to be realized.*

## Introduction

The Time Transfer by Laser Link (T2L2) instrument is passenger of the oceanographic space mission Jason-2, that was launched in June 2008 at an altitude of 1335 Km. On board the Jason-2 satellite, T2L2 consists of an optical system (detection) and an electronic device for the timing (Samain et al., 2014). The principle of the experiment is based on the Satellite Laser Ranging (SLR) technique; thanks to the laser reflector array located on the satellite in support of the precise orbitography (in addition to the Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) system), T2L2 benefits from the 2-way ranging, whose repeatability error and accuracy reach a few millimeters and less than 1 centimeter, respectively (Exertier et al., 2006; Degnan, 1997). At ground level, T2L2 relies on the International Laser Ranging Service (ILRS) network (Pearlman et al., 2002), whose stations are tracking the satellite for 5 to 6 times per day as a maximum, with pass duration of 10 to 15 minutes. The space instrument was characterized in terms of noise and it was properly calibrated; all instrument correction models (geometrical, optical and electronic) have been described in Samain et al. (2014). The on board time scale is insured by the Ultra Stable Oscillator (USO) provided by DORIS, which characteristics (stability of a few part of $10^{-13}$ over 1000 s — Allan standard deviation) were studied before the launch; the drift of the relative frequency bias is around $10^{-11}$ per day which is essentially due to aging and radiative-accumulation of very small effects (e. g. Auriol & Tourain, 2010).

Since 2009, we have conducted several experiments, implementing very different configurations to: *i*) properly measure the performances of the time transfer by laser link (for short and long term stability), *ii*) progress in the measurement (method and hardware) of the ground links (delay, cables, etc.) including the time distribution of pulses between equipment such as clock, SLR system, and GPS antennas, *iii*) compare the T2L2 time transfer to existing microwave techniques such as GPS. In addition, we used the French Transportable Laser Ranging Station (FTLRS, Nicolas et al., 2000) to conduct campaigns from the Observatoire de Paris in addition to European SLR's and the Grasse geodetic observatorie (Guillemot et al., 2012; Samain et al., 2011; Samain et al., 2012).

## Data

T2L2 records an average of 100,000 optical events ($t_B$ epochs) per day, including noise and true laser shots. From 5 to 6 SLR participating stations in 2008, T2L2 implies today 22-24 stations (see Figure 1). They send their data ($t_e$ epochs in UTC and 2-way distances $dt_{2w}$) regularly to the European Data Center (EDC, located in Muenchen, Germany) and to the Crustal Dynamics Data Information System (CDDIS, in the US). Given the very high reliability of T2L2 over time (6 years in space), we developed a data reduction scheme that operates on a daily basis. In parallel, we have developed an interactive website (https://t2l2.oca.eu/) to describe the data over time: ground and board data and statistics. For the web user, it's possible to compute a given ground-to-space time transfer (from a selected set of SLR stations) or to obtain a history over several days. Given the wide variety of clock systems and laser stations, we built a data reduction scheme based on the robust estimation (mathematical and numerical meaning). Statistically, we can say that the estimated noise at 1 s ranges from 45 to 65 ps (Exertier et al., 2010). The average stability achieved in today's data processing is 4-8 ps at 75 s (average of the time standard deviation obtained from many passages of ground to space time transfer for 2 laser stations equipped with H-maser). The ground-to-space time transfer is considered as a basic product from which it is possible to extract both the time synchronization ($\Delta t_{B\text{-}S}$) between board (B) and station (S) clocks and the local relative frequency bias of the on board USO (it evolved from $20.10^{-9}$ in July 2008, to $50.10^{-9}$ at the end of 2014).

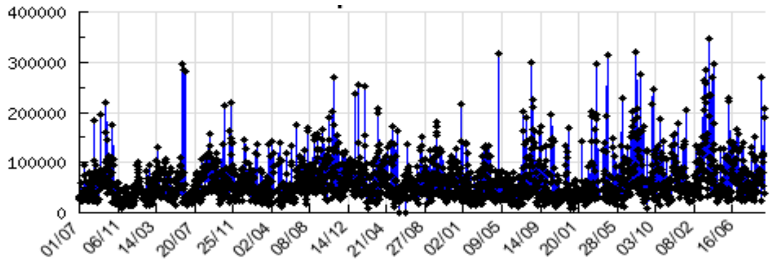


**Figure 1. Number of daily acquired data on T2L2 /Jason-2 from 2008.**

## Ground to ground in Common View

The ground-to-ground time transfer between two SLR stations (S and S') is computed from each available ground-to-space pass ; the goal is to extract the differences ($\Delta t_{B\text{-}S}$ - $\Delta t_{B\text{-}S'}$) in removing the onboard clock ($t_B$). As laser measurements between two (or more) stations are not synchronized on board, we determine separately each synchronisation; after filtering the white noise an interpolation procedure permits to compute ($\Delta t_{B\text{-}S}$) for each round second in the on board time scale. Finally, the search for common seconds (between S and S') led us to

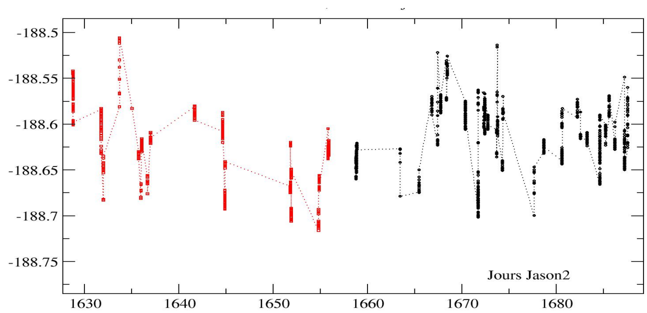


**Figure 2. Time transfer (ns) between FTLRS and MeO fixed station at Grasse Observatory, from December 2012 to January 2013 (Ox unit is in days after the Jason-2 launch).**

directly calculate the difference between the ground clocks ($\Delta t_{S\text{-}S'}$). The duration of a ground-to-ground time transfer CV is of 250 to 600 s, with an average 300 dots. After removing a linear fit, the ground-to-ground stability reaches 10-12 ps over one pass, in average. See an example on Figure 2, where FTLRS and MeO SLR stations in Grasse were used together during two months (from December 2012 to January 2013, with the same H-maser clock). The time evolution of the value of the phase difference (mean of 188.6 ns between both systems) presents a repeatibility error of ~50 ps (Exertier et al., 2014). The time calibration of each SLR station were conducted thanks to dedicated harwdare technologies; the complete error budget of the experiment was properly made by Samain et al. (2014b), leading to the an estimated global error of 110 ps. The role of time calibration is fundamental to ensure that SLR stations guenuinely operates satellite tracking without substantial time lag relative to the common UTC/TAI time scale. A great effort was made in Grasse, first to properly define the reference point of the PPS unit, then to calibrate the necessary permanent GPS link (Laas-Bourez et al., 2013 & 2014). Other developments were made in the framework of the ACES mission and the European Laser Timing experiment (Schreiber et al. 2010).

Finally, end of 2013, a campaign was conducted between European SLR stations, involving SLR and GPS time calibrated systems in Hersmonceux, Grasse and Paris (with the FTLRS). The goal was to compare independently calibrated T2L2 and GPS CV time transfers. This work is under publication (Exertier et al., 2015 expected in the Metrologia journal); we show that the quality of the T2L2 link strongly depends on some tricky points as : the stability of the laser pulse width, the stability of the event timer (and that of the time & frequency distribution), the measurement of the optical to electrical detection delay in detectors (e.g. Prochazka et al., 2014 this issue). The complete error budget of the T2L2 link accuracy leads to 140 ps, whereas the uncertainty on the GPS CV link is estimated at 1.7 ns at best (Rovera et al., 2014).

**The Non Common View case**

The T2L2 non-CV time transfer between remote clocks at ground strongly depends on our ability to accurately integrate the frequency variations of the on board oscillator (DORIS on Jason-2) during the time of flight of the satellite between both SLR stations (from 1000 s to 10,000 s). But for doing that, it is necessary to isolate the physical phenomena from the stochastic effects.

The drift of the DORIS oscillator might be due to (the algebraic sum of) aging (long term time dependency) and frequency changes due to radiation, temperature changes in the spacecraft, and accelerations, vibrations, etc. Several studies were conducted at ground on a new generation of oscillators (the DGXX quartz series), the first of it currently flies on Jason-2 (Auriol & Tourain, 2010). As a result, the following specifications were expected for the USO: $10^{-11}$ per day for aging, 6.8 $10^{-13}$ per degree C, and a very low sensitivity to short term radiation effects (e.g., Galliou et al., 2007). In contrast to the almost linear effects of radiations and aging, the effects induced by the temperature on the frequency variations are at the orbital period of the satellite (of around 6,500 s). In order to propagate the USO frequency over several thousand seconds, we first considered the effects of temperature ($T$) as a third-order polynomial in $T$ (Galliou et al., 2007). Then, we considered also the other small but cumulative effects as an empirical time ($t$) dependency of order 3 in $t$.

The complete model of the frequency variations of the USO is thus based on six empirical coefficients in addition to temperature data. Actually, the temperature of the USO, which is thermally controlled between 8 and 11 degree C, is measured on board every 30 s; the data, which are very noisy but usable, are available on a daily basis. On the other hand, the estimate of the DORIS frequency bias from ground-to-space time transfer passes is reaching $1\text{-}2.10^{-13}$ at best; this value is due to *i)* the unstability of the onboard oscillator over 1000 s and *ii)* to the uncertainty in the frequency accuracy of each H-maser involved at ground level. Convergence of the modelization may be detected based on the number of ''observed'' frequency bias from SLR stations equipped with H-maser. According to the T2L2 passes, the model has to be fitted on a period of a few days; in average, the rms of the fit is of $4\ 10^{-13}$. It is then integrated over the time of flight of Jason-2 between some SLR stations which are in non-CV (some tens of thousands seconds as a maximum). Obviously at this stage, the relativistic effects ("red shift" of the frequency in $U/c^2$, and second Doppler effect in $v^2/c^2$) were included. Thus, the expected error of the overall process is of 1-2 ns over one orbital revolution.

As an example, the frequency model is fitted on 6 days (from January, 1 2013), and is then integrated over 12 hours. First starting from the Grasse (7845) epoch 2nd of January (including calibration relative to UTC) the result of the integration added to that epoch gives a time transfer in non-CV to Yaragadee station (7090) of -1187.7 ns ±4.0 ns in average. In fact, this time transfer is based on two passes between 7845 and 7090, of respectively -1190.5 ns (after 10,000 s), -1193.0 ns (after 17,000 s). The same kind of process is applied between Mac Donald (SLR 7080) and Grasse (January, 5); the non-CV time transfer provides a synchronization of 27.25 ns ±0.6 ns. These results are very encouraging to provide SLR users with a unique and synthetic time scale, thanks to the modeling and monitoring of the DORIS USO by T2L2. Nevertheless, it is still important to realize some time calibration of SLR systems, which calibration is of around 150-250 ns.

**Conclusion and future works**

After 6 years in space, the T2L2 instrument was accepted by CNES to pursue its goals and scientifical applications (notably for space geodesy and fundamental physics) for a new 2-yrs period in 2015-2016. For some applications, as time transfer and physics, the next step will consist to improve the accuracy of the frequency model of the USO in introducing radiations and aging effects in addition to temperature. The goal is to maintain a great level of frequency accuracy and availability, in order to provide non-CV time transfer between the SLR stations of the ILRS network at the level of 1-2 ns.

Finally, we would like to thank CNES for providing data and control of the T2L2 space mission, the ILRS community for providing laser Full Rate data and in particular the EDC/CDDIS data centers for including the T2L2 data (triplets under the form of CRD format) in their data base.

**References**

Auriol, A. & Tourain, C., *DORIS system: The new age*, Adv. Space Res. 46(12), 1484-1496, 2010.

Bezerra, F., Lorfevre, E., Ecoffet, R., et al. CARMEN/MEX Test Board for the Study of Radiation Effects on Electronic Components aboard JASON-2 and SAC-D Satellites, Proc. RADECS2007, IEEE CFP07449-PRT-ISBN:978-1-4244-1704-9, 328, 2007.

Degnan, J., *Satellite laser ranging: scientific and technological challenges for the new millennium*, Proc. SPIE Vol. 3218, p. 80-91, Laser Radar Ranging and Atmospheric Lidar Techniques, Ulrich Schreiber; Christian Werner; Eds. (SPIE Homepage), 1997.

Exertier, P., E. Samain, P. Bonnefond, and Ph. Ghillemot, *Status of the T2L2/Jason2 Experiment*, Adv. Space Res. 46(12), 1559-1565, 2010.

Exertier, P., E. Samain, N. Martin, C. Courde, M. Laas-Bourez, C. Foussard, Ph. Guillemot, *Time Transfer by Laser Link: Data analysis and validation to the ps level*, Adv. Space Res. 54(11), 2371-2385, 2014.

Galliou, S., F. Sthal, X. Vacheret, R. Brendel, P. Salzenstein, E. Rubiola, and G. Cibiel, A Program to Analyse the Origin of Noise in Ultra-Stable Quartz Crystral Resonators, Proceedings of the IEEE Freq. Control, pp. 1176-1181, 2007.

Guillemot, Ph., et al., *Improvement of comparisons between T2L2 & RF Links*, Proceedings of the EFTF 2012, Gothenburg, Sweden, May 23-27 2012, pp 345-348, 2012

Laas-Bourez, M., Samain, E., Courde, C., Oneto, J.L., Exertier, P., Rovera, D., Abgrall, M., Fridelance, P., Guillemot, Ph. *Time and Frequency distribution improvement in Calern/Geoazur laboratory for T2L2 campaigns*. Proceedings of the EFTF & International Frequency Control Symposium (EFTF/IFC) 2013, Prague, Republik Tcheque, July 21-25, pp 869-872, 2013.

Laas-Bourez, M., Courde, C., Samain, E., Exertier, P., Guillemot, Ph., Torre, J.-M., Martin, N., Foussard C., *Accuracy validation of T2L2 time transfer in co-location*, IEEE Trans. on Ultrasonics, Ferroelectrics and Freq. Control, accepted in 2014.

Nicolas, J. et al., *French Transportable Laser Ranging Station: scientific objectives, technical features, and performances*, Applied Optics, Vol. 39 (3), 402-410, 2000.

Pearlman, M., et al., *The International Laser Ranging Service*, Adv. Space Res., Vol. 30 (2), 135-143, 2002.

Rovera, G.D., Torre, J.M., Sherwood, R., Abgrall, M., Courde, C., Laas-Bourez, M., Uhrich, P., Link calibration against receiver calibration: an assessment of time transfer uncertainties, Metrologia, 51(5), 476, 2014.

Samain, E. et al., Time Transfer by Laser Link - *T2L2: Current Status and Future Experiments*, Proc. of the European Frequency and Time Forum, San Francisco, California USA, May 1-5 2011, pp. 378-383, 2011

Samain, et al., *T2L2: Ground to ground Time Transfer*, Proc. 26$^{th}$ European Frequency and Time Forum, Gothenburg, Sweden, May 23-27 2012, pp. 36-40, 2012

Samain, E., Vrancken, P., Guillemot, Ph., Fridelance, P., Exertier, P., *Time Transfer by Laser Link (T2L2): Characterization and Calibration of the flight instrument*, Metrologia, 51, 1-13, 2014

Samain, E., Exertier, P., Courde, C., Fridelance, P., Guillemot, Ph., Laas-Bourez, M., Torre, J.-M., *Time Transfer by Laser Link- A complete analysis of the error budget*, Submitted to Metrologia, December 2014b.

Schreiber, K.U., Prochazka I., Lauber P., Hugentobler U., Schäfer W., Cacciapuoti L., Nasca R., Ground-based demonstration of the European Laser Timing (ELT) experiment, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control 2010, 57(3), 728-737, 2010.