TIME TRANSFER BY LASER LINK - T2L2: FIRST RESULTS OF THE 2010 CAMPAIGN

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Abstract

The Time Transfer by Laser Link (T2L2) experiment, developed by both CNES and OCA, is aimed at performing ground to ground time transfer over intercontinental distances. The principle is derived from laser telemetry technology with dedicated space equipment designed to record arrival time of laser pulses at the satellite. Using laser pulses instead of radio frequency signals, T2L2 permits the realization of links between distant clocks with time stability of a few picoseconds and accuracy better than 100 ps.

The T2L2 space instrument on board the satellite Jason 2 has been in operation since June 2008. Several campaigns were done to estimate both the ultimate time accuracy and time stability capabilities. It includes mainly two kinds of experiments: the first involves two SLR stations on the same site and using the same clock, the second involves two remote SLR stations (Grasse and Paris) in common view. These experiments allowed the demonstration of both a time stability lower than a few tens of picoseconds for integration times from 10 s to 100 s and an accuracy lower than 100 ps for the T2L2 time transfer.

Some important work has also been done to accurately compare T2L2 with microwave time transfer GPS and TWSTFT. These comparisons are based on laser station calibrations with a dedicated T2L2 event timer designed to accurately set the optical reference of the laser station within the PPS reference of the microwave systems.

This paper presents ground to ground time transfer both in common view and non common view configuration, and comparisons between T2L2, GPS and Two-Way systems. Results of the 2010 campaigns are described as well as an insight into the future working plan.

INTRODUCTION

Optical time transfer is an evolution of current time transfer systems profiting from advantages of the optical domain as compared to radiofrequency techniques such as a higher modulation bandwidth, insensitivity to ionosphere and a mono-carrier scheme. After its early predecessor LASSO **[1]**, the T2L2 (Time Transfer by Laser Link) instrument **[2]**, developed by CNES (Centre National d'Etudes Spatiales) and OCA (Observatoire de la Côte d'Azur), will prove the concept of time transfer based on a free-space laser link. The principle is derived from Satellite Laser Ranging (SLR) and relies on the propagation of laser pulses between the clocks to be synchronized. T2L2 will provide the capability to compare today's most stable frequency standards with unprecedented stability and accuracy. Expected T2L2 performances are in the 100 ps range for accuracy, with an ultimate time stability of about 1 ps over 1,000 s and 10 ps over one day.

T2L2 was launched in June 2008 on board the Jason 2 space vehicle. It celebrated its third anniversary in June this year. Though the expected lifetime of the instrument was three years, all the internal parameters and performances are still nominal. After 40 months in orbit and about 27,000 passes over laser stations all around the world, T2L2 has detected about 35 million laser shots. A preliminary evaluation of the performances has been done during the validation phase of the mission, in 2008 **[3]**. Then the experimental program allowed a first characterization of the stability **[4-5]** and the accuracy **[6]** of the time transfer. The objectives of the T2L2 experiment on Jason 2 are threefold:

- Technological validation of optical time transfer, including the validation of the experiment, its time stability and accuracy and of one-way laser ranging.
- Characterization of the onboard Doris oscillator for Jason 2 purposes and a contribution to the Jason 2 laser ranging core mission.
- Scientific applications such as time and frequency metrology (comparison of distant clocks, calibration of RF links), fundamental physics (such as anisotropy of the speed of light), earth observation or very long baseline interferometry (VLBI).

Among the objectives, the last T2L2 campaigns were focused on the ground to ground time transfer, mainly in common view configuration, but also in non common view configuration.

COMMON VIEW TIME TRANSFER

Because the T2L2 instrument is synchronized by the DORIS Ultra Stable Quartz Crystal Oscillator and not an atomic clock, the common view configuration is the most favorable one in terms of performances. Only the short term stability of the clock (together with the noise of both the photon detection and the chronometry) affects the performance of the time transfer. Thus, this configuration allows the evaluation of the ultimate stability of the time transfer and then to do some comparison with GPS and Two Way Satellite Time and Frequency Transfer (TWSTFT). At the end, this configuration should allow the comparison of cold atom clocks with a frequency uncertainty in the 10^{-16} range.

The first evaluation of the common view ground to ground time transfer has been done on the link between the Observatoire de Paris (OP) and the Observatoire de la Côte d'Azur (OCA) in the south of France (about 1000 km) . This link has been chosen because of our capacity to have at both ends a GPS receiver, a Two Way station and obviously a laser station, all of them synchronized by a hydrogen maser and an atomic fountain.

EXPERIMENTAL SETUP

On one hand, at the Observatoire de la Côte d'Azur, we have the MéO laser station, with its 1,5 meter telescope, a Dicom GTR50 GPS receiver, a TWSTFT station, a hydrogen maser and the transportable atomic fountain from the Observatoire de Paris.

The OCA French Transportable Laser Station (FTLRS) was installed on a dedicated platform at OP. The FTLRS has a 13 cm telescope and a 10Hz laser with 10 mJ / 35 ps pulses. Some special authorizations were obtained in order to be able to range with a laser in Paris. The OP mobile atomic fountain (FOM) was installed at OCA during the same period. At OP, FTLRS, the atomic fountains, the GPS receiver (Ashtec Z12-T), and the TWSTFT station were connected to the same H-Maser. At OCA, the MéO laser station (Optical Metrology, a 10Hz laser with 50 mJ / 25 ps pulses sent in a telescope of 154 cm diameter), the mobile atomic fountain the GPS receiver (Dicom GTR50), and the TWSTFT station were also connected to a common H-Maser.

Figure 1. Left: MéO Station at Grasse, built on a 1.54 m telescope; Right: The mobile FTLRS station at Observatoire de Paris.

After a first campaign in 2009, mainly devoted to the validation of the setup and the operations of the FTLRS at Paris, a second campaign started in May 2010 and ended in October.

CALIBRATION PROCESS

The T2L2 has been designed to realize ground to ground time transfer with an accuracy better than 100 ps. If one can neglect the noise coming from the individual ground to space time transfer, this accuracy requires the measurement of the laser pulse start times with an accuracy in the range of 50 ps.

Usual laser stations are only designed to measure the time difference between a start and a stop with an accuracy of the start pulse of typically 100 ns. These 50 ps can only be obtained with a special time calibration based on simultaneous measurements between the usual chronometry of the laser station and a dedicated calibration process. It allows the measurement of the delay between optical pulses when it crosses the reference point of the laser station and the electrical reference coming from the time and frequency laboratory. The reference point at the laser station level is the cross axes of the telescope which is also the space reference for laser ranging. The reference at the time and frequency laboratory is a given output of the PPS distribution unit.

The calibration process relies on a unique equipment to perform measurements: the SigmaTime STX301 Event Timer and an optical module to grab laser pulses from the laser station. The event timer STX301 was developed in the T2L2 framework with 3 separate objectives:

- To make the T2L2 calibration,
- To upgrade, if necessary, laser stations with no proper chronometry,
- To have a versatile high precision laboratory instrument.

The instrument has an internal frequency synthesis that can be slaved on an external 5, 10 or 100 MHz clock reference, two or four independent channels (Electrical and Optical: DC - 20 GHz), and a high stability pulse generator. All of this metrology is driven by an embedded Win 7 computer able to control the hardware and to give to the user a friendly Human Machine Interface permitting the measurement of both absolute start time and time interval, sampling the frequency, and determining the shape of a given signal.

Parameters	Values
Number of independent channels	2 to 4
Time Stability @ 1000s	< 20 fs
Linearity	0.3 ps rms.
Thermal Sensitivity	< 200 fs/°C
Repeatability error Synchronous	< 600 fs rms
Repeatability error Random	700 fs rms
Dead time	130 ns
High speed Acquisition	500 kHz
Continuous rate	35 kHz
Input bandwidth	DC - 20 GHz

Figure 2. STX301 SigmaTime sub picosecond event timer: Key performances.

The optical module is made with a collimation optic connected to a 50 m mono-mode optical fiber (532 nm). The time delay of the fiber is currently considered as a constant. In the near future a special instrumentation will permit the measurement of the variations that could be generated by some temperature changes or constraint variations. The optical module is placed in front of the telescope at a precise distance from the cross axes.

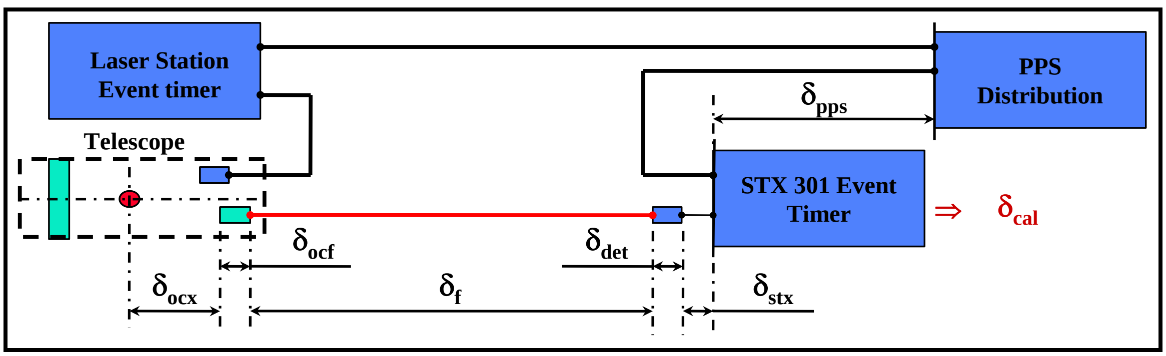

Figure 3. Calibration setup.

The time equation that permits accurately time-tagging laser pulses is given by:

$$\delta T = \delta_{cal} - (\delta_{ocx} + \delta_{ocf} + \delta_{f} + \delta_{det} + \delta_{stx}) + \delta_{pps}$$

where:

- δ_{cal} is the difference between absolute measurement (calibration) and station measurement. δ_{cal} is determined in two steps: first, the PPS synchronization of the SigmaTime STX301 event timer (the PPS synchronization is obtained from a scan of the PPS signal by the event timer that permits the determination of the reference threshold deduced from the inflection point and the synchronization of the timer with this reference threshold) and second, the simultaneous acquisition of an ensemble of laser pulses from the laser station and the calibration station,

- δ_{stx}, δ_{PPS} and δ_f come from the propagation in cables and optical fiber and are measured by the calibration station,
- δ_{ocx} and δ_{ocx} come from the propagation in free space and are determined from the geometrical distance,
- δ_{det} is the propagation inside the detector (optical-electrical) and is deduced from a propagation model (currently studied **[7]**); the delay is in the 100 ps range.

Table gives a preliminary evaluation of the uncertainty budget of the calibration. It allows us to expect a total uncertainty lower than 50 ps.

Table 1. Preliminary uncertainty budget of the calibration.

Term	**Uncertainty (k = 1)**	**Comment**
δ_{cal}	10 ps	STX310 (See Figure)
δ_{stx}	-	δ_{stx} is included in the calibration process of STX301 and set to zero
δ_{PPS}	10 ps	Measured with STX301
δ_f	10 ps	Measured with STX301
δ_{ocx}	3 ps	Geometrical uncertainty = 1 mm
δ_{ocx}	3 ps	Geometrical uncertainty = 1 mm
δ_{det}	< 30 ps	Allocation (30% of total delay ~100ps)
$\boldsymbol{\delta T}$	**< 50 ps**	

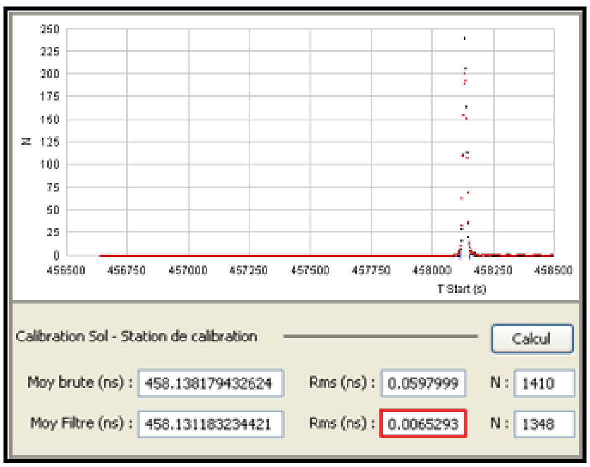

Figure 4. STX301: Example of the distribution of the measurements (scale is 50 ps per division).

Both OP and OCA have been calibrated with the same T2L2 calibration station. Calibrations were performed each time a modification of the setup, either in OP or OCA, occurred. The result of the correction of T2L2 data with calibration data is shown in Figure. The jumps induced by the modifications of the setup are clearly corrected and the noise, lower than 500 ps rms, demonstrates that the uncertainty of the calibration process is at least below a few hundred picoseconds.

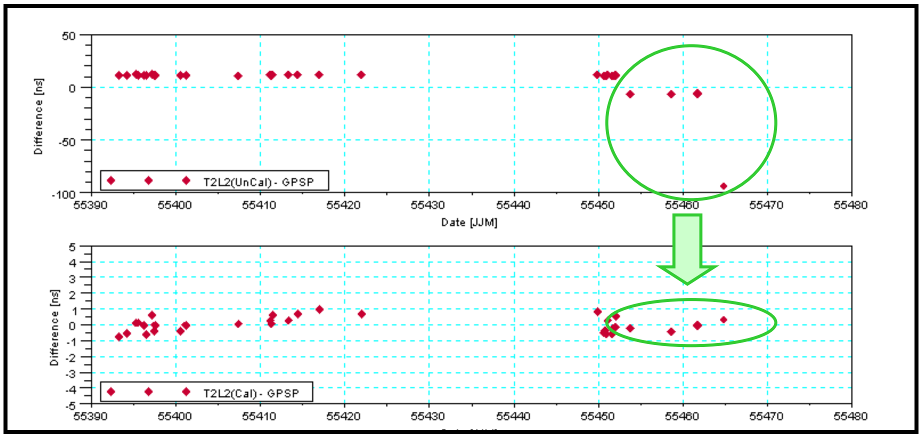

Figure 5. Comparison of T2L2 and GPS Carrier Phase time transfers, without (upper diagram) and with (lower diagram) correction of T2L2 data with results from the calibration of the laser station (the arbitrary offset has been removed).

GROUND TO GROUND TIME TRANSFER

During the 114 days of the 2010 campaign, 56 common view passes were recorded with the FTLRS in Paris. From each acquired pass, an equivalent point representing the average value of the time difference and the average value of the date is computed. The first result extracted from these comparisons is the T2L2 time difference between H-Masers (Figure 6); the long term quadratic drift comes from the relative drift of the two masers. This long term drift can be identified and removed by adjusting a 2nd order polynomial. The residuals that we obtain then allow the computation of first stability of the time transfer (Figure 7) : with a time deviation lower than 2 ns over 10 days, one concludes that the noise introduced by T2L2 over several days is significantly below the noise coming from the H-Masers themselves.

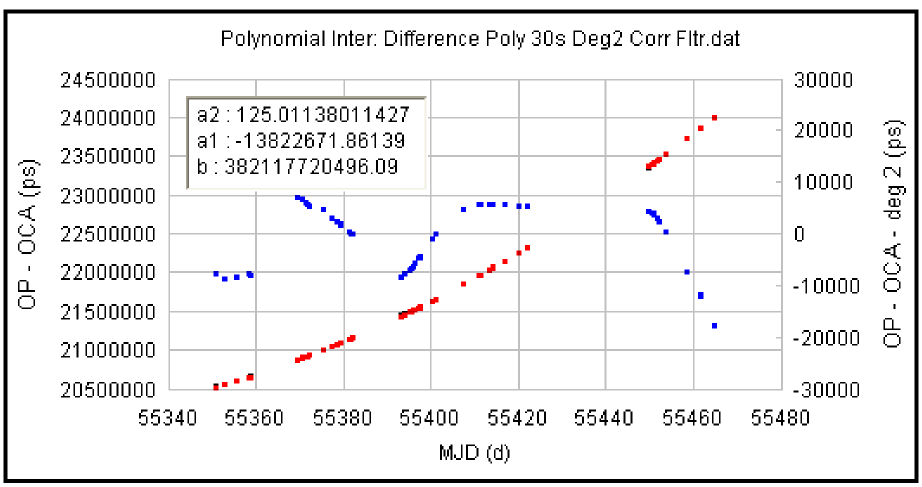

Figure 6. T2L2 time differences between OP and OCA H-Masers. Direct measurements (red, left) and residuals after adjustment and removal of a 2nd order polynomial (blue, right).

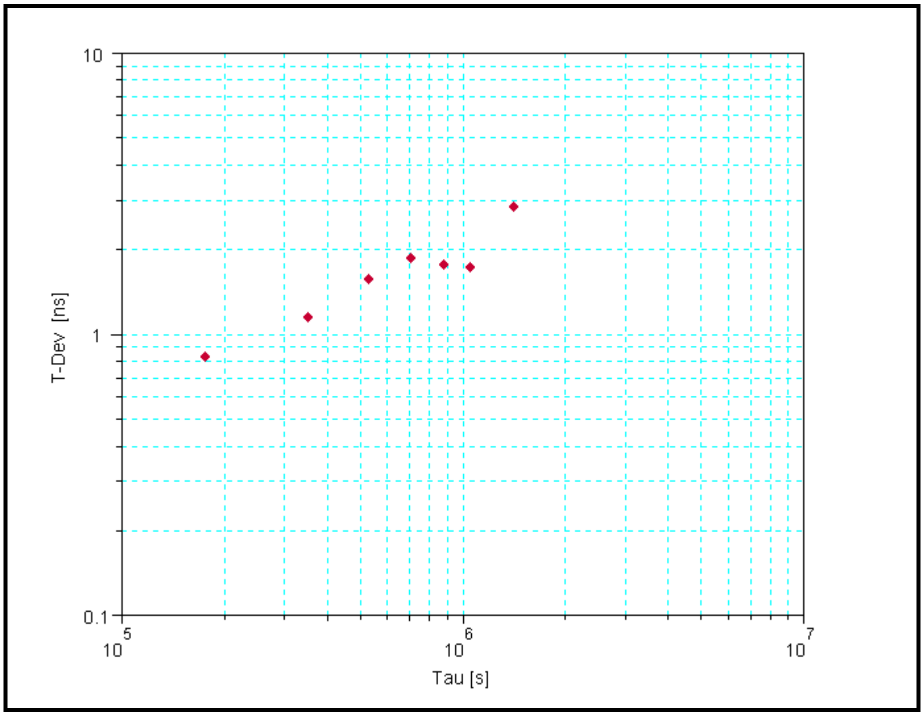

Figure 7. Time Deviation computed from the residuals of T2L2 time differences between OP and OCA H-Masers.

COMPARISON WITH GPS CARRIER PHASE AND TWSTFT

The second important result is illustrated in Figure 13. The graph shows both the time transfer comparison between T2L2 and GPS (carrier phase based) and between T2L2 and TWSTFT (code phase). The GPS analysis is based on the PPP NRCan algorithm (carrier phase technique). This is a preliminary result in which the absolute calibration has not been taken into account; an offset between each curve was introduced to facilitate the graph reading. Regardless of these absolute aspects, the noise between T2L2 and GPS or TWSTFT remains within 2 ns during the 60 days of the campaign, with no relative drift, at least at the nanosecond level. These results are in accordance with the classical long term stability of microwave time transfer systems.

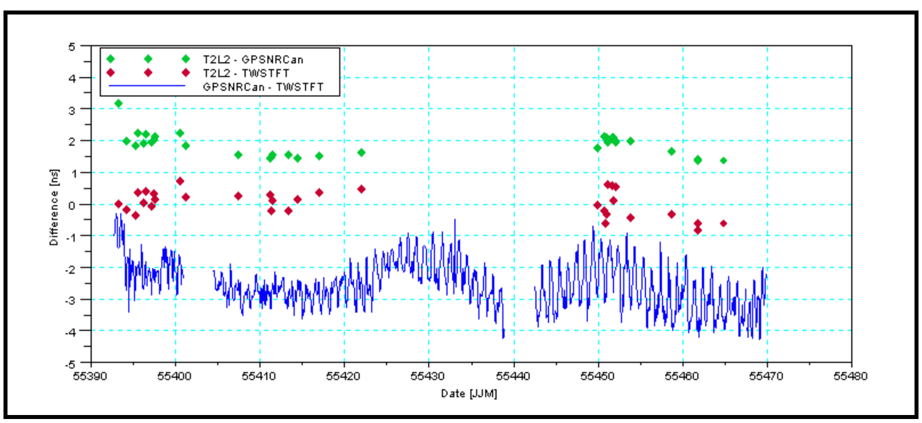

Figure 8. Comparison between T2L2, GPS and Two Way on the link OP-OCA:T2L2-GPS (green), T2L2-TWSTFT (red) and TWSTFT-GPS (blue) (arbitrary offset removed for a better reading of the plot).

The next step is to use the stability and the accuracy of the fountains to improve these results. Unfortunately the fountains were not in operation continuously during the campaign and it is difficult to conclude on that point. This is why a new campaign with the FTLRS in Paris is foreseen, maybe in 2013.

TOWARDS NON COMMON VIEW TIME TRANSFER

The main challenges are first, to deal with data that are sparse and non periodic (in contrast to GPS and TWSTFT data which are continuous or at least periodic) and second, to take into account the drift of the onboard clock.

DATA PROCESSING FOR NON COMMON VIEW TIME TRANFER

T2L2 data are processed in near real time by the Scientific Mission Center at OCA. From each ground to space time transfer (i.e., SLR passes on Jason 2 which provides enough data), a set of differences between the onboard time and the ground time is produced at each round second (onboard time). Raw data (in CRD format) and "round second data" are now available through the T2L2 web site (http://www.oca.eu/heberges/t2l2/home.htm). Ground to ground time transfers are thus directly available by searching, in that file, SLR passes sharing the same round second of time. From these data, the resulting estimation of the time transfer between 2 SLR gives a raw rms of 90ps.

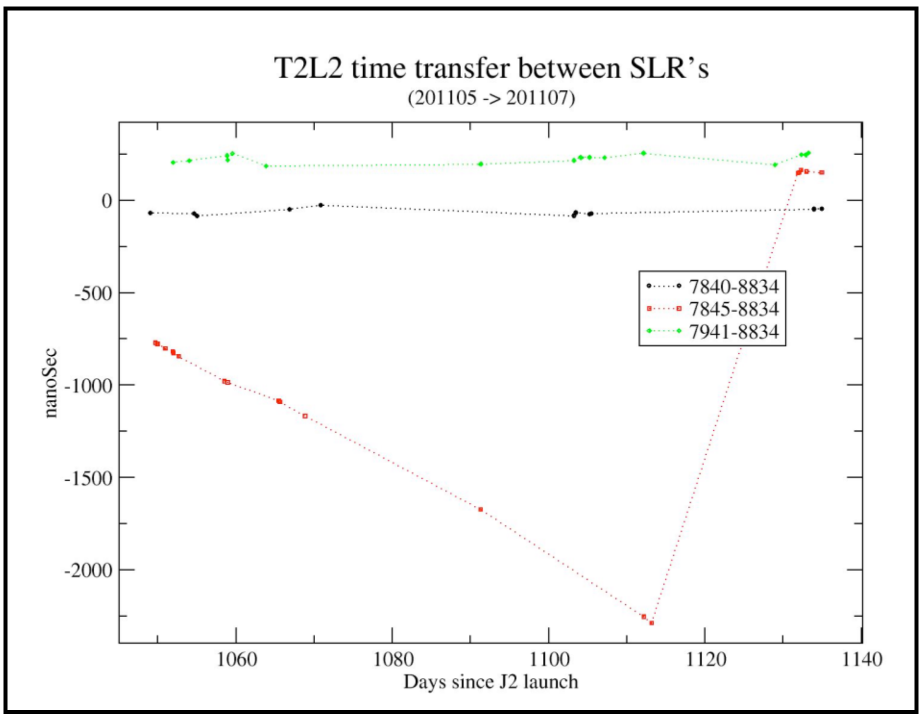

Figure 9. Example of ground to ground time transfer computed by the T2L2 Scientific Mission Center (7840- Herstmonceux, 7845-Grasse, 7941-Matera, 8834-Wettzell).

If this kind of information is very well suited for common view time transfer, it is necessary to develop a synthetic time scale in order to properly transfer time between non common passes. This so-called T2L2 time scale is a continuous time scale corrected from the behavior of the onboard clock. This time scale will rely on a model of the clock in a first step a simple linear frequency drift, and will be steered in a second step from high quality ground to space time transfer (laser station synchronized by H-Maser).

A first simulation of the process was done with real data from the laser stations MéO and FTLRS connected to the same clock (Figure 10). We have first identified and removed from each ground to space time transfer the same linear frequency drift. Then we have adjusted a polynomial on the residuals, one polynomial for each station. The remaining residuals exhibit a noise of about 100 ns rms, in line with what we usually have with T2L2 ground to space time transfer (consistent with the time stability of the onboard clock of $\sigma_x(\tau) \approx 2\times10^{-13}\times\tau\,[\mathrm{s}]$ **[8]**).

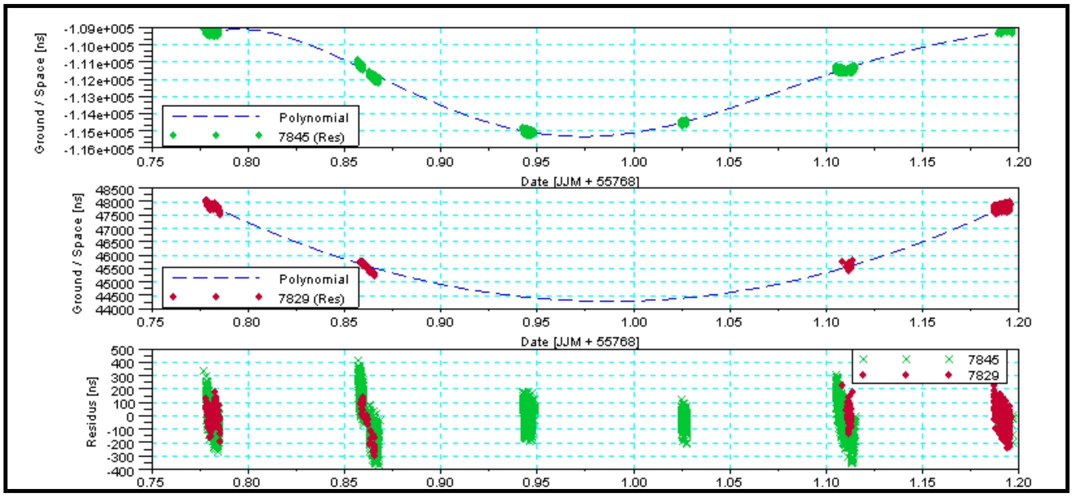

Figure 10. Polynomial adjustment (Linear frequency drift removed, 7845/MéO: Order 6; 7829/FTLR: Order 2) and residuals.

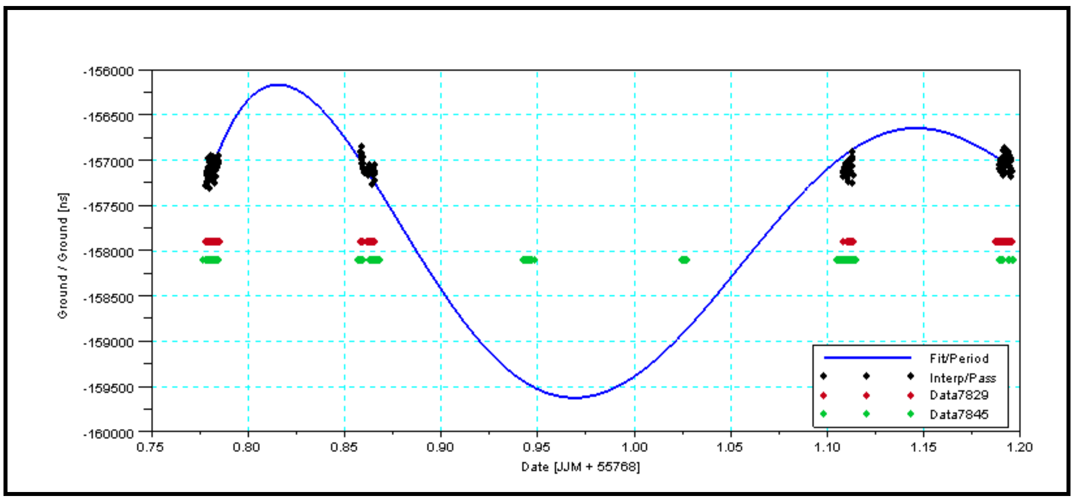

Figure 11. Ground to ground time transfer computed by subtraction of 2 polynomials (blue) and by direct differences of ground to space time transfer (black dots).

Then we can compute the ground to ground time transfer simply by subtracting the two polynomials. Figure 11 shows the comparison between the ground to ground time transfer computed by this direct subtraction and the ground to ground time transfer computed directly from the differences of elementary data (this is possible here because we have some common view passes). The two results are rather consistent. But we must keep in mind that for that test, the two laser stations were synchronized by the same clock so what we were expected is a constant offset rather than an "undulation," clearly introduced by the polynomial process.

It must be possible to improve the process of polynomial adjustment by leaning on the stability of the ground clocks. The principle is to determine the polynomial on the first station and then to identify only the low order coefficients (0, 1 or 2) on the second station. The polynomial represented by these last coefficients describes then the difference of time walk of the ground clocks.

If we go back to the previous case with the stations MéO and FTLRS connected to the same clock, we first completely identify the polynomial with the MéO station (the one with most data). Then, we adjust only the coefficient of order 0 on the FTLRS station, keeping in mind that the 2 stations are synchronized by the same clock, with only a constant delay between them corresponding to the differential electrical length between them. The coefficient of order 0 will represent this delay. The residuals for the FTLRS station have the same level of noise compared to those determined with two different polynomials (Figure 12). This demonstrates that this approach is promising.

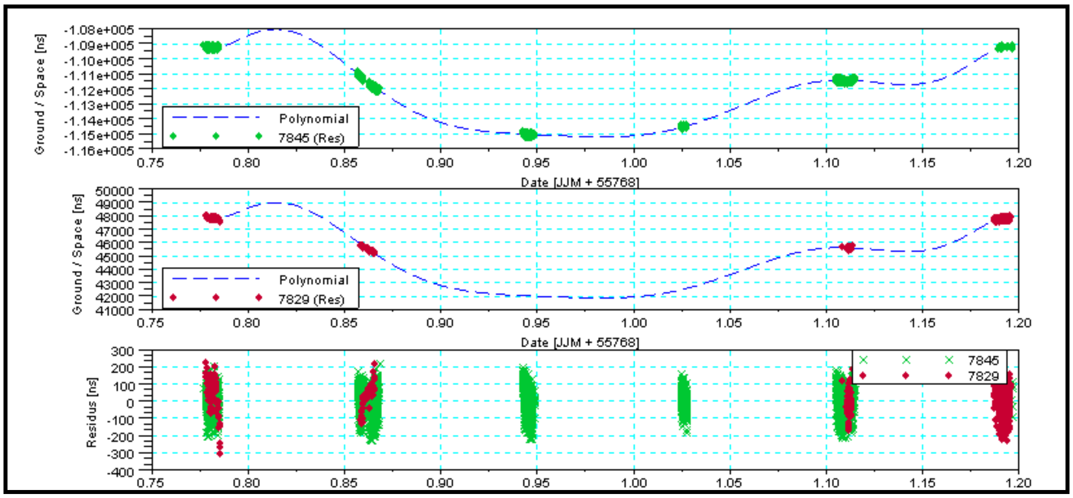

Figure 12. Polynomial adjustment: same polynomial for the two SLR stations (linear frequency drift removed, 7845/MéO; 7829/FTLRS) and residuals.

EXPERIMENTAL SETUP

A first evaluation of the data processing for non common view time transfer is foreseen through a new measurement campaign with the transportable laser station that was installed at Tahiti. This configuration allows some non common view time transfer with the Observatoire de la Côte d'Azur with data on the same orbit. This shall allow also some time transfer with US laser stations in a nearly common view configuration. The setup of the experiment is as follows:

- On the one hand, at the Observatoire de la Côte d'Azur, we have the MéO laser station, with its 1.5 meter telescope and a Septentrio GPS receiver synchronized by the same hydrogen maser.

- On the other hand we have installed at Tahiti, near the NASA laser station MOBLAS 8, the transportable laser station, and a DICOM GTR50 GPS receiver and a maser to synchronize the two laser stations and the GPS receiver.

The campaign started in May and ended in mid-October 2011. During this period, about 90 passes were acquired with FTLRS at Tahiti (only 30 with MOBLAS 8 that was out of order until the end of August), and 300 with MéO at Grasse.

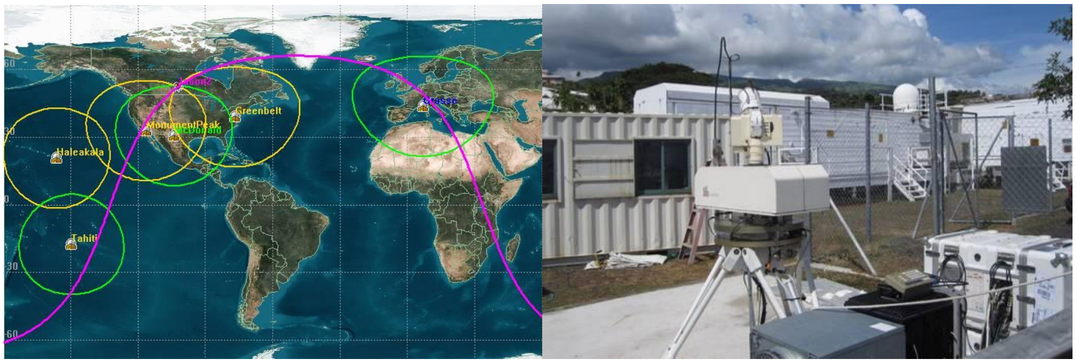

Figure 13. FTLRS at the Université de Polynésie Française,with MOBLAS 8 laser station on the background.

CONCLUSION

After more than 3 years of operation, T2L2 is still nominal. Operations are planned until the end of 2012 and an extension of the mission, hopefully until the end of 2014, will be discussed in April next year.

From the scientific point of view, we have demonstrated a stability of the ground to ground time transfer of 3×10^{-15} over 10 days (Modified Allan Deviation), and the comparison with GPS Carrier Phase and TWSTFT is now limited by the performances of the microwave links between Paris and Grasse. This paves the way for a new comparison between atomic fountains, with FTLRS at Paris and the mobile fountain at Grasse, maybe in 2013, with a frequency uncertainty at the 10^{-16} level.

Meanwhile, the processing of the data has to be achieved to produce non common view time transfers and to process the data of the campaign of Tahiti. It is also planned to pursue the campaign of calibration of the laser stations involved in T2L2 (Wettzell was calibrated in June 2011, Herstmonceux is planned by the end of the year).

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