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 has to perform ground-to-ground time transfer using time tagged laser pulses propagating back and forth between the ground and the Jason-2 satellite. The expected time stability is 1 ps over 1000 s and 10 ps over 1 day and a time accuracy in the 100 ps range. The T2L2 experiment is a joint CNES and OCA space mission. A payload has been installed inside the Jason-2 satellite, which was launched in June 2008. This payload includes some corner cubes (LRA, provided by the JPL), the T2L2 instrument itself, and an ultra-stable quartz oscillator to date the events. The ground network relies on existing laser stations (ILRS network), among them the two stations of the OCA: a fixed one at Grasse and a transportable one currently installed at Observatoire de Paris. Both stations include laser pulses emitter and receptor synchronized on a clock.

First ground-to-space time transfers have demonstrated noise levels of some tens of picoseconds 0 and a preliminary time stability of a few picoseconds over integration times of some tens of seconds, clearly limited by the on-board clock [4].

The current campaign began in June 2010 and involved eight laser stations in Europe and Asia. As some laser stations are also equipped by GPS and TWSTFT devices, this campaign should allow the performance comparisons between these systems operating with different wavelengths and, consequently, different atmosphere delays. With the installation of the SYRTE Mobile Atomic Fountain at OCA (Grasse) and the transportable laser station at SYRTE (Paris), we will perform a time and frequency transfer by laser link between the cold atomic fountains 0 with a frequency accuracy in the 10^{-16} range.

The paper will present the first results of the ground-to-ground time transfer, in common clock and non-common-clock configuration, and a first comparison with GPS.

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14. ABSTRACT
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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 a higher modulation bandwidth, insensitivity to ionosphere, and 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 about 1 ps over 1,000 s and 10 ps over 1 day.

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 (anisotropy of the speed of light, possible drift of the fine structure constant), earth observation, or very-long-baseline interferometry (VLBI).

A preliminary evaluation of the performances has been done during the validation phase of the mission, in 2008 **[3]**. Then the 2009 experimental program has allowed a first characterization of the time transfer stability **[4,5]**.

The 2010 T2L2 experimental program shall contribute to the validation of T2L2 time transfer stability and accuracy through two major experiments. The first one is a common-clock time transfer between two co-located laser stations at the OCA. The common-clock configuration should allow a direct measurement of T2L2 accuracy. The second experiment is an international campaign which involves eight laser stations in Europe and Asia, GPS and TWSTFT links, and cold atomic fountains. Objectives of this second international campaign go from the comparison between T2L2 and existing RF systems to the frequency transfer with an accuracy in the 10^{-16} range.

MISSION STATUS

T2L2 INSTRUMENT

The Jason-2 satellite has been successfully launched on 20 June 2008. The T2L2 instrument has been turned on for the first time a few days later, on 25 June the 25. The expected lifetime is at least 2 years, with an objective of 3 years. The main concerns were:

- The use of non-space-qualified electronics parts: After 30 months of operation, with an availability of 97%, the instrument is still fully operational. All internal parameters are stable, with neither critical drift nor aging.

- The behavior of optical fibers in the space environment: Some simulations and ground experiments made us afraid of a possible total loss of transmission after a few months in orbit. There is no direct measurement of this transmission at instrument level. Nevertheless, we can observe that the number of “noise” events, that is to say “false” optical events induced by the Earth’s albedo and recorded by T2L2, is rather stable. The number of “noise” events recorded is directly proportional to both the albedo intensity and the fiber transmission. When one normalizes the number of “noise” events per minute by the albedo intensity, we observe a small decrease of the frequency of “noise” events (Figure 1) of about 4% per year (in fact, it is about 10% the first year, and around zero those last 12 months). The loss of transmission appears to be negligible for the mission and stabilized. Another approach is possible that relies on the distribution of the dates of the laser pulses detected by T2L2 for a given station and on the single-photon mode. This approach requires that the laser station has a quite regular activity and a very stable link budget. A first analysis, held with the station of Yaragadee between October 2009 and July 2010, do not show drift on this period.

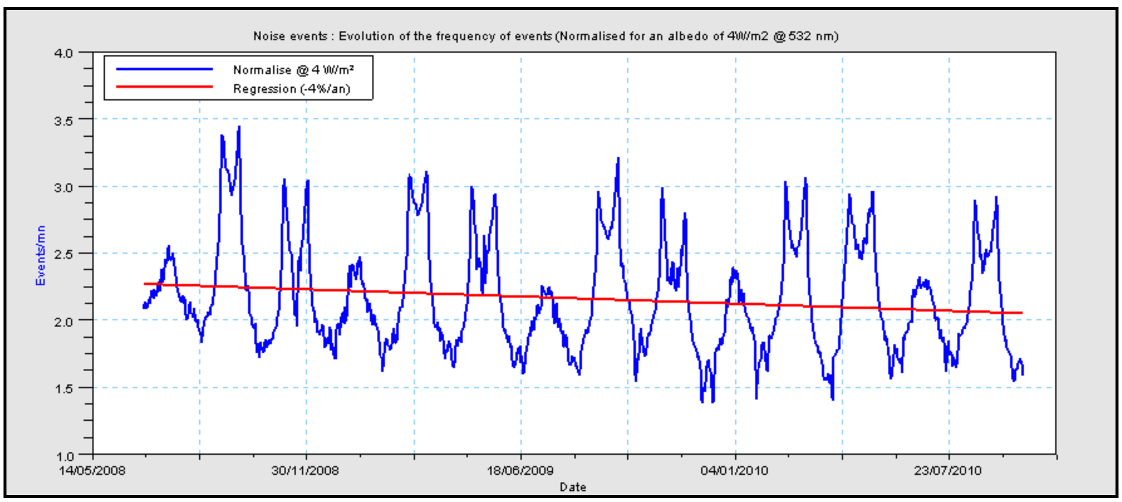

Figure 1. Frequency of “noise” events recorded by T2L2: Short-term variations are induced by the evolution of the attitude of the space vehicle.

From that point and considering the good health of the instrument, CNES has decided to extend the exploitation of T2L2 for 2 more years, until the end of 2012.

DATA PROCESSING

Several steps are necessary to jointly process ground SLR and on-board T2L2 data **[6]**. We can mention:

(i) a data selection specific to each SLR station and satellite pass,
(ii) the determination of the precise time of flight between the SLR station and the T2L2 space instrument,
(iii) the estimation of instrumental corrections,

(iv) the extraction of measurement triplets (the three dates associated to the same laser pulse: emission, board reception, ground reception) from both data sets,
(v) the computation of the ground-to-space time transfer for each pass.

The second and third steps use the Jason-2 precise 1-day orbits (and attitude) and the SLR station coordinates (ITRF2005 solution). The two main corrective terms, the Sagnac effect (between 0 and 30 ns) and the delay between the retro-reflector and the T2L2 nonlinear optics module (around 200 ps), are computed with an uncertainty of 1-3 ps and 2-8 ps **[6]**, respectively. We do not take into account any contribution coming from the propagation in the atmosphere, because, first, it is cancelled at the first order by the ranging measurement included in the T2L2 time transfer and, second, the residuals are negligible with respect to the noise of the on-board clock.

The fourth step, which leads to the identification of all available measurement triplets, is realized by a direct comparison of the times, ground and on-board, of each laser event. The T2L2 instrument uses a pps signal provided by the on-board GPS receiver to link its internal timescale based on a DORIS ultra-stable quartz oscillator to the UTC timescale. The uncertainty is a few 0.1 µs **[6]**. At this level, when several laser stations are in common view, the triplet identification is not ambiguous.

Data are processed by the Scientific Mission Centre (CMS – Centre de Mission Scientifique) at OCA. The main results are accessible through the T2L2 Web site (*http://www.oca.eu/heberges/t2l2/home.htm*):

- **Histo File Description:** The "Histo File Description" contains a quick history of the data processing: One can search for a given SLR pass or a given short period of time (typically a few days) to get the number of available SLR data, or the number of on-board T2L2 data, or finally the number of "triplets"

- **Time Transfer File Description:** The "Time Transfer File Description" will contain services permitting to evaluate the ground-to-space time transfers and a first assessment of the ground-to-ground time transfer between two SLR stations in common view (shall be extended to no common view soon).

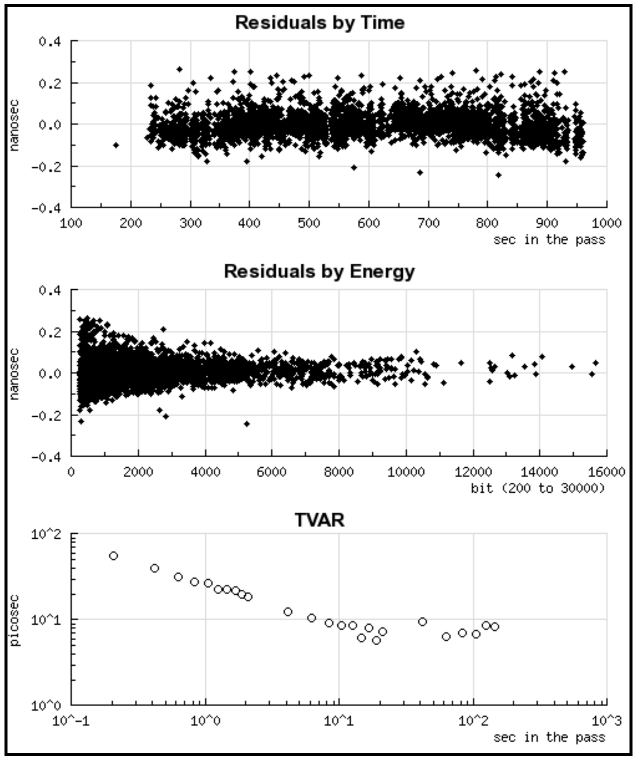

Figure 2. T2L2 Web site: Example of ground-to-space time transfer results (MeO station, Grasse, France, 03/09/2010 23h23-23h40 UTC).

COMMON CLOCK TIME TRANSFER

EXPERIMENTAL SETUP

From April to May 2010, the two French laser stations co-located at Grasse and sharing the same timescale have been used to characterize the link. The first SLR system (called MeO, for Optical Metrology) is a 10Hz laser with 20 mJ/25 ps pulses sent in a telescope of 154 cm in diameter. The second one, the French Transportable Laser Ranging Station (FTLRS), has a 13 cm telescope and a 10 Hz laser with 10 mJ/35 ps pulses. The error budget of each system for ranging measurement has been established to 30 ps and 40 ps, respectively **[7]**. The distance between the two SLR stations is 37 m long (a time delay of about 100 ns).

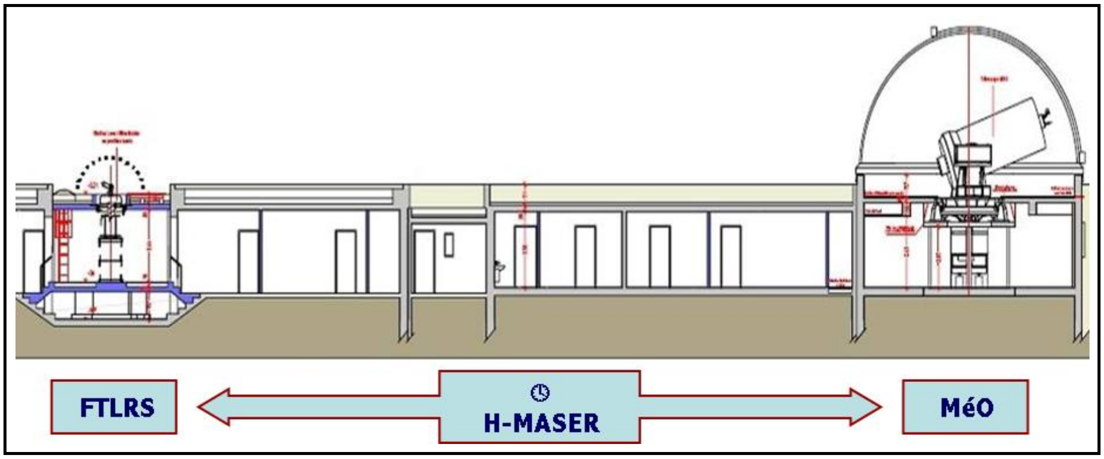

Figure 3. Common-clock time transfer between MeO and FTLRS in zero-baseline configuration at the OCA.

CALIBRATION PROCESS

The ground-to-ground time transfer between the two laser stations, because they are connected to the same clock, should be equal to zero. Nevertheless, to achieve such a result, it is mandatory to measure the propagation delay δT between the time reference of the experiment, i.e. the output of a distribution amplifier, and the time reference of each laser station, materialized by the crossing of the axes of their telescope. For standard ranging needs, this measurement is done with an absolute accuracy of 100 ns, which is clearly inadequate for T2L2. Our goal is to improve this accuracy up to 100 ps.

The calibration of this propagation delay δT relies on a specific calibration station developed especially for T2L2 **[8]**. We have (Figure 4):

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

where:

- **δocx** : Cross-axes of the telescope to fiber-coupling-optic time delay
- **δocf** : Optic-to-Fiber time delay (fiber-coupling-optic internal delay)
- **δf** : Fiber time delay
- **δdet** : High-speed Detector internal delay
- **δstx** : Event timer internal delay between inputs
- **δpps** : PPS distribution to calibration event timer time delay
- **δcal** : Measurement of the calibration station.

Using the same equipment for the calibration of the two stations FTLRS and MeO, we have :

$$\delta T_{FTLR} = \delta cal_{FTLR} - (\delta ocx_{FTLR} + \delta ocf_{Ref} + \delta f_{Ref} + \delta det_{Ref} + \delta stx_{Ref}) + \delta pps_{Ref}$$
$$\delta T_{MeO} = \delta cal_{MeO} - (\delta ocx_{MeO} + \delta ocf_{Ref} + \delta f_{Ref} + \delta det_{Ref} + \delta stx_{Ref}) + \delta pps_{Ref}$$

and

$$\delta T_{FTLR} - \delta T_{MeO} = \delta cal_{FTLRS} - \delta cal_{MeO} - (\delta ocx_{FTLR} - \delta ocx_{MeO})$$

The uncertainty on the measurement of the differential delay is, thus, only driven by the accuracy of the calibration station, about 50 ps **[8]**, and the uncertainty on the measurement of the Optic to Cross axes of the telescope time delay. These delays are measured geometrically between a mechanical reference on the optical system connected to the fiber and the bearing of the telescope elevation axis. The uncertainties on these measurements are 1 mm for FTLRS and 2 mm for MeO, giving a global uncertainty on the delay difference $\delta ocx_{FTLR} - \delta ocx_{MeO}$ of 10 ps. Thus, the total uncertainty on the differential calibration delay $\delta T_{FTLR} - \delta T_{MeO}$ can be estimated to be 71 ps (Table1).

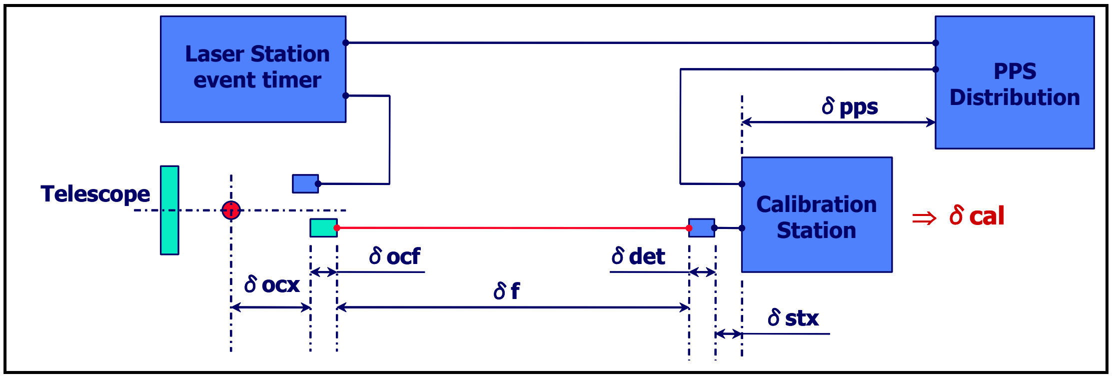

Figure 4. Experimental setup for the calibration of the propagation delay between the local time reference and the laser station time reference.

Table 1. Uncertainty budget of the differential calibration of the two laser stations MeO and FTLRS.

Term	Uncertainty
δcal_{FTLRS}	50 ps
δcal_{MeO}	50 ps
$\delta ocx_{FTLR} - \delta ocx_{MeO}$	10 ps
$\boldsymbol{\delta T_{FTLR} - \delta T_{MeO}}$	**71 ps**

Towards a First Validation of T2L2 Accuracy

Twenty-two T2L2 common passes have been performed between 17 and 25 May with the two stations MeO and FTLRS. The mean time differences between the two stations on each pass and the rms values are shown in Figure 5. The rms values remain within 75 ps. We clearly see in Figure 5 the influence of a change of configuration in the ground setup (the time and frequency distribution has been changed, such as the two laser stations, the GPS receiver, the TWSTFT station, and the DORIS beacon being all synchronized by the same H-Maser), that has lead to a change in the time differences of nearly 10 ns: At the end of May, the time difference measured between the two stations could then be estimated at **157.075 ns ± 75 ps.**

On the other hand, we measured the *in situ* distance between the SLR's by using optical fibers and our calibration process. The result of this direct measurement gives a time difference between the two stations of **157.030 ns ± 71 ps.**

The difference between these two measurements is 45 ps. It remains to evaluate some effects; as the angle of incidence of the laser beam on the T2L2 on-board detector is the same for the two stations, we cannot access the instrumental corrections that depend on this angle of incidence (correction of the distance between the T2L2 nonlinear detector and the retro-reflector, correction of the energy received by the detector and of its effect on the detector delay). However, the order of magnitude of these corrective terms, and on their uncertainties, in the ps range **[6]**, should have a minor influence on the final uncertainty budget.

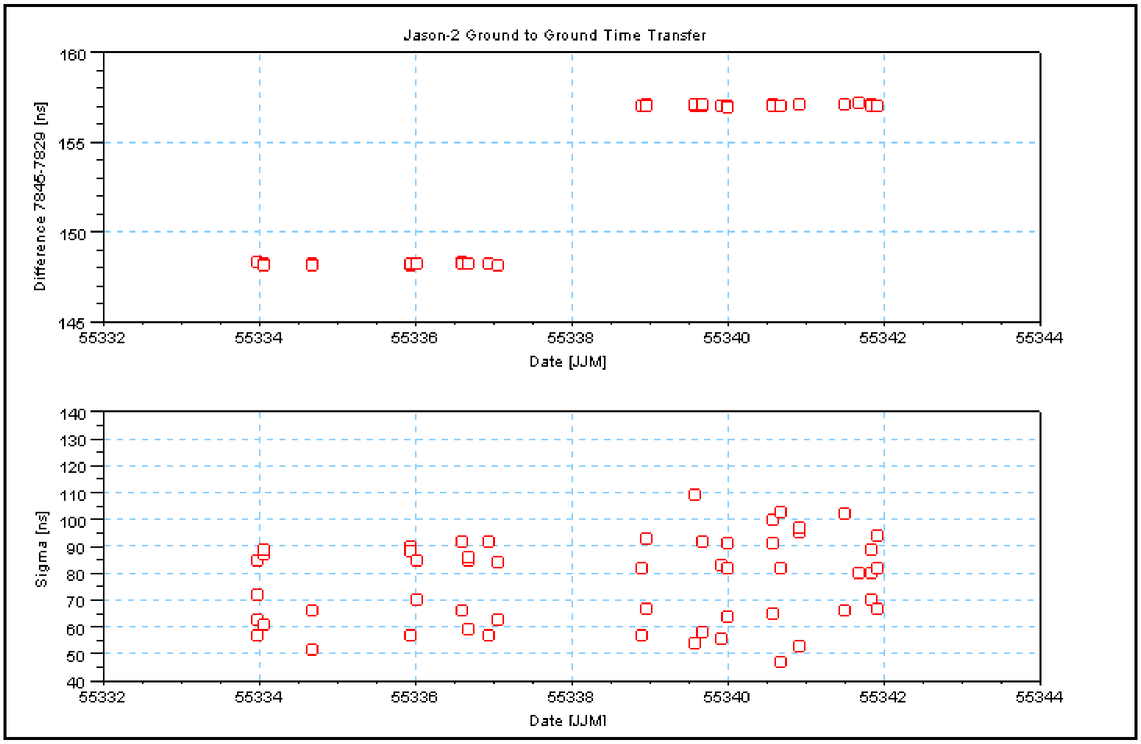

Figure 5. Ground-to-Ground time transfer between the two laser stations MeO (7845) and FTLRS (7829), May 2010.

SECOND T2L2 INTERNATIONAL CAMPAIGN

EXPERIMENTAL SETUP

After a first international campaign in 2009 that has mainly demonstrated the feasibility of such a campaign (with a transportable laser station in the center of Paris) **[5]**, a second campaign was decided on, involving eight laser stations in Europe and Japan (Figure 6). Participating stations were selected because of their particular configurations, use of high-performance ground clocks such as hydrogen-maser or cold-atom atomic clocks, and availability of a TWSTFT station (Table 2).

To complete the network, we installed the transportable laser station at the Observatoire de Paris and the SYRTE Mobile Atomic Fountain at Grasse, near the fixed laser station MeO. Thus, we expect to be able to perform a time and frequency transfer between the cold atomic fountains **[10]** with a frequency accuracy in the 10^{-16} range.

The campaign started at the beginning of June 2010 and stopped at the beginning of October 2010. FTLRS operations were stopped for 3 weeks at the end of August due to operational constraint. During this period, with four to six passes per day of Jason-2 above each laser station, a little bit more than 1150 "laser" passes have been successfully realized. That allows 650 common-view configurations between two stations (Table 3) and 88 passes between Paris and Grasse for the comparison of the two cold atomic fountains.

Figure 6. Second T2L2 international campaign: Stations network (because it has not be able to access to Jason-2, the Borowiec station in Poland did finally not take part into the campaign).

Table 2. Second T2L2 international campaign: Station network (because it has not be able to access to Jason-2, the Borowiec station in Poland did finally not take part into the campaign).

Site	Clock	Time Transfer
Caussols (FRA)	Fountain + H-Maser	GPS – TWSTFT Europe
Paris (FRA)	Fountain + H-Maser	GPS – TWSTFT Europe
Borowiec (POL)	H-Maser	GPS – TWSTFT Europe
Koganei (JPN)	Fountain	GPS – TWSTFT Asia
Simosato (JPN)	Cs/Rb	GPS
Zimmerwald (CHE)	Qx/GPS	GPS
Herstmonceux (GBR)	H-Maser	GPS
Matera (ITA)	Cs	GPS
Wettzell (DEU)	H-Maser	GPS

Table 3. Synthesis of the activity of the second T2L2 international campaign: 1.155 passes, 650 in common view. % of triplets represents the proportion of laser shots detected by the T2L2 instrument and identified by the CMS versus the number laser shots recorded by the ground station.

Site	Passes with triplets	% of triplets	**Passes with triplets in Common View**					
			Paris	Zimmerwald	Grasse	Matera	Wettzell	Simosato
Herstmonceux (GBR)	169	26	47	14	87	33	19	
Paris / FTLRS (FRA)	140	16		22	88	43	36	
Zimmerwald (CHE)	85	33			35	27	21	
Grasse (FRA)	350	22				77	58	
Matera (ITA)	190	90					38	
Wettzell (DEU)	167	72						
Koganei (JPN)	29	33						5
Simosato (JPN)	25	70						

Stability of the Ground-to-Space Time Transfer

Time stability lower than 10 ps for integration times of a few tens of seconds has already be demonstrated for T2L2 over some single passes **[6]**. The T2L2 international campaign and the capability, for the T2L2 Scientific Mission Center, to process all data in near real time give us the opportunity to have a systematic evaluation of this stability for each pass.

Figure 7 presents typical values of time stability achieved for some stations involved in the T2L2 campaign. One must keep in mind that, for integration times longer than a few tens of seconds, this stability is limited by the on-board clock (DORIS Ultra Stable Quartz Oscillator) time (in)stability, which is 5 ps at 30 s and 10 ps at 100 s. Figure 7 clearly shows the influence of the station setup, i.e. clock and event timer, on the performances of the link: For the best station, one can reach time stability lower than 10 ps for integration times from 10 s to 100 s.

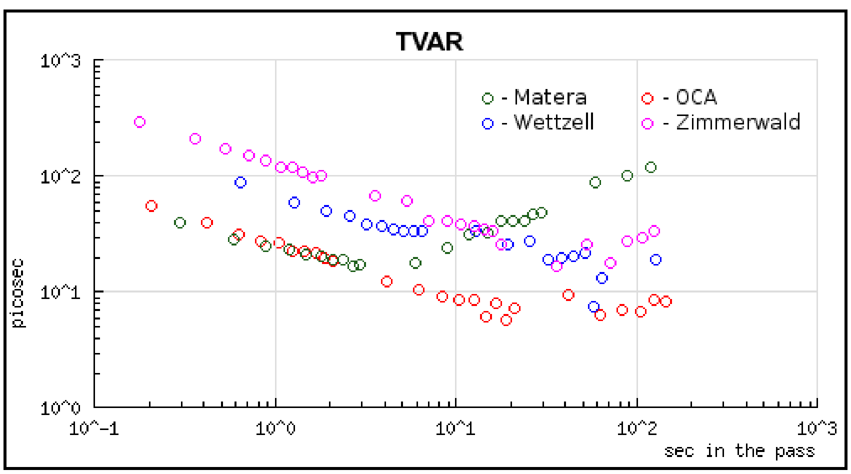

Figure 7. Ground-to-space time transfer stability (T-Var): Zimmerwald (02/09/2010 @ 00h36), Grasse (03/09/2010 @ 23h23), Matera (05-09-2010 @ 01h49), Wettzell (06/09/2010 @ 16h44).

FIRST COMPARISON BETWEEN T2L2 AND GPS ON OP-OCA LINK

The number and the relative regularity of passes in common view during this second campaign shall allow a direct comparison between T2L2, GPS, and TWSTFT. At this step of data processing, only a first comparison between GPS and T2L2 has been performed and is presented here.

T2L2 data are first processed by the T2L2 Scientific Mission Center to compute ground-to-space time transfer for each laser pulse detected by the instrument. Because data are clearly asynchronous, they are extrapolated in order to have ground-to-space time transfers at the same date for each station in the T2L2 reference frame. Two methods are used:

- By adjusting a fourth-order polynomial on all available data and then computing the ground-to-space time transfer for each round second in T2L2 time. Even if there is a hole in the data, the time transfer is calculated. We then compute the single differences between the two stations for each second between the beginning and the end of the common view.

- By adjusting a second-order polynomial on a sliding window of 30s. The ground-to-space time transfer is computed for each round second in T2L2 time only if there are data available in the [-15s ; +15s] window around the round second. We then compute the single differences between the two stations for each second where there are data for the two stations between the beginning and the end of the common view.

At the end, we compute a unique value for the whole pass by averaging the date and the value of each individual ground to ground time transfer. The space clock is modeled by a first-order polynomial (frequency offset and linear drift) in order to cancel the slope of the time transfer difference and eliminate the error that would have been introduced by the computation of the mean value of dates.

Figure 8 compares the results of the two methods for the whole campaign, from June to October. One of the significant differences between them is that, in the first method (unique fourth order polynomial), all points are calculated from the first date to the last date of the common view period of the pass, whereas in the second method (sliding second-order polynomial), differences are calculated only if there are enough points in the interval of 30 s to calculate a point for each station.

GPS data are acquired thanks to two GPS geodetic receivers, one Ashtech Z12-T in Paris and one Dicom GTR-50 in Grasse. Each receiver is linked to the same H-maser, as is also done for the laser stations. Time transfer between the two receivers is computed using a Carrier-Phase Time Transfer/Precise Point Positioning method with ambiguity resolution on zero-difference measurements developed by CNES **[9]**. Typical performances of the method are given in Figure 9, with frequency stability of a few 10^{-15} for integration times around 10^5 s.

One must keep in mind that the method use to resolve ambiguities is not fully accurate for time transfer: An uncertainty remains and the results could be shifted by an entire number of "narrow lane" wavelength $\lambda_c = \lambda_1\lambda_2/(\lambda_1 + \lambda_2)$, where λ_1 and λ_2 are the wavelengths of the two GPS carriers, i.e. 10.7 cm or 0.356758 ns. As long as the data set is continuous, the uncertainties are the same. Nevertheless, any gap in the data could lead to a change in this uncertainty from one data set to the next one.

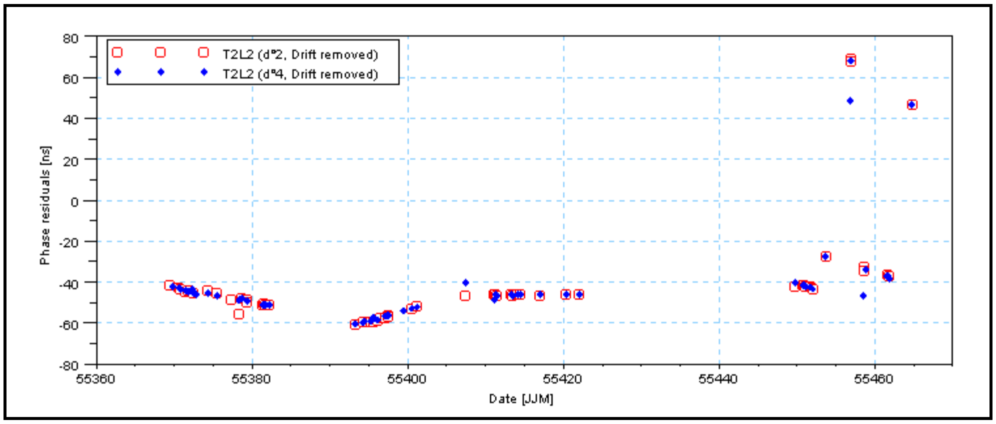

Figure 8. T2L2 ground-to-ground time transfer: Comparison of the two solutions, unique fourth-order polynomial on the whole pass, or sliding second-order polynomial on 30 s (same quadratic drift removed on the two data sets).

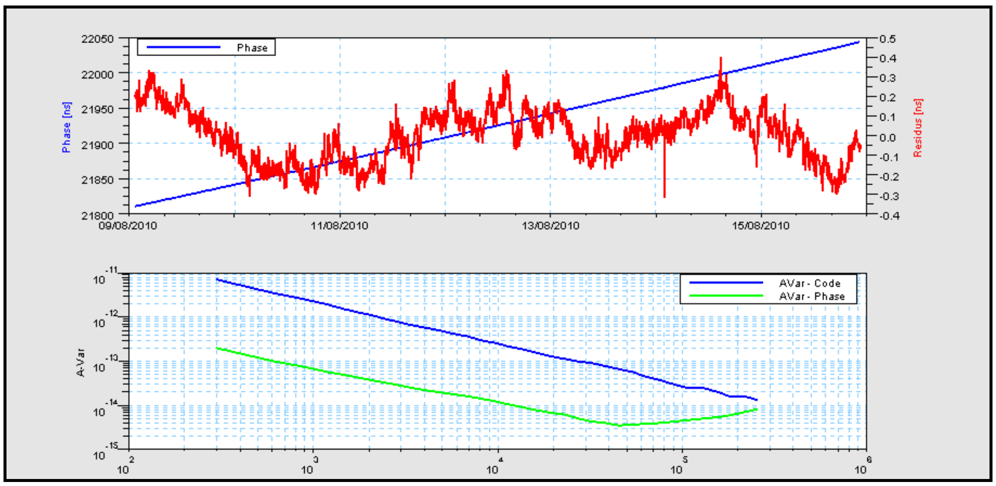

Figure 9. Typical performances of Carrier-Phase Time Transfer/Precise Point Positioning method with ambiguity resolution on zero-difference measurements (OP/Z12-T vs. OCA/GTR50 link, H-masers).

Among the 88 T2L2 common-view passes between Paris and Grasse, 56 have been retained for the comparison with GPS. Others have been rejected because of the low number of data or the standard deviation of the data in the pass. The result of the comparison is given in Figure 10. The direct comparison of data shows a nice coherency of the two T2L2 and GPS solutions (Figure 10, top). To go further, one can adjust and remove a quadratic drift. To do so, we adjusted a second-order polynomial among GPS data, and removed the same polynomial from both T2L2 and GPS data. Once again, the residuals show a good coherency of the T2L2 and GPS solutions (Figure 10, bottom), with an offset of 115 ns. This offset clearly comes from the "not yet performed" calibration of laser stations.

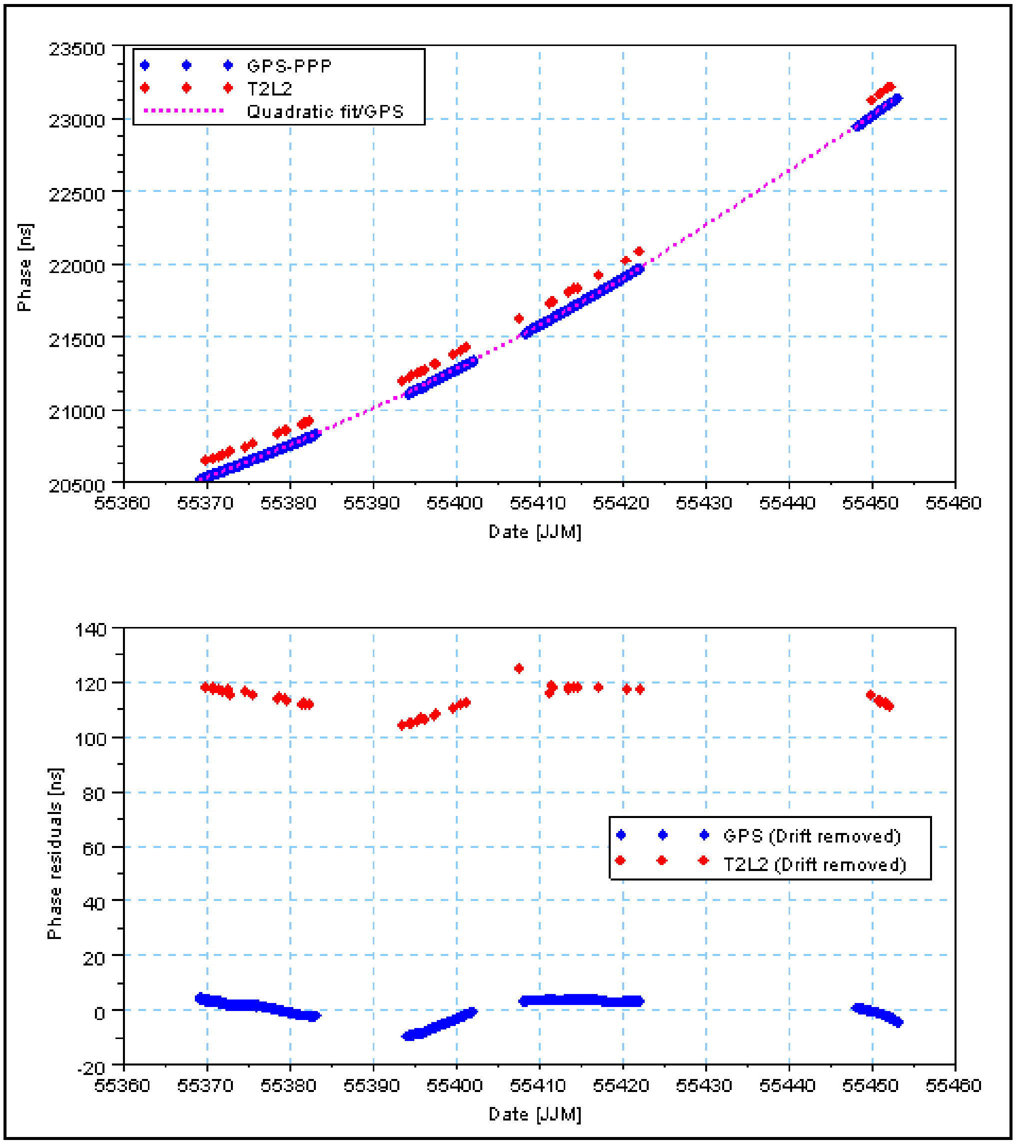

Figure 10. Ground-to-ground time transfer between Paris and Grasse: T2L2 and GPS solutions (top), T2L2 and GPS residuals (same quadratic drift removed on the two data sets, bottom).

Figure 11 (top) presents the differences between T2L2 time transfer and GPS solutions extrapolated at T2L2 dates. It shows two things:

- First, the rms noise for each period, i.e. corresponding to each GPS continuous data set, is between 0.3 and 0.5 ns
- Second, there is an offset between the mean values of each period, an offset that corresponds to an entire number of "narrow lane" wavelength λ_c.

We can use this offset to fix the “wide lane” ambiguity and reprocess GPS data: T2L2 and GPS data are then fully in aligned (Figure 11, bottom).Thus, the quality of T2L2 time transfer can be used to resolve the “wide lane” ambiguity in case of a discontinuous GPS data set.

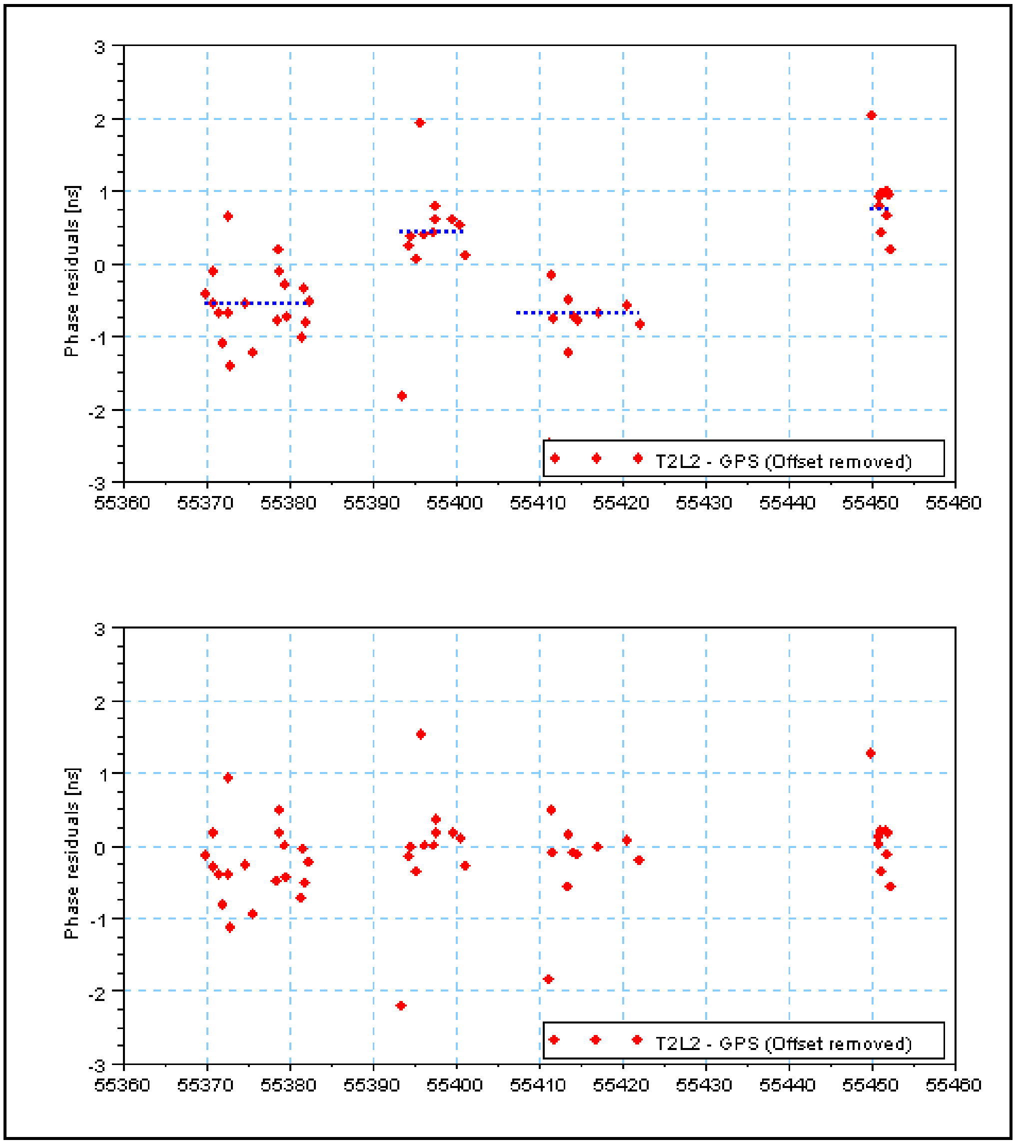

Figure 11. Difference between T2L2 and GPS ground-to-ground time transfer (115 ns offset removed) before (top) and after (bottom) resolution of the “wide lane” ambiguity thanks to T2L2 data.

CONCLUSION

Two T2L2 campaigns took place this last year. T2L2 data are now processed in near real time to calculate ground-to-space and, when in common-view configuration, ground-to-ground time transfer.

The results have allowed, first, confirmation of the short/mid-term time stability of the time transfer, lower than 10 ps for integration times from 10 s to 100 s and, second, validation of its accuracy at 45 ps in a common-clock configuration.

T2L2 Ground-to-ground time transfer has been compared with a GPS Carrier-Phase solution. The rms noise of the differences of the two solutions is in the [30 ps, 50 ps] range. With such a noise, T2L2 data can be used to fix the “wide lane” ambiguity of the GPC Carrier-Phase process.

Future exploitations of T2L2 data are already planned, which include, among other things, the estimation of the long-term stability of the time transfer, a comparison with TWSTFT and, hopefully, a frequency transfer between two cold atomic fountains with a frequency accuracy in the 10^{-16} range. Further, the configuration of the last T2L2 international campaign shall allow some tests of the anisotropy of the speed of light.

At the experimental level, and with the extension of the mission for at least 2 more years, future T2L2 activities include a calibration campaign for all the laser stations involved in the program and new campaigns with the transportable station in 2011 and 2012.

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