# Time Transfer by Laser Link - T2L2 : First Data

**E. Samain**[1]**, Ph. Guillemot**[2]**, P. Exertier**[1]**, D. Albanese**[1]**, P. Berio**[1]**, O. Laurain**[1]**, F. Para**[1]**,
J. Paris**[1]**, J.-M. Torre**[1]**, H. Viot**[1]**, P. Vrancken**[1]**, I. Petitbon**[2]**, S. Leon**[3]

[1]OCA – Observatoire de la Côte d'Azur, Caussol, France
[2]CNES –French Space Agency, Toulouse, France
[3]CNES –French Space Agency, Paris, France

etienne.samain@obs-azur.fr

## Abstract

*The T2L2 (Time Transfer by Laser Link) project, developed by CNES and OCA will permit the synchronization of remote ultra stable clocks and the determination of their performances over intercontinental distances. The principle is derived from laser telemetry technology with a dedicated space equipment deigned to record arrival time of laser pulses at the satellite. T2L2 was accepted in 2005 to be on board the Jason-2 altimetry satellite. It has been successfully launched from Vandenberg in 2008. T2L2 acquired the first laser pulses a few days after the launch.*
*First analysis permitted to validate some important characteristics of the instrument such as sensitivity, noise, dynamic, event timer precision and ground to space time stability. The instrumental model of the whole experiment that will permit to perform very precise time transfer at the pico-second level is currently under development.*

## 1. Introduction

T2L2 [1],[2] is a two way time transfer technique based on the timing of optical pulses emitted by a laser station and detected by a dedicated space instrument. T2L2 was accepted as a passenger instrument on the Altimetry Jason-2 satellite [3] in 2005.

Basically, T2L2 realizes a space to ground time transfer between the ground clock linked to the laser station and space clock of the satellite. The ground to ground time transfer between several remote clocks at ground is obtained through these individual space to ground time transfers. It can be obtained in a common view mode, when the distance between the laser stations is smaller than roughly 5000 km, or in a non-common view mode when the distance is larger.

The ground segment of the experiment is a laser station able to time both the start and the return time with a resolution at the ps level (Fig. 1). The laser stations track the satellite as soon as the satellite is in the right field of view during the whole duration of the pass.
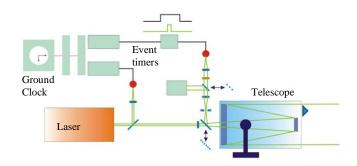
**Figure 1.** Laser station designed for T2L2

The space instrument is based on a photo detector and an event timer linked to the space clock. A laser ranging array (LRA) is also used to reflect the laser pulse toward the laser station. This LRA is provided by the JPL, basically for the orbit of the satellite through the laser ranging technique. The space clock is an ultra-stable oscillator (USO) coming from the Doris equipment.
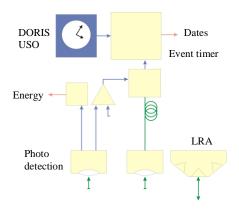


**Figure 2.** Synoptics of the T2L2 Space instrument

The mass of the T2L2 space equipment is 8 kg for the electronic module which is inside the satellite and 1.5 kg for the photo detection module located outside. Jason-2 is a French-American follow-on mission to Jason-1 and Topex/Poseidon. Conducted by NASA and CNES, its goal is to study the internal structure and dynamics of ocean currents. The satellite was placed in a 1,336 km orbit with 66° inclination by a Delta launcher. The time interval between two passes varies from 2 to 14 hours with a maximum duration of about 1000 s.

For a given laser pulse emitted by the laser station one get two dates at ground and one date at the satellite. From these 3 dates (which are called a triplet) we can extract the time delay between the ground clock and the space clock.

## 2. Exploitation

Since the launch, the exploitation phase started for at least 2 years and probably 5 years.
The objectives of the T2L2 experiment on Jason-2 include [4]:

- Validation of optical time transfer, including the validation of the experiment, its time stability and accuracy. It should further allow to demonstrate one-way laser ranging
- Scientific applications concerning time and frequency metrology allowing the calibration of radiofrequency time transfer (GPS and Two-Way), fundamental physics with the measurement of light speed anisotropy and alpha fine structure constant
- Characterization of the on-board Doris oscillator [5], especially above the South Atlantic Anomaly (SAA).

The T2L2 exploitation is driven by a T2L2 working group and implemented by an Instrumental Mission Center. The T2L2 working group is divided in 5 themes:
- Laser Station Network: communication between laser stations, schedule and priority, design of some dedicated instrumentation at ground
- Scientific Mission Center: data formats, definition of the  data reduction algorithms, data distribution
- Microwave comparison and Time scale: T2L2-TwoWay-GPS comparisons with the permanent network, realization of some dedicated experiments with some mobile equipments
- T2L2 validation:  collocation, common view, optimization of the instrumental model, Link budget

The Scientific Mission Center is responsible for developing the software for data reduction, for processing the ground and space data and for the dissemination of the products.

The Instrumental Mission Center objectives are threefold:
- Downloading data from the space segment, upload some remote controls to the instrument
- Processing a first level of data reduction
- Monitoring the  results and the space instrument

## 3. Laser ranging requirements

T2L2 relies on the Laser Ranging network. The degree of participation will depend on the hardware used, but every laser station can contribute. The following table gives the scientific objectives achievable as a function of the equipment level for a given laser station.

| Objectives | Interval meter | Event timer | Rubidium slaved on GPS | Cesium | H-Maser or atomic fountain | GPS or Two way time transfer | Laser pulse width < 100 ps | Laser pulse width > 100 ps | Start epoch Calibration |
|---|---|---|---|---|---|---|---|---|---|
| Time Transfer validation | o | x | ✓ | ✓ | ✓ | - | ✓ | ~ | ✓ |
| Time and frequency metrology | o | x | o | ✓ | ✓ | ✓ | ✓ | ~ | x |
| One-Way laser ranging | o | x | ~ | v | ✓ | - | ✓ | ~ | x |
| DORIS support | o | x | o | ~ | ✓ | - | ✓ | ~ | - |
| Link budget analysis | ~ | x | ✓ | ✓ |  | - | ✓ | ✓ | - |
| Fundamental physics | o | x | o | o | ✓ | - | ✓ | o | ✓ |

x : required ; ✓ : ideal ; ~ : sufficient ; o : unsuitable ; - unnecessary

It is absolutely necessary to get the laser station data in the full-rate form with a time resolution in the pico-second range. The stations should measure the start events with an event timer connected to the clock that has to be synchronized. The new CRD format (full-rate version) is the nominal and official format for T2L2.

Some scientific objectives require the absolute start time of the transmitted laser pulses with accuracy in the 50 ps range. For that purpose, the T2L2 team will propose some calibration campaigns of the laser stations concerned. It will permit to measure (with a calibration station developed by OCA) the time delay between the laser pulses at the crossing axes of the telescope mount and the Pulse Per Second (PPS) signal of the reference clock (Fig. 3).
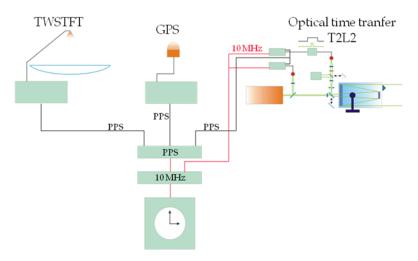


**Figure 3.** Delay determination between the optical pulse at the cross axe of the telescope and the electrical reference coming from the Time and frequency lab

T2L2 can detect some laser events even if the laser station does not obtain echoes. In order to exploit these events it is essential to record the entire laser start epochs even if there is no echo. T2L2 includes a self-asynchronous pre-triggered system so that laser stations can range normally without any synchronization constrain. Arrival times are recorded onboard and then downloaded to the Instrument Mission Center (CMI) every 2 hours. The laser events are identified after a post processing conducted by the Scientific Mission Center that allows reconstructing triplets (start time - return time and arrival time onboard), for every laser station. The T2L2 detection module includes a level compensation system to correct for varying amplitude during the pass over the station. It takes into account the distance evolution and the variation of the atmospheric transmission which both depend on the elevation angle. In order to obtain an energy level constant onboard, the laser energy of the station should remain constant during the whole pass. The return level should be adjusted at ground with some neutral density filter in front of the station return detector. Laser stations can operate in both a single pulse mode and a pulse train mode. In the pulse train mode, T2L2 will only detect the first pulse so that the other pulses will be ignored. Laser stations can work in a KHz mode (T2L2 dead time is roughly 200 μs) but the energy per pulse is usually low in that kHz regime. It is necessary to minimize the divergence of the laser beacon in order to reach the minimum threshold.

The following list are the important laser station characteristics in order to be compliant with the T2L2 project:

- Wavelength : 532.1 +/- .5 nm
- Event timer connected to the clock
- CRD Full Rate data : Upload to EDC
- No synchronization required
- Laser pulse Energy
- Min: 1 mJ sq = 10 µrad
- Max: 1 J sq = 5 µrad
- Pulse width 10 ps up to 500 ps (FWHM)
- Mono pulse or semi train
- Microwave link comparison: Time tag the start pulses with an accuracy of 50 ps (OCA calibration campaign)

## 4.  First results

Among the whole laser ranging community, 16 stations provide the full rate data needed for the triplets extraction (start, return and arrival onboard). 8 of them use the right data format (CRD) that permits to extract the start epoch of the laser pulses at the ps level, and the others with a data format that only permits to get the epochs with a resolution of 100 ns.

Up to now, 5 to 15 passes coming from these 16 laser stations are extracted every day.
Figure 4 gives an overview of the laser pulse energy received and measured by T2L2 onboard Jason-2.
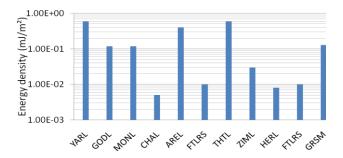


**Figure 4**. Energy received in the plane of the satellite of a few laser stations

A very preliminary link budget analysis has demonstrated a good agreement between the energy emitted by the stations and the energy received.

## 5.  Ground space time transfer

### 5.1 Triplets extractions
The events recorded by the T2L2 space instrument don't contain any information of the source: the events of all the laser stations are blended together. The first step of the treatment consists in recognizing the laser events recorded by T2L2 with those emitted by the stations. The absolute frequency offset and the delay between space and ground are known with an accuracy that permits to directly recognize the events by their dates.

## 5.2 Instrumental corrections

The instrumentals corrections TCorr concern both the space and the ground segments.

At ground, the accuracy is obtained by an internal calibration. During the pass on the satellite (or just before or just after) some events are also acquired on a calibration target located at a known position. The final propagation delay is the difference between the data directly obtained on the satellite and those obtained on reference target.

At the satellite several considerations have to be taken into account [6]:
- Geometrical delay between the reference point of the T2L2 detection module and the reference point of the LRA. This is obtained with the attitude information given by the stellar sensors of Jason-2 and the knowledge of the geometry of the space optics.
- Time walk compensation of the photo detection module which is sensitive to the photon number received. This is done through the information given by the linear photo detector of the instrument that give, for each event detected, an energy received.
- Angular compensation of the photo detection. This is also computed from the attitude information.
- Event timer calibration based on some internal calibrations automatically generated.

## 5.3 Time of flight determination

The determination of the time of flight $T_{Flight}$ between the ground and the space segment is of course fundamental for the time transfer computation. It permits to directly compare the start time $T_{Start}$ at the station and the arrival time at the satellite of every laser events. This time of flight is based on the difference between the start time and the return time in the frame of the ground station divided by 2 and corrected by the distance between the LRA and the photo detection module $T_{Proj}$. At this stage the time of flight can be directly used echo by echo. If the precision of the measurements is optimal, this process is the best one: the uncertainty of the satellite position and the uncertainty introduced by the atmosphere are removed. It is also possible to compute a synthetic time of flight obtained over an integration duration of few tens of seconds. This method is pertinent in two cases:
- The return time at the laser station is more noisy than the noise introduce by the atmosphere [7]: this integration permits to decrease the noise by roughly $1/\sqrt{N}$, where N is the number of return integrated.
- The return photo-detector of the station is not "time-walk compensated": mean photon number is set very low (typically 0.1). In this case, a lot of detections onboard the satellite don't have a corresponding detection at ground and this synthetic time of flight permits to reconstruct a triplet with only one start time and one arrival time.

This synthetic time flight can be fitted on the time of flight measurement from a satellite orbit solution with a low order polynomial.

## 5.4 Ground to Space time transfer

The ground to space time transfer $T_{GS}$ represents the time offset between the space and ground clocks. It is deduced from the difference between start time at ground and the arrival time at the satellite, which is compared with the time of flight $T_{Flight}$ corrected by the Sagnac delay TSagnac .
We have:

$$T_{GS} = T_{Start} + T_{Flight} - T_{Sagnac} + T_{proj} + T_{corr}$$

Figure 5 is an illustrations of such a ground to space time transfer between the French mobile FTLRS station and the T2L2 space instrumentation. From the full rate data one can then compute a short term interpolation (typically 30 s) with a low order polynomial fit. This fit allows us to generate some interpolated data at some precise instant in the satellite time scale.

This is crucial in order to be able to compare ground to space time transfer coming from different laser stations at ground.
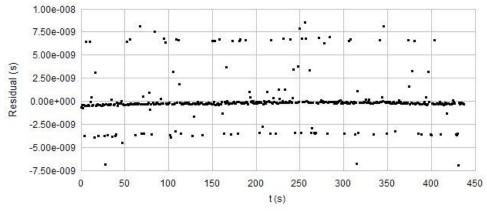


**Figure 5.** Ground to Space time transfer between the T2L2 DORIS oscillator and OCA's FTLRS.

## 6. Performances

Figure 6 represents the time stability measured by T2L2 of a pass acquired by the Wettzell station. It represents the time stability of the Wettzell's Hydrogen Maser compared to the T2L2's DORIS quartz oscillator. One obtain 40 ps @ 1 s and 7 ps @ 30 ps. For time integration greater than 30 s this measurement is limited by the DORIS time stability which is 5 ps @ 30 s and 10 ps @ 100 s.
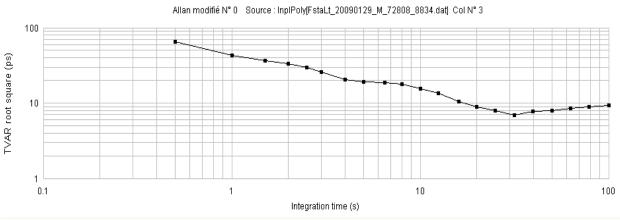


**Figure 6.** Time stability measured by T2L2 of the Wetzell's H-Maser compared to the T2L2's DORIS oscillator

## 7. Conclusions

T2L2 relies on the whole Laser Ranging network. Every laser station can contribute. Up to now 8 laser stations in the world have the right configuration for T2L2. Several other laser stations will participate but some data format and hardware upgrades are still needed.

The T2L2 time stability measured between space and ground is very promising: it has been possible to measured the phase between an Hydrogen Maser at ground and the T2L2's

DORIS oscillator with a stability of only 7 ps. This results represents the best time stability never obtained between a space clock and a ground clock.

A lot of works are still required to understand the physic and to improve the instrumental model of the hardware but the global performances seem to be in accordance with the specifications of the project.

A calibration campaign over several laser stations will permit to realize some absolute time transfer at ground with an accuracy better than 100 ps.

## Acknowledgment

## References

[1] P. Fridelance, E. Samain, C. Veillet, Experimental Astronomy, 191 (1996)

[2] P. Fridelance, C. Veillet, Metrologia, 32, 27 (1995)

[3] E. Samain et al, International Journal of Modern Physics D, Vol. 17, No. 7 1043–1054 (2008)

[4] Ph. Guillemot et al., Proceedings of the 20th EFTF (2006)

[5] Ph. Guillemot et al., Proceedings of the 23th EFTF / 63th IEEE-IFCS Joint Meeting (2009)

[6] P. Vrancken, Thèse de doctorat de Science de l'Univers de l'Université Nice – Sophia Antipolis (2008)

[7] Bender P.L., , no. 36 (edited by J.C. de Munck and T.A. Th. Spoelstra), Netherlands Geodetic Commission, 1992, 117-125.