Time Transfer by Laser Link T2L2
First Results

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Abstract— **The optical time transfer project T2L2 has been successfully launched from California in 2008 on the Jason-2 satellite. T2L2 permits the synchronization at the pico-second level of remote ultra stable clocks and the determination of their performances over intercontinental distances. The principle is derived from laser telemetry technology with a space equipment designed to record arrival times of laser pulses at the satellite. Since the launch, several thousands of passes have been acquired by the laser ranging community.**

A first analysis permitted to validate the characteristics of the instrument such as sensitivity, noise, dynamic, and time stability.

After reminding the principle, the exploitation plan, and the objectives, the paper will present the first stability obtained in the picoseconds level between an hydrogen maser at ground and an ultra stable oscillator in space.

I. Principle

T2L2 [1],[2] is a very high resolution two way time transfer technique based on the timing of optical pulses emitted by a laser station and detected by a dedicated space instrument. After several proposals on the Mir Space Station, ISS, GIOVE, and Myriade, T2L2 was finally accepted as a passenger instrument on the Altimetry Jason-2 satellite [3].

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 laser station (Fig. 1) includes a telescope, a pulsed laser, some photo detection devices and two event timers connected to the ground clock, one to time tag the start event, the other for the return. The energy by pulse is between 400 µJ to 1 J and the pulse width is in the range of 20 ps up to 200 ps. The laser rate is between 5 Hz to 2 kHz. The laser stations range on the satellite as soon as the satellite is in the right field of view and generally during all the duration of the pass.

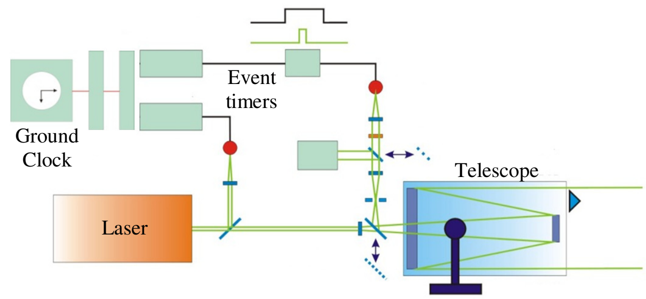

Figure 1: Laser station designed for T2L2

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.

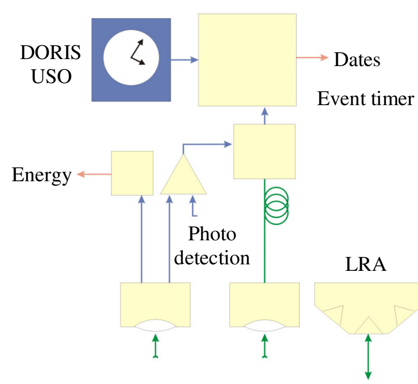

Figure 2: Synoptics of the T2L2 Space instrument

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 (Fig. 3) 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.

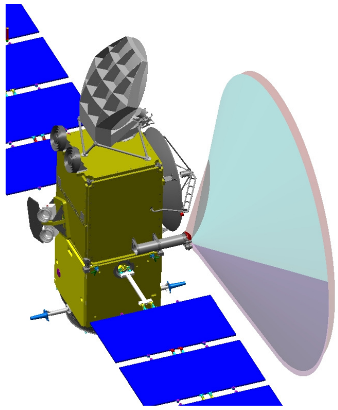

Figure 3: Jason-2. The cone at the extremity of the boom represents the field of view of both the LRA and the T2L2 optical module.

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.

II. Exploitation and Objectives

The BCD phase of the T2L2 space instrument started by the end of 2005. After some qualification campaigns, the instrument was integrated onboard Jason-2 in mid 2007. Jason-2 was launched from Vandenberg in California in June 2008. 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

III. First Results

T2L2 relies on the laser ranging network which includes 40 international laser stations. Among them, 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 (Fig 4), and the others with a data format that only permits to get the epochs with a resolution of 100 ns.

Country	Clock	Time Transfer
France MeO	HM + Cesium	TWSTFT-GPS
France Mob	_	_
Germany	HM + Cesium	GPS
England	Rubidium	GPS
Italy	HM	GPS
Switzerland	Osc GPS	GPS
Australia	Cesium	GPS
China	Rubidium HM	GPS-LTT

Figure 4: laser stations with the right CRD data format that permit to extract the event epoch with the ps resolution (HM : Hydrogen Maser)

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

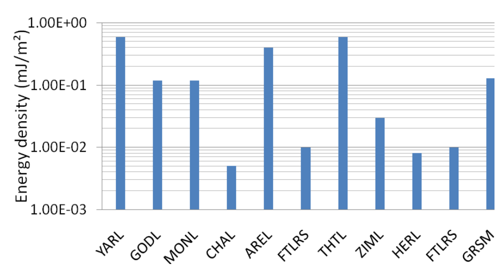

Figure 5: Energy received of a few laser stations

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

IV. Ground Space Time Transfer

Several steps are necessary to proceed the data.

A. 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.

B. Instrumental corrections

The instrumentals corrections T_{Corr} 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.

C. 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" (the propagation delay inside the detector is sensitive to the photon number received) and to avoid the artificial noise that would be introduced by the fluctuation of the photon number, a neutral density is introduce in the optical path of the detection to obtain a very low mean photon number (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. Figure 6 illustrate such a fit over a pass obtain with the Wettzell station (Germany) with a 3 order polynomial.

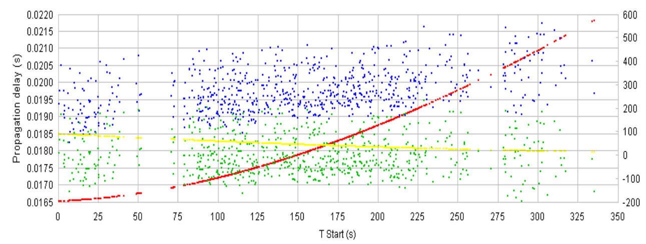

Figure 6: The red curve represents the direct time of flight between the station and the satellite. The blue dots are the difference between the global orbit of the satellite and the measurements. The green dots is the polynomial fit.

D. 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 T_{Sagnac} .

We have:

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

Figure 7 is an illustrations of such a ground to space time transfer. 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 8 illustrates the energy received by T2L2 during the same Wettzell's track. It can be seen that the energy measured is quite constant over the pass.

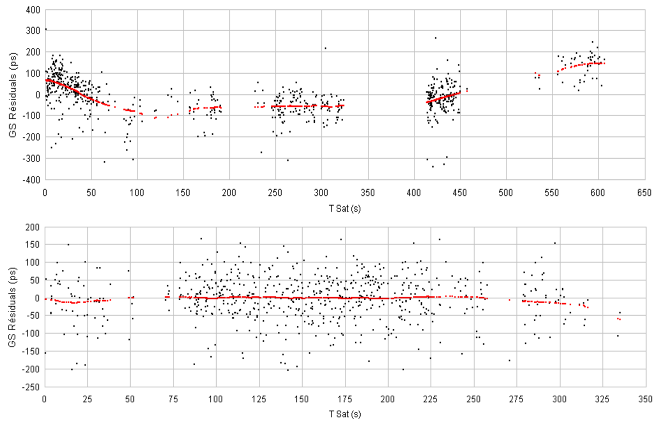

Figure 7: Ground to Space time transfer between the T2L2 DORIS oscillator and OCA's Cesium Clock HP 50171A (above) and Wettzell's H-Maser (below). For both plots, a one order polynomial has been removed to take into account the frequency offset between DORIS and the ground clocks. The black dots are the full rate data. The red curve is a short term interpolation (30 s) made from a 3 order polynomial.

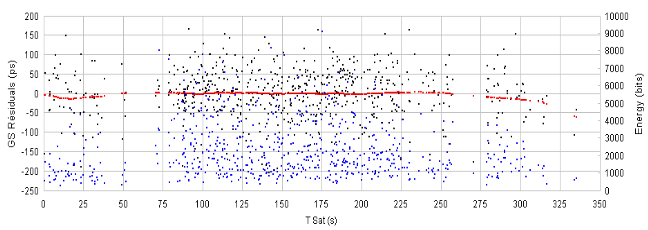

Figure 8: Blue dot: Energy measured for each event.

V. Performances

The plot of the ground to space time transfer residuals as a function of the energy received (Fig. 9 above) by the T2L2 space instrument shows that the trend is flat. This mean that the time-walk correction applied in the model is well fitted with the real instrument. It can also be seen, that the precision depends on the energy received (Fig. 9 below). This a known phenomena due to statistical multiplication of electron-holes inside the photo-detector. Up to know, the better precision observed in the high energy level is 30 ps rms.

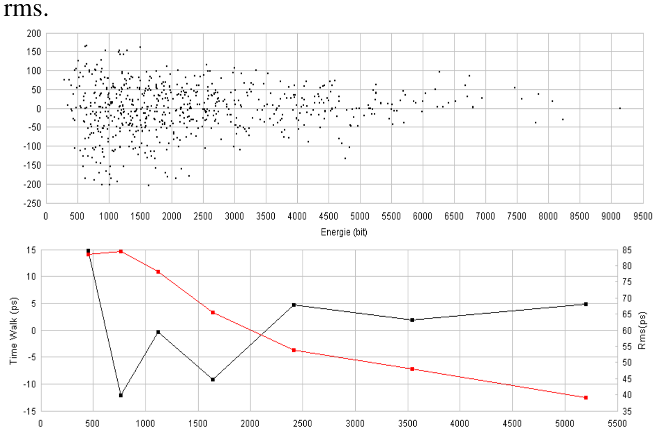

Figure 9: Time walk of the Ground to Space time transfer (ps) as a function of the energy measured by T2L2 (above). Higher is the energy better is the precision. It can be seen that the trend is fairly flat. The graph below shows the Time walk mean value (black) and the precision (red) as a function of the energy.

The time stability computed by the time variance of the residuals of the figure 7 is shown in figure 10. This represents the time stability measured by T2L2 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.

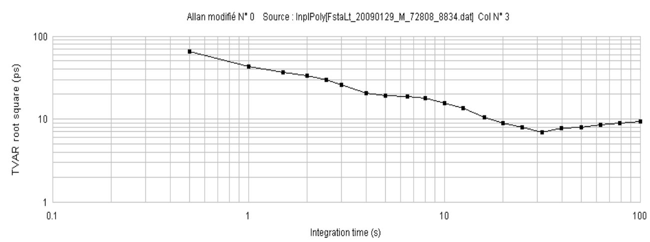

Figure 10: Time stability measured by T2L2 of the Wetzell's H-Maser compared to the T2L2's DORIS oscillator

VI. Conclusion

Up to now 8 laser stations in the world have the right configuration for T2L2. Several other laser stations could participate but some data format 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 precision 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 be envisioned soon for time scale and time transfer comparison. This should permits to realize some absolute time transfer at ground with an accuracy better than 100 ps.

Acknowledgment

The authors would like to thanks all the laser ranging stations that have participate to the project. Many of them have adapted their hardware, upgraded their data format and spent a lot of time to understand the T2L2 requirements.

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