TIME TRANSFER BY LASER LINK − T2L2: AN OPPORTUNITY TO CALIBRATE RF LINKS

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Abstract

The T2L2 instrument, The "Time Transfer by Laser Link" experiment T2L2 [1], under development at OCA (Observatoire de la Côte d'Azur) and CNES (Centre National d'Etudes Spatiales), France, has been successfully launched with the Jason-2 space vehicle on 20 June 2008 and switched on 5 days later. Besides the validation of the laser link time transfer scheme, T2L2 on Jason 2 has a whole panoply of science goals, including a possible contribution to the construction of international timescales such as TAI through the calibration of existing systems such as GNSS and TWSTFT, with an improvement of at least one order of magnitude as compared to the best calibrations performed so far (about 1 ns exactitude). It will further permit performing fundamental physics tests such as the measurement of a possible drift in the fine structure constant by comparing clocks of various atomic species over the Jason 2 mission lifetime. T2L2 will also permit precise characterization of the DORIS Ultra Stable Oscillator aboard Jason 2 and demonstrate for the first time in orbit one-way laser ranging.

After a short reminder of principles and of foreseen and measured performances of the T2L2 experiment, we present the first preliminary in-orbit results, including space-to-ground and ground-to-ground time transfer. We then conclude with an overview of the future exploitation campaigns, such as the comparison of different Cs fountains of the Observatoire de Paris, including the mobile fountain FOM and the French transportable laser station.

I. 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 higher modulation bandwidth, insensitivity to ionosphere, and mono-carrier scheme. After its early predecessor, LASSO, the T2L2 (Time Transfer by Laser Link) instrument **[1]**, 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).

The Jason-2 satellite was successfully launched on 20 June 2008 from Vandenberg Air Force Base in California. After the first health tests on satellite level, the T2L2 instrument was turned on for the first time on June 25. The first recovered telemetry data showed satisfying data, corresponding to expectations. The first measured "scientific" data, the cw background level (sun albedo) has also been identified to be as expected. The timing mode was first activated on June 30. The first identified laser pulse time tags corresponded to the ones emitted from the Yarragadee (Australia) SLR station (Figure 9). The measured energy showed a very satisfying link budget. First data triplets $\{t_S, t_B, t_R\}$ were identified on a pass of 2 July 2008 with six laser stations.

II. T2L2 PRINCIPLE

The T2L2 payload, launched in June 2008 together with the Jason-2 space vehicle dedicated to the observation of the oceans, consists in the T2L2 instrument itself, the ultra-stable oscillator of the DORIS receiver as the reference clock and a laser retro-reflector (LRA - Laser Ranging Array) to reflect the light pulses.

T2L2 allows the synchronization of remote clocks on Earth and the monitoring of satellite clocks. The experiment is based on the propagation of light pulses between the clocks to be synchronized. The light pulses carry the temporal information from one clock to another.

The ground and satellite clocks (the ultra-stable oscillator USO of DORIS in the case of Jason-2) to be synchronized are linked to a laser station and to the T2L2 space equipment, respectively. The T2L2 payload is constituted of a photo-detection device, a time-tagging unit, and a retro-reflector. The laser station emits asynchronous, short light pulses (~ 20 ps FWHM) towards the satellite. Retro-reflecting corner-cubes return a fraction of the received photons back to the station. The station records the start (t_S) and return (t_R) time of each light pulse. The T2L2 payload records the arrival time (t_B) in the temporal reference frame of the onboard oscillator. These data are downloaded to the ground via a regular microwave communication link. For a given light pulse emitted from station A, the synchronization χA between the ground clock A and the satellite clock is then derived from :

$$\chi_A = \frac{t_S + t_R}{2} - t_B + \tau_{\text{Relativity}} + \tau_{\text{Atmosphere}} + \tau_{Geom}$$

Figure 1 shows the synoptic of the whole T2L2 space instrument. The photo-detection unit is composed of two avalanche photo-detectors. One is working in a special "Geiger" mode for precise chronometry; the other one is in linear gain mode in order to trigger the system and to measure the received optical energy **[4-6]**. The event timer is a dedicated design, built with a programmable logic array at 100 MHz for rough timing and a vernier for precise measurement with a resolution of 1 ps **[7]**.

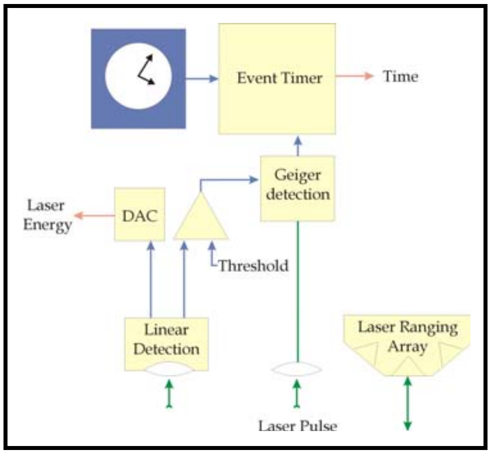

Figure 1. Synoptic of the whole T2L2 space instrument. The linear photo-detection is able to pre-trigger the Geiger module with an advance of a few ns. This delay is generated by an optical delay line connected to the Geiger detection.

II. T2L2 FLIGHT MODEL

The T2L2 instrument is divided in two parts:

- On the one hand, the electronics subsystem (SSE), a box of 8 kg with a footprint of 270 mm × 280 mm and a height of 150 mm with a total power consumption of about 42 W, is mounted inside the payload module, on the X+ wall

- And on the other hand, two optical units for linear and nonlinear detection are mounted on an interface plate with an active thermal control and fixed on the LRA boom. Whereas the linear detector is housed inside the linear unit, the nonlinear detector is housed in the electronic unit and so that the nonlinear detection unit is linked to the electronic subsystem, thanks to an optic fiber.

The performances of the T2L2 Flight model have been determined during two main test campaigns, first before the delivery of the instrument, then during its integration on the Jason-2 space vehicle. The goals of these campaigns were first to determine the true performance of the instrument and second to establish calibration tables in order to compensate raw data from all the "imperfections" of the instrument. The main concerns are the behavior of the event timer, i.e. the characterization of its internal reference signals (internal calibrations are used to analyze and compensate the fluctuations of the reference signals; Figure 3), and the dependency of the nonlinear internal propagation time on the energy of the laser pulses (Figure 4).

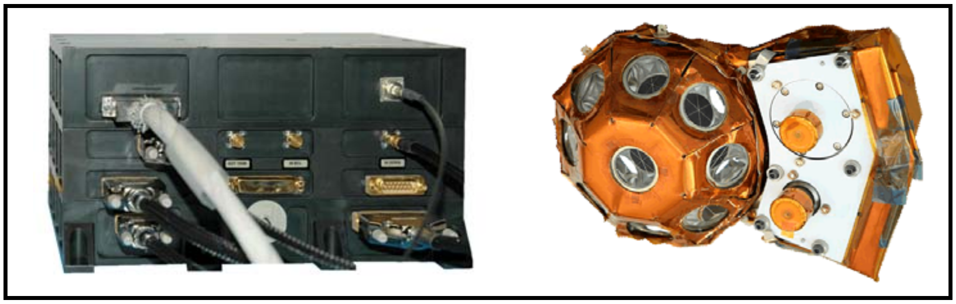

Figure 2. T2L2 flight model: the electronic unit (left) and optical units together with the LRA (right).

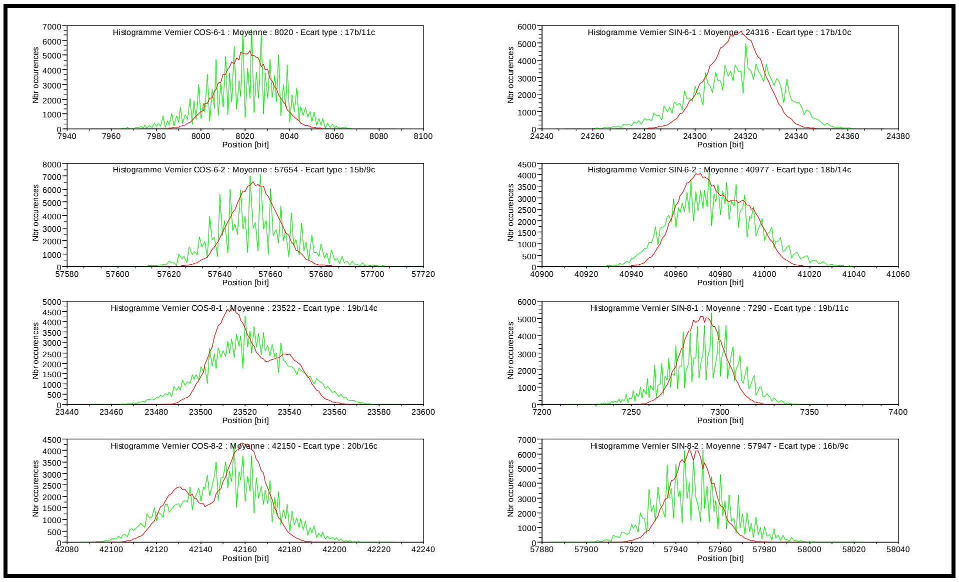

Figure 3. Internal calibrations of the reference signal (evolution over one week, in orbit data): Signals are spread out by the thermal variations (Green - not compensated, Red – compensated). The Full Width Half Maximum is about 1 to 1.5 ps (the splitting of some peaks is due to some thermal and internal signal synchronization concerns).

As a conclusion, these test campaigns allows one to confirm the performance of the instrument over a wide range of operating conditions (single-photon or multi-photon mode, various angle of incidence of the light, different temperatures, vacuum or atmospheric pressure, …). And results are very promising, with a precision of the nonlinear detection lower than 5 ps in multi-photon mode (and even if it is greater than expected, 35 ps measured for 20 ps specified, in single-photon; Figure 5) and a stability which is nearly to fully fulfilling the requirement (Eq. 1) in the single-photon/worst-case mode (Figure 6):

$$\text{Requirement: } \sigma_x^2(\tau) \le K_1^2 \times \tau^{-1} + K_2^2 \times \tau^{+1} \text{ with } K_1 = 12.6\, ps\sqrt{s} \text{ and } K_2 = 12.6\, fs/\sqrt{s} \qquad \text{(Eq.1)}$$

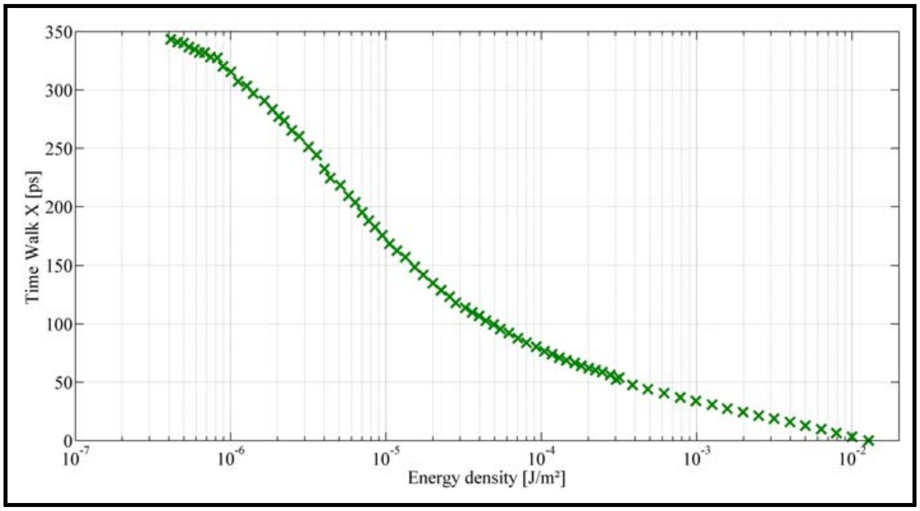

Figure 4. Nonlinear detector internal propagation time (time walk) versus energy of laser pulses.

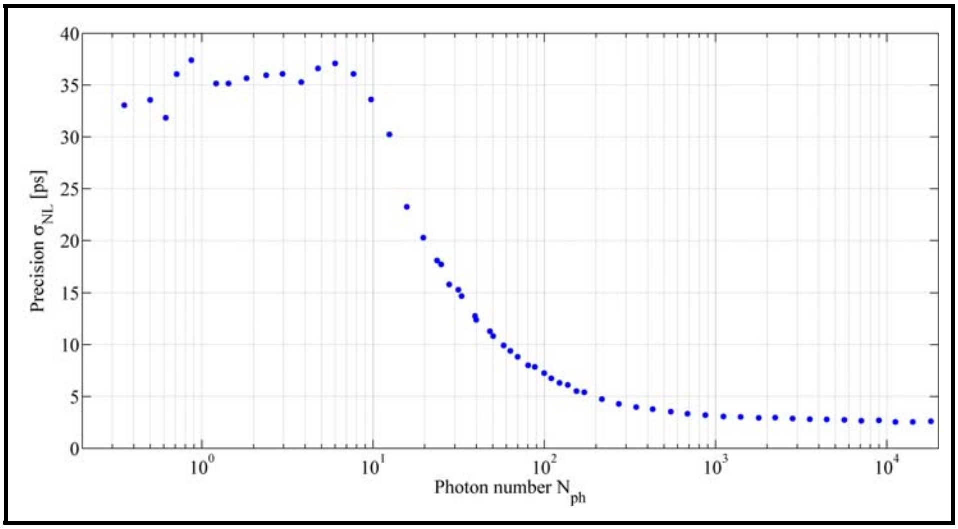

Figure 5. Precision of the nonlinear detection versus energy of laser pulses: In single-photon mode, the precision (35 ps) is greater than expected, maybe because of a misalignment between the light beam and the detector.

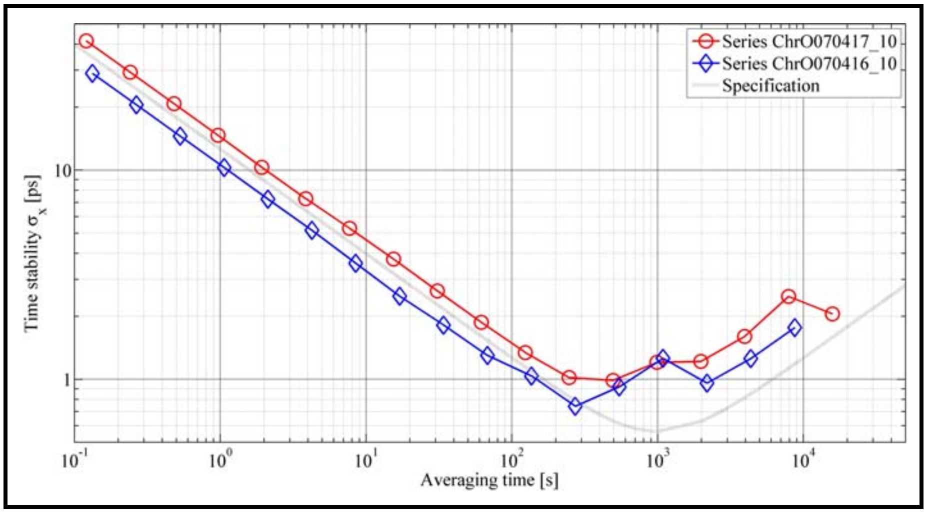

Figure 6. Stability (time variance) of the whole detection/event timer chain in single-photon mode.

III. TOWARDS THE COMPARISON OF T2L2 WITH GPS AND TWO-WAY

These ground measurements allow us to update our preliminary error budget for both ground-to-space and ground-to-ground time transfer **[10]**.

Figure 7 gives some predictions for two such time transfers, between MéO (fixed SLR Station, Observatoire de la Côte d'Azur) and FTLRS (French Transportable Laser Station, placed at SYRTE/Observatoire de Paris) and between MéO and WLRS (Wetzell, Germany) **[12]**. Parts (a) and (c) give the expected time stability over one common pass (with integration times of 500 and 700 s, respectively). Parts (b) and (d) give the averaging performed over the six to seven passes per day and then further averaged over up to 10 days. One has to keep in mind that the averaging times used, τ' (abscissa), reflects the actual elapsed time and not the acquisition time. Please note that the curves (b) and (d) may only indicate a lower level of the time stability, since pure white noise behavior was assumed; there may appear other long-term nonrandom processes that inhibit this assumption.

Figure 7 further shows the time stability of some frequency standards like some cesium fountains of the Observatoire de Paris (OP/SYRTE) and a commercial hydrogen maser. The graphic indicates that T2L2 shall permit comparison of high-performance frequency standards for integration times of some hundreds to thousands of seconds (over some passes).

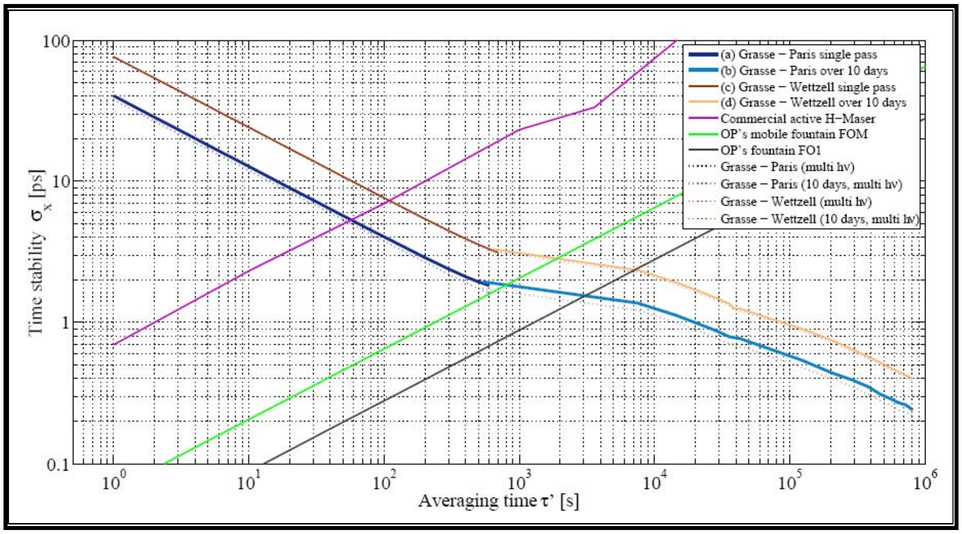

Figure 7. Time stability of two ground to ground time transfers, including averaging over multiple passes **[12]**.

We may finally proceed to the calculation of the whole resulting uncertainty budget: The combined uncertainty u_C is calculated with the quadratic sum of the A-type and the B-type contributors. The A-type contributors are the standard deviations from the mean, that is to say the rms of the single measurement (precision), divided by the square root of the number of measurements.

Table 1 summarizes all contributors for a ground-to-space time transfer. The uncertainty of a ground-to-space time transfer is about 30 ps for all types of laser stations and common-view configuration.

For the determination of a ground (station clock A) to ground (station clock B) time transfer, we calculate the quadratic sum of the combined uncertainties $u_{C,AS}$ and $u_{C,BS}$. One finds that the uncertainty in the T2L2 common-view time transfer is expected to be about 43 ps for all types of laser stations. One can note that the driving factor of the accuracy budget is the calibration and the local reattachment to UTC, and not the instrumentation.

Thus, with an expected improvement of at least one order of magnitude as compared to existing systems, T2L2 shall allow the calibration of various existing radiofrequency time and frequency transfer systems like GPS or TWSTFT, and comparisons of cold atomic clocks at a level never reached before. Continuous comparison of T2L2 and Two-Way shall be possible by using a network of ground stations equipped with both SLR and Two-Way and spread out all around the world. Moreover, the availability of both transportable SLR stations (FTLRS – France, TROS – China) and Two-Way stations (TUG – Austria, TimeTech – Germany) shall allow extension of the network with the possibility of performing some specific experimentations one some major TAI links. For intercontinental comparison, when common views are not possible, the use of a SLR relay station could also be envisaged (SLR relay station is mandatory if we want to reduce the contribution of the DORIS USO in the case of a non-common-view time transfer).

Table 1. Residuals of the time transfer computed on 1 July for the FTLRS (raw data in black, 2nd-order polynomial in red, residuals in blue) **[12]**.

System	Contributor	Type	u_C [ps]	Comment
T2L2	Timer	A	≈0	
		B	≈0	
	Photo-detection	A	1	
		B	2.7	
Mission	DORIS	A/B	≈0	Common view
	Geometry	A	≈0	Distance between LRA and Detectors vs. attitude restitution
		B	3	
Other	Relativity	A/B	≈0	
	Atmosphere	A	0.6	
		B	≈0	
SLR Station	Start Detection	A	0.1	
	Return	A	0.9	MéO station (FLTRS : 1.7 ps)
	Ground timer	A	0.2	× 2
	Calibration	B	15	MéO station (FLTRS : 20 ps)
	T/F vs SLR Cal.	B	25	SLR Station reattachment to local UTC
Ground to Space Transfer :			**30**	
Ground to Ground Transfer :			**43**	Common view

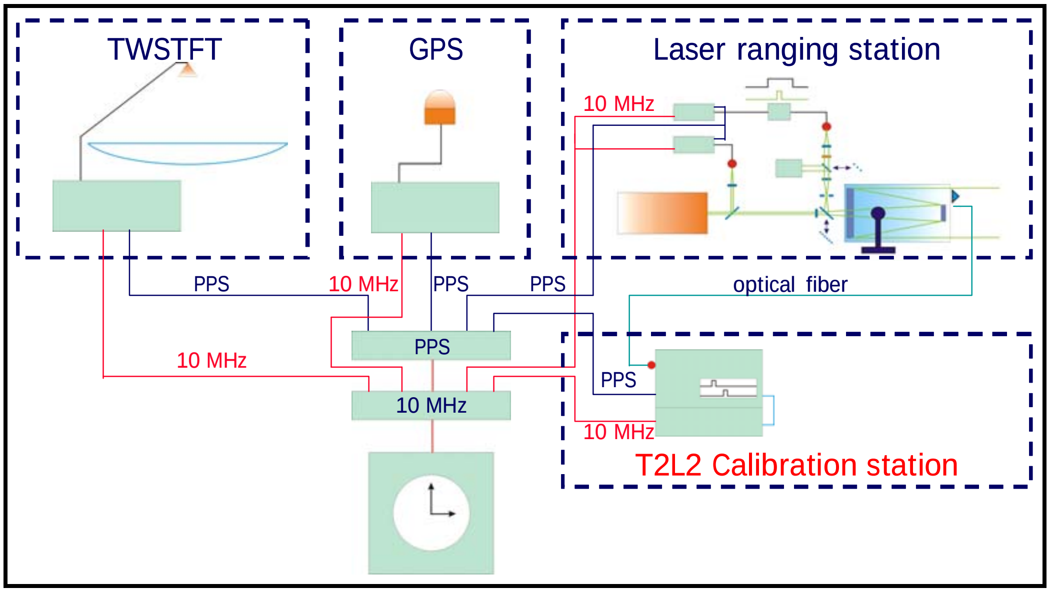

Figure 8. T2L2, GPS, and Two-Way intercomparison scheme.

IV. PRELIMINARY GROUND-TO-SPACE TIME TRANSFER

Thanks to the very first measurements of T2L2, one can proceed to a first evaluation of the short-term stability of the T2L2 time transfer.

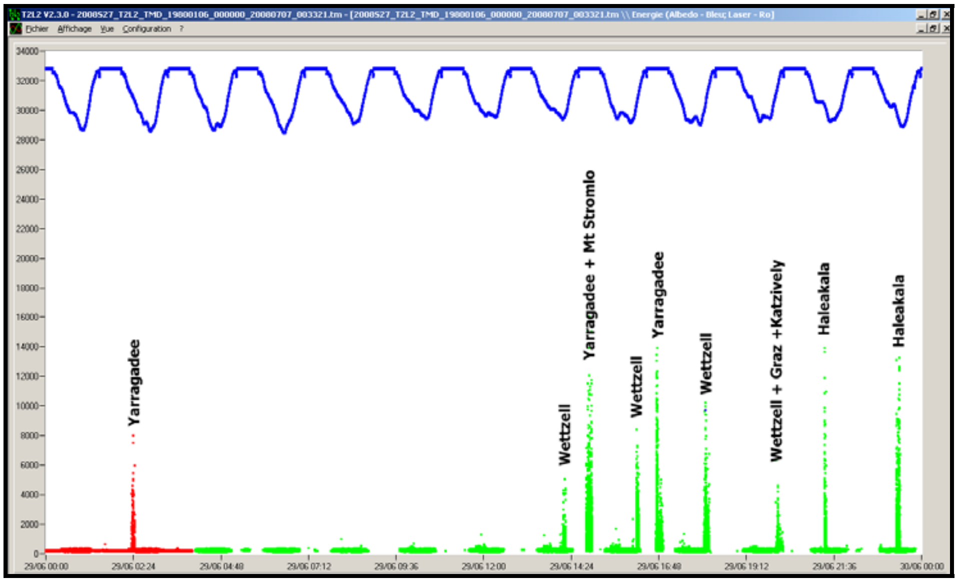

Figure 9. Detection of first SLR stations: CW background (sun albedo, higher value for penumbra, lower for daylight) in blue; energy of detected laser pulses in red and green (higher energy for "true" laser pulses, lower energy for noise events, mainly during daylight conditions).

The first step of the analysis of T2L2 data is the reconstitution of the « triplets », that is to say to merge data from the instrument with data from ground stations in order to associate to each event recorded by T2L2 the corresponding event from the SLR station. The CMS (Centre de Mission Scientifique/Scientific Mission Centre) has developed different algorithms to do that. The first one uses the prediction of the onboard date (t_B) from both the ground start (t_S) and return (t_R) dates and a prediction of the onboard time deduced from the GPS data (i.e. from the PPS signal distributed by the onboard GPS receiver and dated by the T2L2 instrument). The uncertainty of the prediction lower than 1 µs, mainly driven by the precision of the PPS, is sufficient the resolve the onboard date of laser pulses. A second one is based on the punctual synchronization of the T2L2 internal counter with UTC and the propagation with this counter of the T2L2 internal time frame. The long-term drift and initial tuning of the DORIS USO is then sufficient to guarantee the precision of 1 µs. The success rate is between 90 and 100% (100% means that one has found an onboard date for each ground event) for MOBLAS SLR (US SLR scattered about the world), whereas it is only 35 to 55% for European stations. This is under investigation. At the first order, the main difference is that most of American stations use MCP detectors, when European stations use photo-diodes for the detection of the return pulse.

At this step, triplets { t_S; t_B; t_R} have to be corrected from propagation imperfections, relativistic effects or instrument biases, that is to say:

- Correction of the Sagnac effect,
- Compensation of the internal delay of the nonlinear detector with the energy of the laser pulses,

- Correction of the relative positions of the LRA and the T2L2 detectors, and
- Compensation of the bias between linear and nonlinear detectors.

At this time, these corrections are still not implemented at the CMS (work is ongoing). So it is impossible to evaluate the long-term behavior of the time transfer, these phenomena being predominant. Nevertheless, an estimation of the short-term stability is possible by deducing from the data a 2nd-order polynomial. Figure 10 shows data from a pass over the French Transportable Laser Ranging Station (FLTRS) on 1 July. The standard deviation of the residuals is about 67 ps rms. The residuals are spread out by the distribution of the energy, not corrected at this step. By filtering the data with their energy and limiting the energy repartition over one octave, which leads to a standard deviation of the residuals of 40 ps rms (Figure 11). One can note that this result is the quadratic sum of all the onboard and ground noises; among them the FLTRS contribution is of 25 ps.

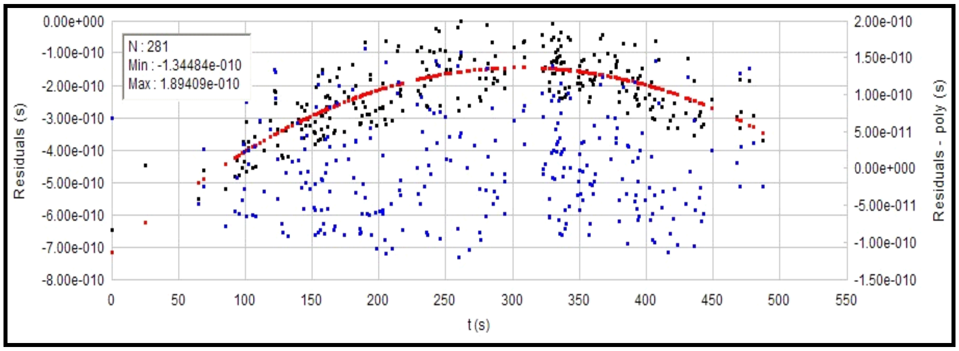

Figure 10. Residuals of the time transfer computed on 1 July for the FTLRS (raw data in black, 2nd-order polynomial in red, residuals in blue).

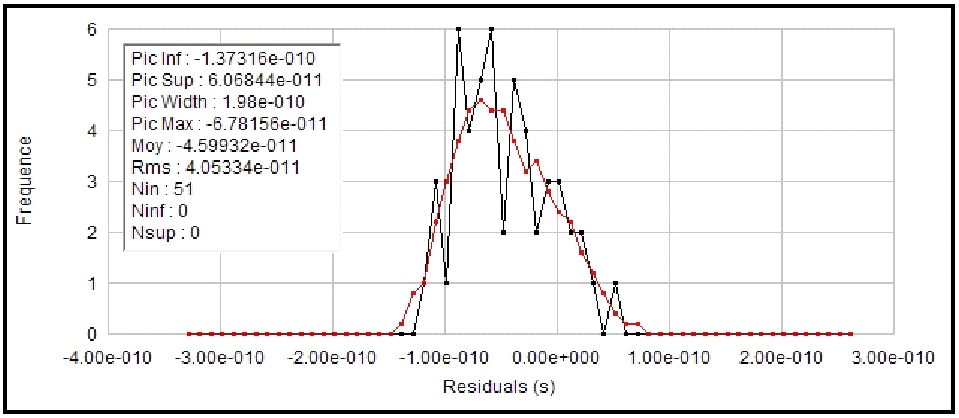

Figure 11. Histogram of residuals for laser pulses with energy filtered over one octave: Standard deviation is about 40 ps rms.

It is then possible to compute a first time variance from these residuals, even if the fit with a 2nd-order polynomial introduces a bias for durations from 100 s. For the FTLRS pass and without any filter on the energy of the laser pulses, the time variance is about $1\times10^{-10}\times \tau^{-1/2}$, with $\tau_0 = 1.7$ s (Figure 12).

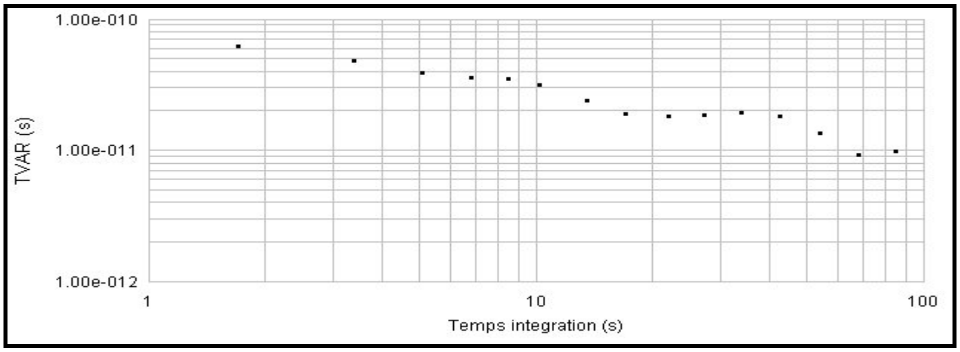

Figure 12. Time variance computed from the residuals (2^{nd}-order polynomial removed, no filter on energy).

V. CONCLUSION

The T2L2 instrument, launched 20 June and turned on 25 June, is now fully operational. The first data exhibit an unequalled short-term stability of a few tenths of picoseconds. The introduction of first relativist corrections and second instrument corrections shall allow in the next months the evaluation of the long-term performance of the system.

In the same time, some dedicated performance will be set up to improve these first results: Zero-baseline and common-clock measurements will be performed at the Observatoire de la Côte d'Azur in the beginning of 2009, and a transfer between to cold-atom atomics in Paris and Grasse is scheduled for spring, 2009. To go further, these first results open some new opportunities for the calibration of the GPS and Two-Way links used for TAI computation, the first with a limited network of European laboratories.

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