TIME TRANSFER BY LASER LINK - T2L2 : CURRENT STATUS OF THE VALIDATION PROGRAM.

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Abstract - The Time Transfer by Laser Link (T2L2) experiment is a joint Observatoire de la Côte d'Azur (OCA) and CNES space mission that will perform ground to ground time transfer. Using laser pulses instead of radio frequency signals, we are expecting a time stability of about 1 ps over 1,000 s and 10 ps over one day and a time accuracy in the 100 ps range.
The T2L2 instrument is on board the Jason-2 space vehicle. Launched in June 2008, it has been working since this date. After a six months period devoted to the characterization and the calibration of the system, the mission has started its "operational" phase in January 2009. First ground to space time transfers have demonstrated noise levels of some tens of picoseconds and a preliminary time stability of a few picoseconds over integration times of some tens of second, clearly limited by the on-board clock.
The 2009 T2L2 experimental program has contributed to the calibration / validation of T2L2 performances through two major experiments. The first one is a common clock time transfer between two co localized laser stations at the OCA : a fixed one MeO (for Optical Metrology) and the French Transportable Laser Station (FTLRS). The second experiment is the validation of remote clock comparisons using both laser and radio frequency techniques. This validation has been done using 3 regular laser stations (OCA France, Poland, Japan) and also the FTLRS station installed at Observatoire de Paris (SYRTE). The availability on those sites of GPS and TWSTFT stations allows a direct comparison with T2L2.
In parallel, data processing has been improved. It now includes a compensation of the dependency of the time walk of the detector with the energy of the laser pulse and some initial filtering and interpolation process. Influence of the angle of incidence of the laser beam on the detector will also be introduced soon, together with the finalization of the filtering and interpolation strategy.
The co location campaign took place from April to September 2009, with the two laser stations MeO and FTLRS connected to the same cesium clock. The FTLRS station has then been moved into Paris for 4 weeks between October and November 2009. After reminding the principle and the objectives of the mission, this paper will present first results of these experiments.

1. INTRODUCTION

Optical time transfer is an evolution of current radiofrequency time transfer systems profiting from advantages of the optical domain such as 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 a time stability of about 1 ps over 1,000 s and 10 ps over one day.

The objectives of the T2L2 experiment 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 has been successfully launched on June the 20th, 2008. The T2L2 instrument has been turned on June the 25th and is fully operational since this date. An average of 12 laser stations, sending their data in the new CRD format (full data with ps date), participate every day to the mission.. A few more stations send their data in the old MERIT format (full data but with 100 ns date).

Table 1 : Laser activity detected by T2L2 (2009, CRD Data)

Station	Activity [months]	Total number of passes	Average number of passes per month	Average number of echoes per pass	Average percentage of triplets per pass
Matera (Italy)	8	213	27	825	90
Wettzell (Deutschland)	12	712	59	583	67
Koganei (Japan)	5	112	22	1360	54
Grasse-MeO (France)	12	311	26	1700	21
Grasse-FTLRS (France)	5	52	10	3000	7
Zimmerwald (Switzerland)	12	426	36	2542	28
Mc Donald (USA)	9	87	10	404	56
Changchun (China)	12	555	46	9438	7
Mt Stromlo (Australia)	12	568	47	350	12
Herstmonceux (England)	12	515	43	11667	20
San Fernando (Spain)	3	38	13	600	23
Simeiz (Ukrainia)	12	152	13	101	4

After a preliminary evaluation of the performances [3], the experimental program shall contribute to the calibration / validation of T2L2 performances through two major experiences. The first one is a common clock time transfer between two co localized laser stations at the OCA: a fixed one MeO (Optical Metrology) and the French Transportable Laser Station (FTLRS). The second is a distant comparison (Europe and Asia) between laboratories that have on the same sites a laser ranging station, a GPS receiver, a Two-Way station and a high performance atomic clock (H-Maser or cold atoms clock). Such a configuration shall also allow a direct comparison of T2L2 with RF systems.

2. T2L2 PRINCIPLE

T2L2 allows the synchronization of remote clocks on Earth and the monitoring of space clocks. It 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 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, an event timer 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 on-board oscillator which is then downloaded to the ground via a regular microwave communication link. The set of these 3 dates {t_S, t_B, t_R} is called a "triplet". For a given light pulse emitted from station A, the synchronization $T_{GS[A]}$ between the ground clock A and the satellite clock is then derived from (1) :

$$T_{GS[A]} = \frac{t_S + t_R}{2} - t_B + \tau_{Instr} + \tau_{Sagnac} + \tau_{Geom} \tag{1}$$

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. Fig 2 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], [5], [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].

Fig. 1 : T2L2 electronic unit (Left, 8 kg and 48 W), and optical units together with the LRA (Right, 2.2 kg and 2 W).

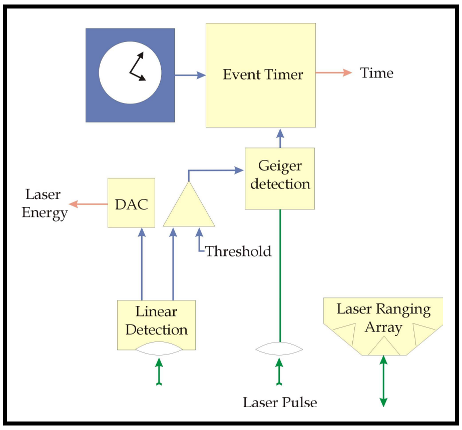

Fig 2 : Synoptic of the whole T2L2 space instrument. The linear photo detection is able to pre-trigger the Geiger module with an advance of a few ns.

The performances of the T2L2 Flight model have been determined during 2 main test campaigns, first before the delivery of the instrument, then during its integration on the Jason-2 space vehicle [8]. The goals of these campaigns were first to determine the true performances of the instrument and second to establish calibration tables in order to elaborate a model of the instrument. At the end, these test campaigns allowed to confirm the performances 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…) : The requirements (2) are nearly fulfilled even in the single photon / worst case mode (Fig. 3) :

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

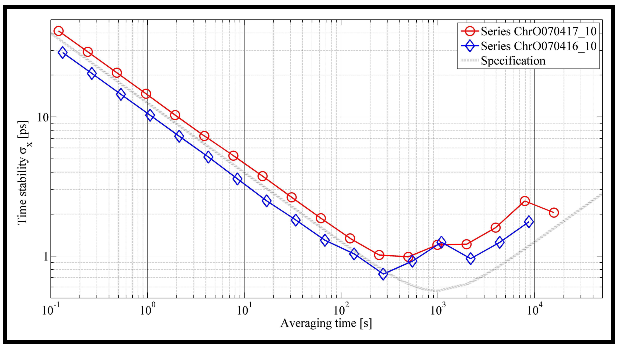

Fig. 3 : Stability (Time variance) of the whole detection / event timer chain in single photon mode.

3. DATA PROCESSING

Data are processed on a weekly base by the T2L2 Scientific Mission Center. After having collected space and ground data, from respectively the Instrument Mission center (CNES) and from ILRS, several steps are necessary to go from elementary data to time transfer.

3.1 Triplets Extractions

The events recorded by the T2L2 space instrument do not contain any information on the source since the events of all the laser stations are blended together. The first step of the treatment consists in associating the laser events recorded by T2L2 with those emitted by the stations.

We first have to synchronize T2L2 local time with UTC. The absolute frequency offset of the local oscillator and the delay between space and ground are known with an accuracy that permits to directly recognize the events by their dates. The process consists then in comparing, for each laser event, the computed arrival dates, deduced from the departure date and the orbit, with the on-board UTC dates.

3.2 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_S at the station and the arrival time at the satellite for 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,corrected by the distance between the LRA and the photo detection module τ_{Geom} and corrected by the speed aberration. At this stage the time of flight can be directly computed 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 a few tens of seconds. This method is pertinent in two cases:

- When the return time at the laser station is more noisy than the noise introduced by the atmosphere: this integration permits to decrease the noise by roughly $1/\sqrt{N}$, where N is the integrated number of returns.
- 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). To avoid the artificial noise that would be introduced by the fluctuation of the photon number, a neutral density has to be introduced 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 do not have a corresponding detection on ground and this synthetic time of flight permits to reconstruct a triplet with only one start time and one arrival time.

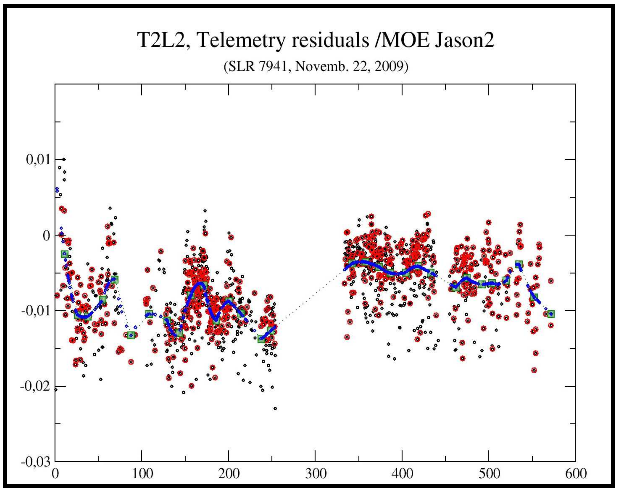

Fig. 4 : Time of flight determination : Telemetry residuals
(Black : Laser events, Red : With triplets, Blue : Synthetic time of flight)

3.3 Computation of geometrical and instrumental corrections

Several corrections have to be taken into account [8] :

- The Sagnac effect: at this step, a pure geometrical and iterative correction is computed, a complete relativistic approach being foreseen later in the processing scheme, based on a new theoretical model [9] ;
- The event timer drift: a complete characterization of the timer has been performed before the launch. It allowed us to compute some calibration tables that are adjusted thanks to automatic internal calibrations at instrument level ;
- The 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 ;
- The time walk of the photo detection module which is sensitive to the number of received photons : A polynomial model has been developed from the data acquired during the ground characterization of the instrument (Fig. 5) ;
- The influence of the incidence angle of the laser beam at instrument level : Here also, a polynomial model has been developed from the data acquired during the ground characterization of the instrument (Fig. 6).

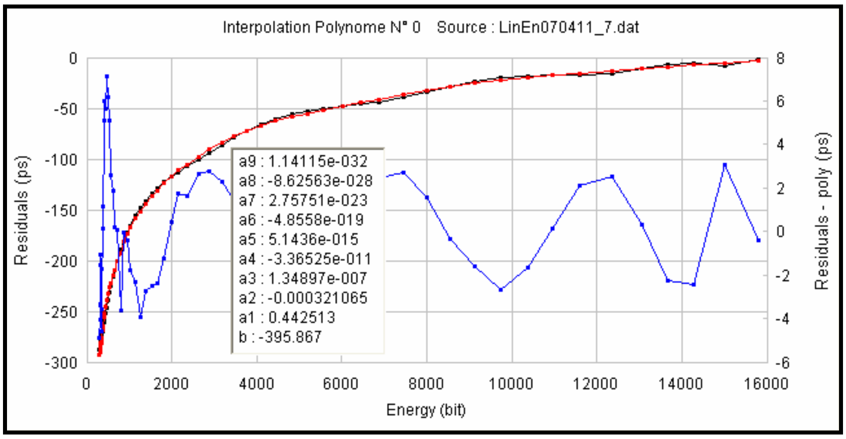

Fig. 5 : Correction law of the time walk versus the energy of laser pulses.
(Left scale : Ground measurements in black and polynomial model in red ;
Right scale : Residual between model and measurements in blue)

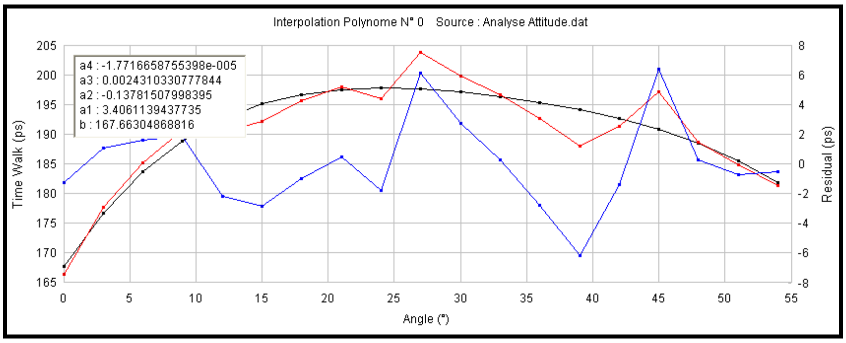

Fig. 6 : Correction law of the time walk versus the angle of incidence of laser pulses.
(Left scale : Ground measurements in black and polynomial model in red ;
Right scale : Residual between model and measurements in blue)

Then, data have to be filtered, to remove events corresponding to the detection of sun light photons, and to be interpolated at the same epoch (every second for example) in T2L2 proper time to allow ground to ground time transfer, either in common view or non common view configuration. This work is still under progress at T2L2 Scientific Mission Center. Nevertheless, preliminary data are already available on the T2L2 web site (http://www.oca.eu/heberges/t2l2/home.htm).

4. COMMON CLOCK TIME TRANSFER

4.1 Experimental Setup

From June to July 2009, the two French laser systems located at Grasse have observed common Jason2 passes. The first SLR system (called MeO, for Optical Metrology) consists in a telescope of 154 cm and a 10Hz laser with 20 mJ / 25 ps pulses. The second one, the French Transportable Laser Ranging Station (FTLRS), has a 13 cm telescope and a 10Hz laser with 10 mJ / 35 ps pulses. The error budget of each system has been established to 30 ps and 40 ps, respectively [10]. The distance between the two SLR stations is 35 m long (around 100 ns).

Being both connected to the same Cesium time system, it is then possible to compute the absolute time difference via the T2L2 space instrument. Obviously, if the theoretical time difference is 0, what is really computed is the value of the one way inter-calibration between both systems (SLR & clock). Nevertheless, such a configuration removes some common mode effects, mainly geometric effects related to the angle of incidence of the laser beam on the space instrument.

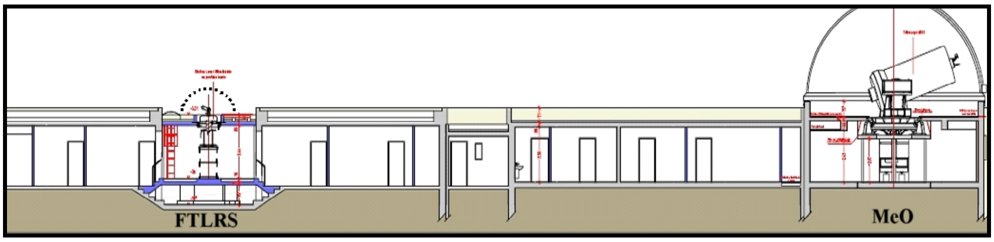

Fig. 7 : FTLRS and MeO laser stations at OCA/Calern

4.2 First Results

Fig. 8 gives an example of a common pass between the 2 laser stations MeO and FTLRS. We clearly see that we have less data with FTLRS than with MeO. This comes from the optical link budget of the FTRLS station which is just at the limit for the altitude of Jason-2. Residuals of the ground to space time transfer exhibit an RMS noise of 68 ps for FTLRS ground to space transfer, 65 ps for MeO.

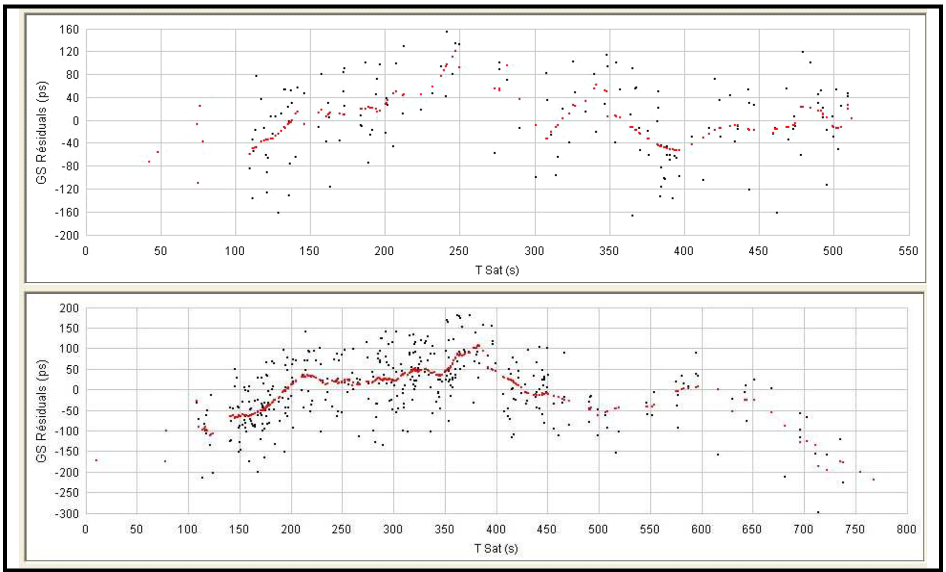

Fig. 8 : Residuals (drift removed) of a time transfer with FTLRS (Top) and MeO (Bottom) (May 29th, 2009) : Full rate data (Black dots) and interpolated data (red dots).

For the computation of the ground to ground time transfer (Fig. 9), elementary ground to space time transfers have been interpolated at each round second using for this first analysis a degree 1 polynomial fitted over 30 s. The degree and the time length of the polynomial will obviously affect the stability of the time transfer for time integrations smaller than the time length of the polynomial used. That has to be adjusted, depending on the performances of the ground clocks involved in the comparison.

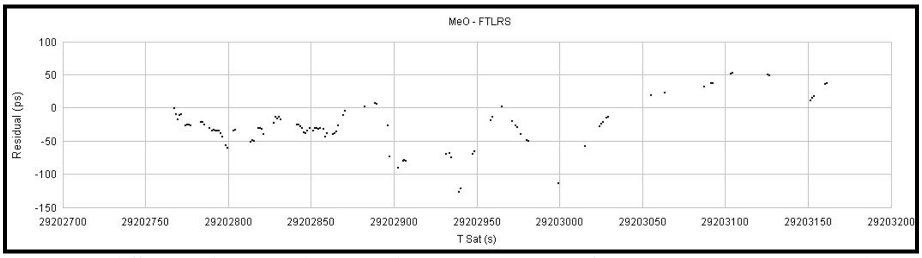

Fig. 9 : Direct difference between the ground to space time transfers MeO – FTLRS presented in Fig. 8. The residuals show a noise of 42 ps RMS.

It is possible to compute from this data a time stability (Fig. 10). Results give a stability of a few tens of picoseconds for integration durations between 1 to 100 seconds. But those results are clearly affected by the polynomial feet and the poor number of data from FTLRS. Particularly, one would expect a white phase noise behavior for short durations. Nevertheless, the value of about 20 ps at 100 s is close to the expected stability of T2L2. And it should be improved by increasing the link budget of FTLRS to reach 1 ps over 1000 s

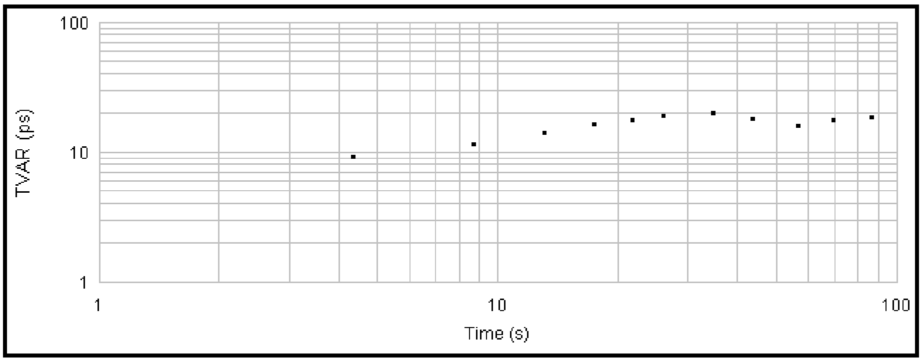

Fig. 10 : First evaluation of ground to space and ground to ground time stability (T-Var).

4. FIRST T2L2 INTERNATIONAL CAMPAIGN

Among its scientific objectives, 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 all over the world. Moreover, the availability of both transportable SLR stations (FTLRS – France, TROS – China) and Two-Way stations (TUG – Austria, TimeTech – Deutschland) shall allow extending the network with the possibility to perform some specific experimentations on some major TAI links.

A first experience was organized for a few weeks in October 2009. Four laboratories in Europe and Asia were involved (Table 2), all of them having GPS, Two-Way and laser station (Excepted for the Observatoire de Paris where we decided to install the French transportable laser station because of their particular situation with 2 Two-Way stations for Europe and Asia).

Table 2 : Network of station for the 2009 T2L2 campaign

Laboratory	Laser	GPS	Two-Way	Clock
OCA (France)	Yes	Yes	Europe	Cs, HM
OP/SYRTE (France)	FTLRS	Yes	Europe + Asia	Fountain, HM
AOS (Poland)	Yes	Yes	Europe	HM
NICT (Japan)	Yes	Yes	Asia	Fountain

110 laser passes have been performed by the four laser station during 17 days, most of them from OCA and NICT (Table 3). Because of a too huge divergence of the laser beam, the optical link budget at AOS was not sufficient to

access the T2L2 instrument, and the situation was nearly the same in Paris with FTLRS. Those two stations will be upgraded before the next campaign foreseen between May and September 2010. Data analysis of this campaign is still under process.

Table 3. Laser activity for the 2009 T2L2 campaign (number of passage, i.e. with at least one triplet)

Laser activity	AOS	OCA	OP	NICT
Number of triplets	0	8853	310	7043
Number of passes	0	35	7	18

5. CONCLUSIONS

The first year of exploitation of T2L2 helped to validate the performance of the system: results obtained up to now are in accordance with specifications, with time stabilities of a few tens of picoseconds for ground to space and ground to ground time transfers. More than 10 laser stations have invested in the project and are now heavily involved. Preliminary data and some useful information are available on the T2L2 web site at: (http://www.oca.eu/heberges/t2l2/home.htm).

Clearly, these results should be strengthened in coming months thanks to the continuous operation of T2L2 but also through a new campaign involving the FTLRS in Paris and cold atoms clocks, beginning in may 2010. Moreover, whereas the initial mission was planned for 2 years until June 2010, an extension of the mission has just been requested to CNES to continue T2L2 until 2013.

ACKNOWLEDGEMENTS

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