T2L2 Flight Model Metrological Performances

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***Abstract*— The T2L2 (Time Transfer by Laser Link) space instrument 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 dedicated space equipment T2L2 embarked on the satellite Jason 2. The T2L2 instrument has just been integrated on the satellite that should be launch in mid-2008. The T2L2 scheme will allow an improvement of one to two orders of magnitude as compared to the performances of existing time transfer systems. This paper focuses on a detailed description of the T2L2 flight model, its electronic and optical sub-systems and its functionality. The T2L2 space instrument is based on photo-detection of laser pulses by avalanche photo diodes and therefore equipped with two optical subsystems located on the outside of the satellite, in the vicinity of the LRA retro reflector of the Jason 2 satellite. The electronic subsystem is housed inside the satellite and principally consists of an event timer, a signal conditioning and delay adjustment system, a controller and respective power supplies. We report on the global performances of the whole instrumentation that were measured during an exhaustive test campaign with a dedicated test bed.**

I. Introduction

T2L2 "Time Transfer by Laser Link" [1] is a high performance time transfer experiment. It is based on a space instrument that has been designed at CNES (Centre National d'Études Spatiales) and OCA (Observatoire de la Côte d'Azur). It will be launched in 2008 aboard the Jason 2 altimetric satellite. T2L2 on Jason 2 will permit to perform time transfer between remote ground clocks and to compare their frequency stabilities with a performance never reached before. In common view mode (i.e. two laser stations are communicating with T2L2 at the same time), T2L2 will measure the stability of remote ground clocks, itself having a time stability in the range of 1 ps over 1000 s [2]. The objectives of the T2L2 mission are threefold:

The first one is a technological objective with the validation of optical time transfer by itself. The second one is time and frequency metrology, fundamental physics, earth observation and the validation of the one-way laser ranging concept. The third one is the improvement of the orbit accuracy deduced from the remote control of the quartz oscillator used in the DORIS positioning system.

The development plan of the space instrument was very short. The first decision to put T2L2 on Jason 2 was decided by CNES in july 2005. Three months later, we started the realization of a breadboard in order to evaluate precisely both the design and the performances. The development of the engineering model was started in February 2006 over a period of 6 months. In the mean time, we started also the realization of the flight model, which was delivered at CNES in the beginning of 2007. We have then performed a set of measurements during a dedicated campaign of 2 months. This campaign allowed both the calibration and the characterization of the space instrument.

For this purpose we designed a test bed [3] including a pulsed laser having characteristics similar to the ones used in laser ranging, an event timer for the chronometry reference, and some instrumentations capable of measuring many parameters like optical power, energy density, temperatures...

II. T2L2 Description

T2L2 is a follow-on mission to LASSO [4], [5] which was proposed in 1972 and launched in 1988 on Meteosat P2. It is based on the propagation of light pulses between the clocks to be synchronized. It uses laser stations at ground and a space segment linked to a space clock. In the frame work of Jason 2 the space clock is the DORIS oscillator which is linked to the T2L2 space instrument and used as a time reference. Laser stations at ground emit asynchronous short light pulses (~20 ps FWHM) towards the satellite. A laser ranging array (LRA) located near the T2L2 photo detection system1 returns a fraction of the received photons back to the ground station which records, for each laser pulse, the start and return time. LRA on Jason 2 is not dedicated for T2L2 and was initially designed for laser ranging. The T2L2 payload records the arrival time in the temporal reference frame of the on-board oscillator. These data are downloaded to the ground via a regular microwave communication link. The synchronization between the ground and space clocks is then derived a-posteriori from these data. The T2L2 ground segment is a laser ranging station2 with a special instrumentation to measure accurately both the start and return time of laser pulses. There are roughly 40 laser stations in the world that range satellites and moon and roughly 25 that range Jason 1 regularly. A typical laser station includes a pulsed Nd:Yag Laser (20 to 200 ps) at 10 Hz, a telescope (~1 m) , 2 event timers or an intervalometer.

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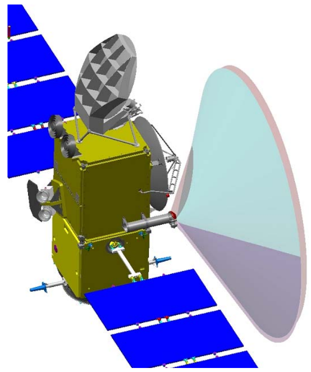

Fig. 1. The Jason 2 satellite. The cone on the right is the field of view from T2L2 requiered to see the whole earth

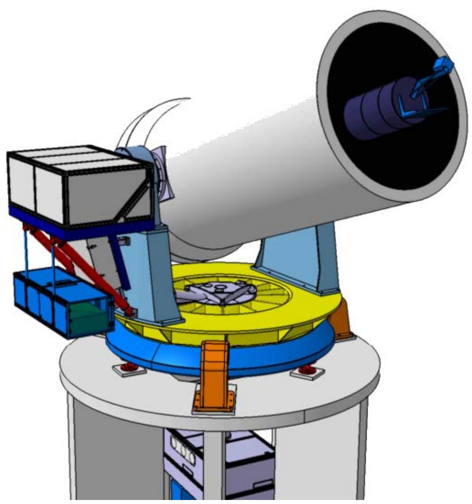

Fig. 2. A typical laser ranging station

III. T2L2 SPACE INSTRUMENT

Figure 3 shows the synoptic of the whole T2L2 space instrument. The photo-detection unit has two avalanche photo-detectors. One is working in a non linear "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, [6], [7], [8]. The time tagging unit 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 [9].

The Geiger mode is obtained with a transient negative voltage beyond the breakdown voltage of the diode. It remains in its state "off" without electric current until the light pulse creates a self sustaining avalanche and the photodiode experiences a transition to its state "on" where a saturation current occurs. The transition from the state off to the state on is used as the reference time of the light event. The photodiode must be brought back to its state off before another detection becomes possible. The voltage beyond the breakdown is applied on the diode just before the arrival time of the laser pulse in order to minimize the rate of false events (roughly 5 ns). The signal coming from the linear detection is used to build the Geiger voltage. An optical delay line permits to set a positive delay between the linear and non-linear photo detections. This delay line is made with an optical fiber. Each detection has an optical module the get the right field of view corresponding the visibility of the whole earth.

The linear detection gathers in a small cylinder (80 mm) the

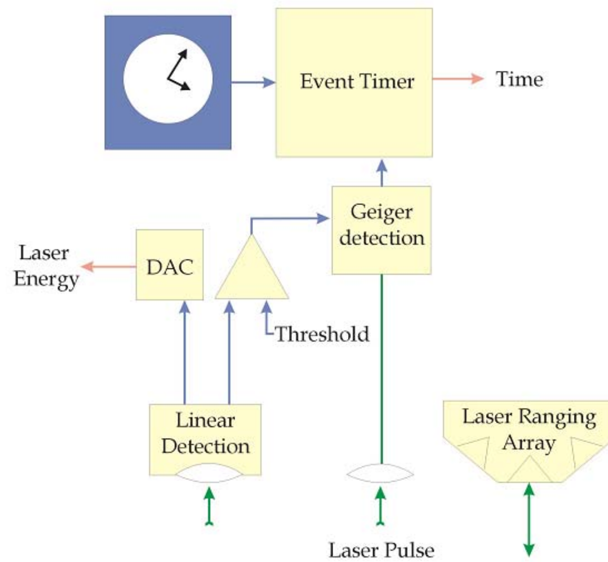

Fig. 3. Synoptic of the whole T2L2 space instrument

photo detector and its optical module. The non-linear detection is divided in three parts: the optical module, an optical fiber and the Geiger detector. The linear photo detection and the non-linear optical module are located outside the satellite very close to the laser ranging array (Figure 4). The optical delay line, the non-linear photo detector, the time tagging unit and also the global power supply and the microprocessor are inside a unique housing (250 x 250 x 150 mm3) inside the satellite (Figures 5 and 6). The external modules are linked to the instrumentation inside the satellite by an electric connection and an optical fiber. The precise study and the realisation of the optical components have been done by SESO (France). The realisation of the electronic cards, the software and the integration of the instrument have been done by EREMS (France).

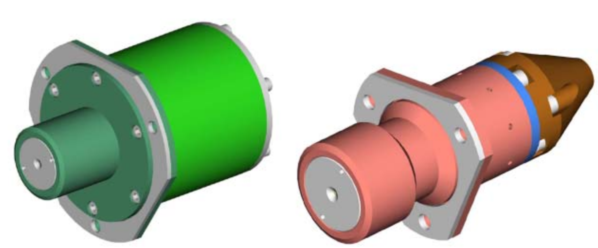

Fig. 4. On the left side the non-linear optical module ; on the right the linear photo detection

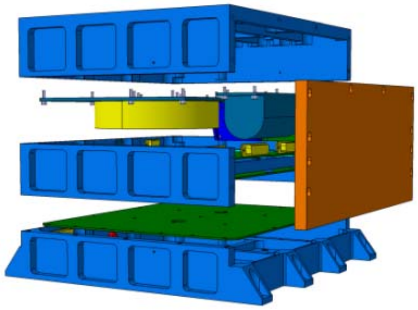

Fig. 5. T2L2 instrument inside the satellite. The yellow cylinder is the delay line

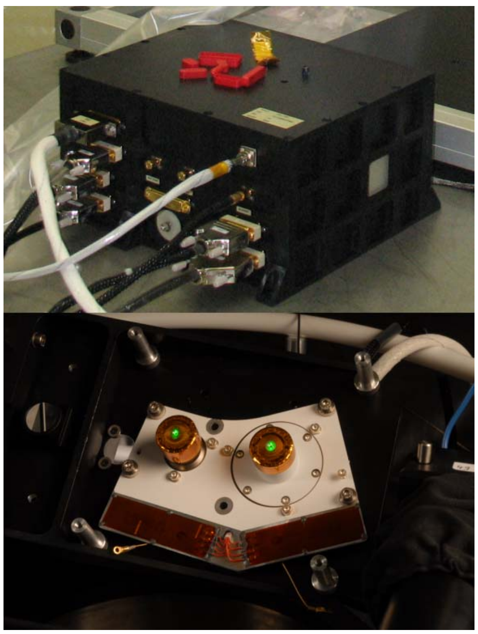

Fig. 6. The instrument inside the satellite (above) and the optical modules (below)

IV. Characterization of the space instrument

The test bed was designed to fully characterize the T2L2 space instrument. A large number of measurements are conducted for both calibrations and performance evaluations. A first campaign of 2 months has been conducted recently in a stand-alone (SA) mode and a second one is still running now with T2L2 integrated on the satellite Jason 2 (AIT).
The measurements that have been done are gathered in Table I The main components (Figure 7) of the test bed are:

- a Solid state Vanadate Laser (HQ Laser) able to generate light pulses in the range of 20 ps (FWHM)
- a 2 axes gimbals to emulate the attitude of the satellite
- a power meter and a low noise CCD to respectively evaluate the absolute energy per pulse and the energy density
- two atomic clocks for time reference
- two event timers for chronometry reference
- CW optical source for sun light emulation

TABLE I
Metrological tests

Measurement	Type
Event timer data reduction	Calib. SA
Time walk compensation of non linear photo detection	Calib. SA
Differential detection gain linear / non linear detection	Calib. SA
Event timer time stability (electric)	Perfo. SA
Photo detection time stability (optic)	Perfo. SA
Magnetic field sensitivity	Perfo. SA
Optical Sensitivity	Calib. SA
Signal to noise ratio: detection	Perfo. SA
Detection threshold	Perfo. SA
Detection linearity	Calibration
Solar flux sensitivity	Calibration
DORIS oscillator time stability	Perfo. AIT
Event timer data reduction	Calib. AIT
Detection threshold	Perfo. AIT

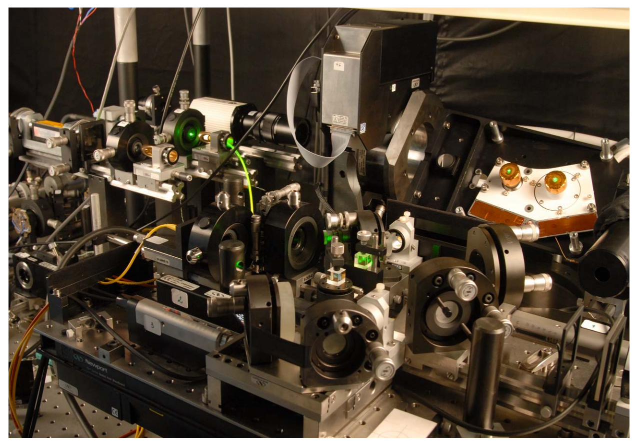

Fig. 7. Optical bench of the T2L2 test bed ; on the right, the T2L2 optical modules interated on the 2 axes gimbals

V. Performances

Four Gigabytes of data have been acquired during the stand-alone campaign at CNES. Data are presently under analysis and the results presented here are preliminary.
Frequency synthesis:

- $\sigma_x = 60.10^{-15} \times \tau^{-\frac{1}{2}}$; $0.001 < \tau < 3$ s
- $\sigma_x = 30.10^{-15} \times \tau^{0}$; $\tau > 3$ s
- Thermal sensitivity: 0.5 ps/°C

Event timer:

- Repeatability error: 2 ps rms
- Time stability synchronous events @ 1 kHz (TVAR):
- $\sigma_x = 50.10^{-15} \times \tau^{-\frac{1}{2}}$; $0.001 < \tau < 3$ s
- $\sigma_x = 30.10^{-15} \times \tau^{0}$; $\tau > 3$ s
- Thermal sensitivity: 0.4 ps/°C
- Linearity over 100 ns (see Figure 8)
- Maximum acquisition rate: 5 kHz

Optical chronometry:

- Single photon precision: 38 ps rms
- Single photon distribution (see Figure 9)

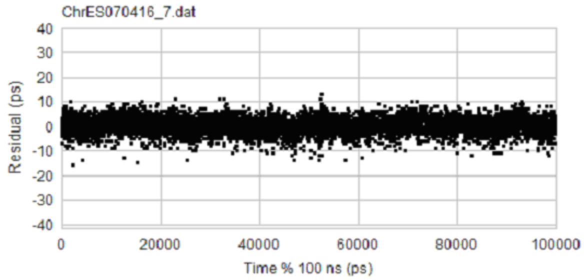

Fig. 8. Event timer linearity over frequency period 100 ns. The overall rms (limited by the bench) is 2.8 ps

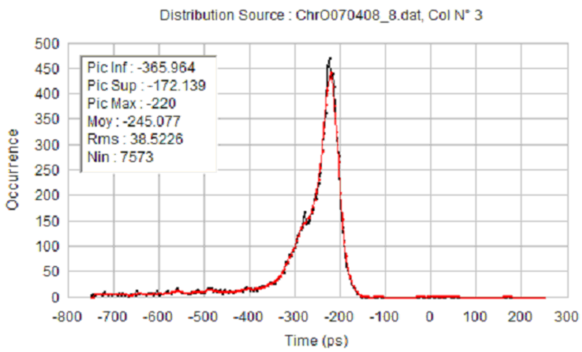

Fig. 9. Chronometry distribution in a single photon mode. To get the single photon mode, the optical beacon in front of the non linear beam is attenuated by a factor 1000 as compared to the linear chanel. (time is negative on the graph)

Energy quantification

- Dynamic: > 10^4
- Response (see Figure 10)

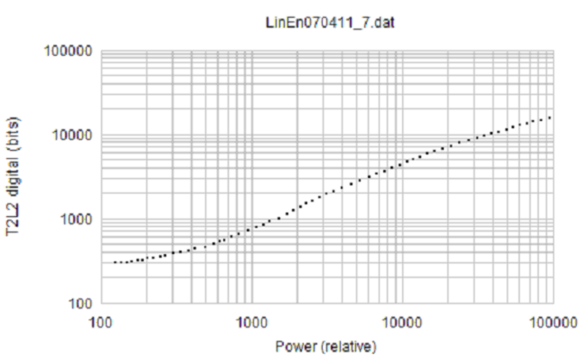

Fig. 10. Energy quantification measured by T2L2 versus external power measurement

Photo detection Time Walk and photo detection repeatability error (see Figure 11)

- @ Detection limit: 40 ps rms
- @ Maximum power: 3 ps rms

VI. Conclusions

After the decision taken by the CNES to put T2L2 on the satellite Jason 2 in July 2005, the space instrument is

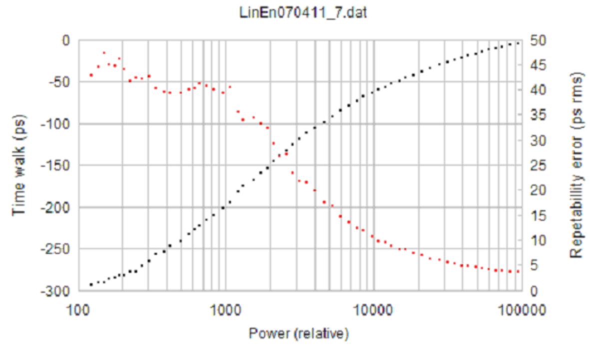

Fig. 11. Time walk of the over all photo detection (linear and non linear). The relative power of 1000 is equivalent to a mean photon number of 1. The plot is shown over a dynamic of 3 order of magnitude but the real dynamic is greater than 4

at the present time integrated on the satellite. The stand-alone campaign permits to calibrate and to evaluate the whole parameters of the instrument. These measurements will permit to reduce raw data that will be acquired in the future and also to understand precisely the comportment of the instrument during operation. This will allow the fit a precise instrumental model for the future the time transfer. A large amount of data has to be analysed to conclude this study. Furthermore some data acquisitions are still required in the satellite integration mode. This will be done in the very near future.
Globally, the T2L2 space instrument measurements are in a good agreement with the initial specifications. Nevertheless a preliminary analysis of the detection efficiency shows a significant deviation from the initial link budget that is not yet understood.
The launch of the satellite is scheduled in June 2008. The lifetime of the T2L2 instrument is at least 2 years after the launch. The satellite Jason 2 could be operational during 5 years. 20 laboratories, laser station and time and frequency laboratories, should be implicated in the project. 10 laser stations are, at the present time, ready to run T2L2.

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