The T2L2 Metrological Test Bed

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***Abstract*— The new generation of optical time transfer (T2L2 [1], [2] - Time Transfer by Laser Link) under development at OCA and CNES will allow the synchronization of remote ultra stable clocks and the determination of their performances over intercontinental distances. The principle is based on the propagation of light pulses between laser telemetry stations connected to the clocks that have to be synchronized. Expected T2L2 performances are in the 100 ps range for accuracy, with an ultimate stability better than 1 ps over 1,000 s and than 10 ps over one day and will thus allow an improvement of one to two orders of magnitude with respect to the performances of existing time transfer systems.**

In this paper we report on a test facility designed to derive the metrological performances of the T2L2 space instrument and to perform calibrations of electronics and optics. This test bed is capable of subjecting the flight instrument to the experimental conditions it will meet in orbit. For this purpose, the test bed consists of several subsystems: an optical subsystem in order to illuminate T2L2's optics with faint laser pulses (simulating laser stations) and background illumination, an electronic subsystem including a high performance timing system for reference timing and a mechanical subsystem for simulation of different angles of incidence (corresponding to the elevation of the satellite with respect to a laser station). The experimental setup also includes a DORIS space clock engineering model in order to simulate the conditions on the satellite Jason 2, and alternatively a Rubidium and H-Maser for stability measurements.

With this instrumentation it is possible to simulate the experimental conditions of operation of the space instrument and thus derive their impact on the metrological performances and therefore the quality of the time transfer.

After a short review of the instrument architecture we give a detailed description of the metrological test bed and its subsystems. We then outline the calibration and performance tests that were carried out on the T2L2 flight model and conclude.

I. Introduction

T2L2 is a novel time transfer space experiment relying on an embarked instrumentation and satellite laser ranging (SLR) ground stations. The time transfer scheme is based on optical pulses timed in the different clock time scales of the laser stations and of the satellite, respectively.

The T2L2 payload, developed by OCA (Observatoire de la Côte d'Azur) and CNES (Centre Nationale d'Etudes Spatiales) will be embarked on the French-American ocean altimetry satellite Jason 2 whose launch is scheduled for mid 2008. After assembly by the industrial partners and after passing successfully the phase C/D review the T2L2 flight model was subjected an exhaustive metrological test campaign. This test series aimed at the following:

- the calibration of optical and electronic parameters of the different instrument subsystems. The result of these calibrations are correction tables to translate the raw data from satellite telemetry into real dates that serve for the final time transfer.
- the derivation of the instruments performance in terms of time metrology.

In this paper we focus on the presentation of the test apparatus that was developed for this purpose. This test bed consists of several subsystems:

- an optical subsystem simulating the SLR laser station and background illumination;
- an electronic subsystem including inter alia a high performance reference timer, different clocks and the overall control electronics;
- a mechanical subsystem simulating different incidence angles of the laser beam.

We then give an outline of the conducted calibration and performance tests.

II. The T2L2 scheme

A. Principle of operation

The T2L2 time transfer scheme is based on laser pulses traveling from SLR ground stations to the satellite and back: In order to synchronize a ground clock A connected to a SLR station with the satellite clock, the station emits short laser pulses (FWHM: 20 ps, $\lambda = 532\mathrm{nm}$) towards the satellite. The departure time t_s of the light pulse is recorded with a highly precise and stable event timer in the ground clock frame. At arrival at the satellite, the pulse is similarly reflected by a retro reflector and timed by the embarked T2L2 event timer giving the date t_b in the satellite reference frame. The reflected pulse is equally collected by the ground station telescope and timed, giving t_r.

For a given pulse, the time transfer χ_A may thus be computed:

$$\chi_A = \frac{t_s + t_r}{2} - t_b + \tau_{Relativity} + \tau_{Atmosphere} + \tau_{Geometry}$$

In this way two distant ground clocks A and B may be synchronized: the on board oscillator transports the temporal information from A to B. For acquisitions in *common view* mode (i.e. A and B are firing on the same time towards the satellite what is true for up to 3,000 km baseline in the case of Jason 2) the stability of the oscillator may be neglected. Time transfers over larger distances (*non-common view*) are affected by the stability of the on board clock.

B. Instrument Description

The T2L2 space instrument is composed of two subsystems:

- an optical subsystem and an
- electronic subsystem.

Fig. 1 shows the synoptic of the T2L2 instrument supplied by OCA. This system is complemented by the LRA (Laser Ranging Array), a retro reflector assembly supplied by JPL for the Jason 2 mission and a DORIS positioning system USO. The optical subsystem implies a 'linear' and a 'non-linear channel'. The front optics of both channels are designed to see the whole earth surface resulting in a field of view (FOV) of ±55° for the Jason 2 orbit and include similarly:

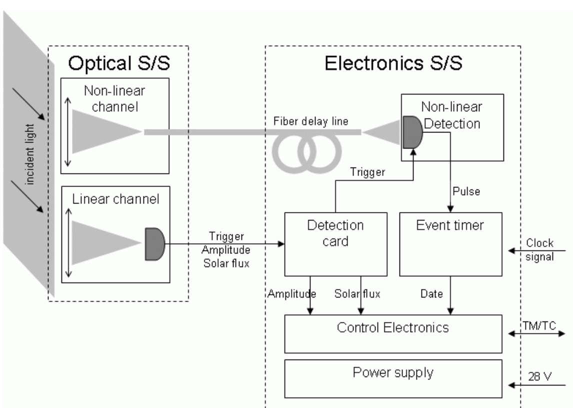

Fig. 1. Schematic of the T2L2 space instrument

- collimation optics consisting of a set of lenses;
- a spectral filter for noise reduction;
- a neutral density filter with radial variation for equalization of the laser pulse energy levels for incidence angles between nadir (maximum flux) and ±55° (minimum).

The linear channel collimates the light onto a linear APD photo detector that has a triple purpose: triggering the non-linear detection chain, measuring the laser pulse amplitude and the cw background noise.

The non-linear channel collimates the light into a multi-mode optical fiber that transports it towards the electronics subsystem which is located in the inner of the satellite and houses the non-linear detection system. The latter consists of an APD working in a special 'Geiger' mode for precise timing and is triggered by the electric signal provided by the linear detection. The Geiger APD output signal is strongly afflicted with a time-walk ([3]) over photon number wherefrom the need to know exactly the incoming laser pulse energy.

The resulting signal is eventually timed by the T2L2 event timer that is connected to the Jason 2 DORIS OUS. The event timer consists of a programmable logic array working at 100 MHz for rough and a vernier for precise timing resulting in a resolution of less than 1 ps. A control electronic recovers all digitized data and pilots the instrument settings.

In addition to the nominal instrument interfaces (10 MHz clock signal, PPS in, optics, Jason 2 power supply and MIL Std 1553 bus) the T2L2 flight model disposes over following interfaces uniquely for the metrological tests:

- an ECL signal input (towards T2L2 event timer),
- an internal synthesized 100 MHz (timer) output and
- an RS 422 communication port.

C. Experimental conditions

The T2L2 space instrument will be embarked on the ocean altimetry satellite Jason 2. This satellite will be launched in mid 2008 and put in a circular orbit of 1,336 km altitude and 66° inclination; this orbit features six repeating ground tracks per day with a dead time of about 120 min between the passes of each about 1,000 s.

As described above, in order to allow time transfers over intercontinental distances, the optics were designed with a FOV of 110° comprising the whole globe but excluding direct view of the sun during nominal operation (i.e. satellite is nadir pointed). This configuration leads to the integration of a significant background noise from the atmosphere reflected sun irradiance.

Also, the angles of incidence vary over one pass and from one to another; they are known from the satellite orbit and attitude data with the respective precision.

Further, following points have to be taken into account:

- the received energy per laser pulse varies from one pulse to another as the laser beam will have features similar to speckles on satellite level;
- the polarization of the incident light wave is unknown: this has to be taken into account for potential differential polarization-dependent propagation in the optics of the two channels;
- the point of reflection (by the LRA) is not co-located with the point of detection; both depend on the angle of incidence;
- possible multi-reflection in the optics of the continuous flux from all angles of incidence and beyond could cause more noise than expected.

III. Test Bed description

In the following we describe the architecture of the test bed employed during the metrological test campaign that was performed in the CNES (French space agency) clean room facilities in Toulouse, France during March and April 2007. The test bed consists mainly of three sub-ensembles (see figure 2), a set of time/frequency and control electronics, an optical bench supplying laser pulses and continuous background illumination and a mechanical subsystem for the generation of different incidence angles.

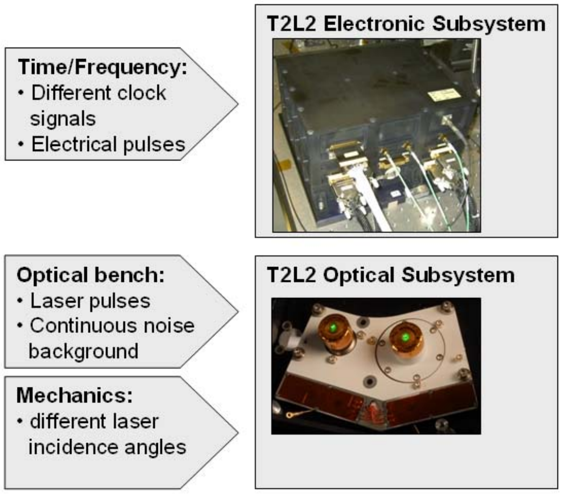

Fig. 2. Schematic of the metrological test bed

A. Time/Frequency and Control Electronics

The test assembly disposes of different clock types: for normal operation, i.e. the absolute evaluation of timing performance in a common clock experiment a Rubidium clock is employed, replaced by an H-Maser for mean to long term stability measurements supplied by the CNES Time/Frequency department.
In order to estimate the T2L2 overall performance in conjunction with Jason 2's DORIS space clock CNES further supplied a DORIS engineering model.

As a reference timer serves a two-channel THALES (former Dassault Electronique) event timer, offering 2 and 5 ps precision, respectively. In the following chart the timer's stability is plotted.

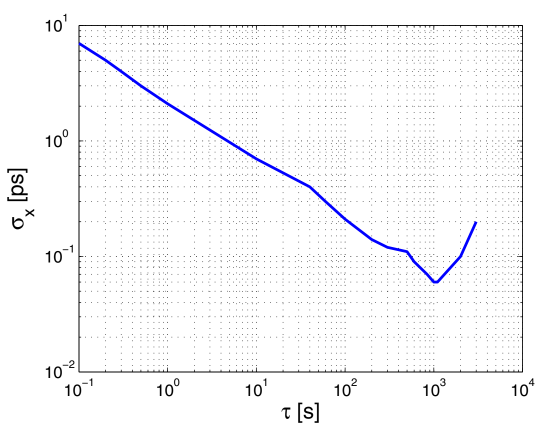

Fig. 3. Stability of the Thales reference timer

The electronics segment further generates electronic pulses (ECL) at a selectable repetition rate, alternatively synchronous or asynchronous to the clock signal. These signals are used for the evaluation of the T2L2 event timer in a pure electronic environment. A frequency synthesis of 100 MHz for the synchronization of the laser pulses is also included (see section optical bench).
The whole test apparatus (electronics, optical bench and mechanics) is piloted by a control PC with a dedicated software; the PC also retrieves the data frames generated by T2L2 whereas the telecommands are produced and sent over the MIL Std 1553 bus by a separate PC, as a part of T2L2's electronic ground support equipment (EGSE).

B. Optical bench

The optical bench produces two laser beams illuminating the T2L2 optics. In order to simulate at best a typical satellite laser ranging station, a SESAM modelocked Nd:YO_4 cavity is employed; this cavity produces IR (1064 nm) laser pulses of 19 ps length at a repetition rate of 100 MHz and an average power of 3.5 W. The cavity offers the possibility to synchronize the laser rate to an external reference. As an SLR station typically works with repetition rates of 10 Hz to some KHz, the test setup permits to down select the repetition rate by a series of two pulse pickers (range: single shot to 1 MHz).
After frequency doubling (SHG) to 532 nm, the laser pulse energy is set via a motorized waveplate-polarizer ensemble. Further, a small diode pumped solid-state cw laser is mixed

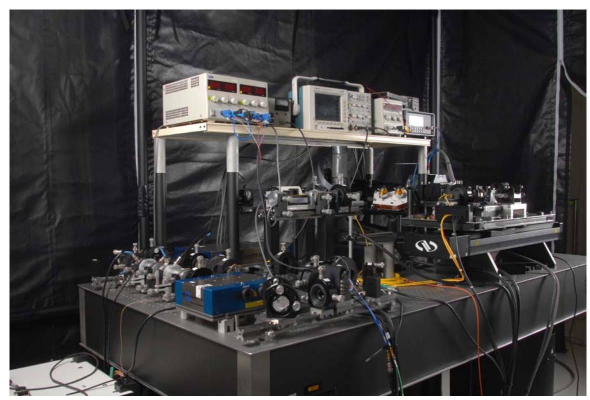

Fig. 4. The test bed optics and mechanics

to the pulsed laser beam in order to generate a continuous background signal to the laser pulses. for the simulation of the noise background T2L2 will meet in orbit, a grid of LED (with white emission spectrum corresponding to white cloud cover) may be mounted in front of the T2L2 optics, filling the whole FOV.
An energy calibration bench permits to regularly control the laser pulse energy and the beam profile, consisting of following elements:

- a high precision power meter with associated detector and
- an extremely low noise CCD camera of Andor Systems for integrating images of the beam profiles.

Before being transmitted on the T2L2 optics the laser pulses are time tagged by a high precision APD connected to the reference timer (corresponding to a laser station's departure time tag).

C. Mechanical subsystem

In order to subject the T2L2 optics the laser beam under different angles of incidence, they are mounted on a two axis gimbal mount covering the whole possible incidence range of ±55 °.
The effect of different operation temperatures is studied by heating or cooling the electronic subsystem in a dedicated furnace.

IV. Calibration of instrumental parameters

The T2L2 event timer produces raw dates (64 bits, 1 ps resolution) that have to be corrected for various instrumental parameters before being useful for time transfer. In this section we describe these parameters and the associated tests that were performed.

A. Timer Calibration

The event timer consists of two stages: a counter based on a FPGA running on 100 MHz for rough timing (10 ns resolution) and a vernier running on an internally generated 100 MHz signal (issued from the USO supplied 10 MHz), offering a final resolution of 1 ps. One important measurement is the determination of the non-linearity of this reference frequency. This is obtained by the timing (by T2L2 and the reference timer) of asynchronous (i.e. random) electronic pulses. By this means, the reference signal is completely described and higher order harmonics may be calculated that serve for the correction of future dates.
As aging could change the harmonics' characteristics during the lifetime of the instrument, the instrument itself is able to generate calibration signals at known temporal positions; with the timing of these calibrations evolutions of the reference signal may be taken into account.
The transition constant, i.e. the moment of switching from one state to another of the counter w.r.t. the reference signal is equally determined.

B. Optics Calibration

The optical calibration measurements are summarized in the following:

- Laser pulse energy measurement by linear avalanche photodiode: the multiplication gain is derived for different applied polarization voltages. The detected photon number is traced over actually incoming photon number.
- In the same manner, the measurement of the continuous sun noise background signal has to be calibrated by the use of the cw laser.
- Time walk correction: as mentioned above the temporal response of the non-linear photodiode shows a strong dependence on photon number (compare figure 5). For this reason an energy measurement is associated to each date. The time walk has to be precisely determined for all expected photon levels.
- Detection threshold: the detection threshold is determined as a function of sun noise.

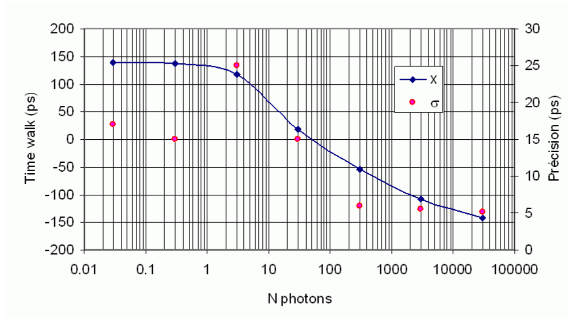

Fig. 5. Timewalk of engineering model [4] non-linear APD

- Optics differential transmission: As the linear and non-linear channel have different optical architectures, their transmission may depend on the angle of incidence. As the response of the Geiger APD is intrinsically non-linear a comparison of the energy throughput of both channels in only possible in simple photon mode where the photon number may be estimated by Poisson statistics. By this means we may establish a correction table for real present photon number over the two attitude angles in comparison to the one measured by the linear channel.
- Optics differential propagation delay: In the same way as for the transmission the optical path may vary for different attitudes; the time delay has to be determined for all incidence angles.
- Detection equivalence point: With the measurement above, the relative displacement of the detection reference point as a function of attitude has already be determined. The absolute position with respect to the mechanical reference is determined by timing a laser pulse reflected in the aperture plane of the optics in addition to T2L2's measurement.

V. T2L2 performance tests

A. Timer performance

The timer's performance is determined by following tests:

- Vernier linearity: the linearity of the calibration corrected reference signal is verified.
- Time stability of frequency synthesis (internal reference signal): The 100 MHz signal provided by T2L2 is logically divided to a rate measurable by the reference timer (e.g. 1 kHz); one obtains following time deviation:

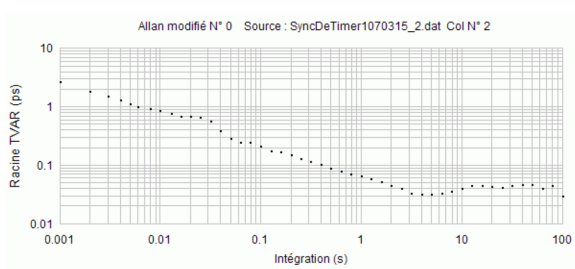

Fig. 6. The T2L2 internal reference signal time deviation

- Event timer: time stability in calibration mode. The internally generated calibration pulses are timed.
- Event timer: time stability of asynchronous events; ECL pulses generated by the test bed electronics are routed both to T2L2 and the reference timer, the comparison gives the precision and time stability.

B. T2L2 in optical mode

The following tests emphasize the performance of the whole T2L2 instrument employing both optics and the timing device.

- The SNR of the detection chain is derived by determining the minimum laser pulse energy provoking an event, for all sun noise levels. In the same way, the false measurement rate may be derived.
- Timing sensibility towards laser energy level: The deviation of the date and the evolution of the precision as a function of laser power level after correction with the calibration data is identified (time walk residual).
- Timing sensibility towards laser repetition rate: The deviation of the date for different repetition rates is resolved.
- Sensibility towards polarization: As once again the optics may be afflicted with a differential transmission as a function of angle of incidence and light polarization, the measured pulse energy may vary from the actual one present on the non-linear diode. As the polarization is an arbitrary parameter in orbit, there is no means of correction; we establish an error budget for the two orthogonal polarizations as a function of attitude.
- Precision and stability of the whole detection/timing chain for asynchronous measurements.
- Global measurement: Acquisitions with all concerned parameters varying (attitude, laser energy, noise power etc.) permit to fully simulate a typical orbit pass. With the application of the correction tables the consistency of the established error budget may be checked.

VI. Conclusion and Outlook

The T2L2 metrological test bed permitted to fully characterize all of T2L2's instrumental parameters. The data analysis is in progress and will allow the establishment of correction tables for the conversion of raw data into real dates exploitable for time transfer. The performance of T2L2, its subsystems and the whole time transfer scheme will be fully determined.

After slight modification, the test bed is currently (June 2007) used for final measurements on T2L2 during satellite integration in Thales Alenia Space facilities in Cannes, France. This permits to verify the so far derived performance in the real satellite environment (DORIS USO, Jason 2 power supply etc.). Further, a detailed analysis of the DORIS clock may be performed by the bias of the T2L2 instrument.

Jason 2 is scheduled to be fully integrated and tested in 2007 before being launched into orbit in mid 2008.

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