TFTS: a transfer standard for Frequency and Time Interval Inter-Laboratory Comparisons

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***Abstract*— This paper examines the study, the implementation and the preliminary tests of a transportable reference standard for inter-laboratory comparisons, called TFTS, to be used for comparisons in the field of frequency and time interval measurements. This device will allow the reference laboratory to assess the testing capabilities of the metrological Centres recognized by SIT.**

I. INTRODUCTION

The scope of the development of a transportable reference standard for inter-laboratory comparisons called TFTS (Time and Frequency Travelling Standard), to be used in the field of frequency and time interval measurements, is to allow for periodic assessment of the metrological capabilities that have been recognized to a calibration laboratory accredited by the Italian Calibration Service SIT. Until now, both at the national and international level, it has not been possible to obtain satisfactory results in the experimental trials, carried out either in the frame of the regional organizations for accreditation or by SIT, among the laboratories accredited in these areas. The main reason for this can be found in the instability and limited reproducibility of the travelling standards used - free quartz oscillators and rubidiums - when compared with the levels of uncertainty commonly accredited.

Moreover, since the levels of uncertainty for which a calibration centre may be accredited span in a considerable range (from 10^{-7} to 10^{-13}), we should have travelling standards adequate for the different requirements in order to follow the approach recommended by the EA (European Cooperation for Accreditation) for these periodic exercises, that are intended to check the consistency of the calibration work performed in the different accreditation systems that are signatories of the Multilateral Agreement (MLA) of EA.

To meet these requirements, an instrument was developed that exploits the accuracy resulting from the use of an atomic oscillator disciplined by the GPS (Global Positioning System) reference time signals, which is also capable to simulate, according to chosen settings, the main parameters, in terms of frequency deviation and drift, of a reference oscillator tailored to fit the metrological capabilities to be verified. It can also allow to generate reference time signals such as pulses of known width and period, or pair of pulses to generate Start / Stop events with defined delays. In the followings, the criteria adopted for the design of the instrument and the first test results obtained will be described.

II. TFTS DESCRIPTION

The instrument design is based on the approach adopted since a decade in Italy to remotely ensure the metrological traceability of the reference standards of secondary laboratories to the national time standard of Italy UTC (IT), which assumes as transfer standard the reference signals continuously transmitted by the GPS satellites [1].

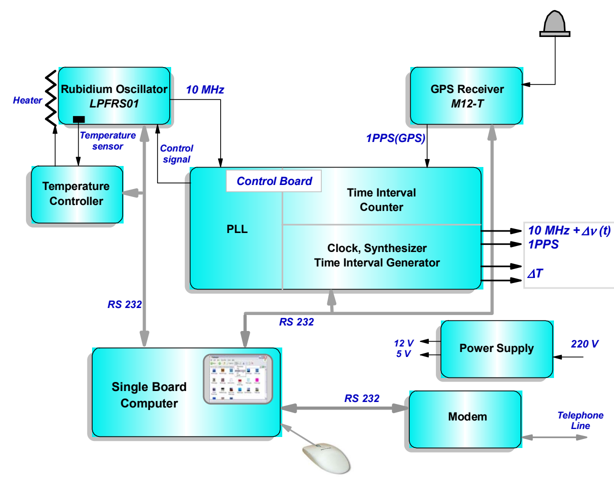

Figure 1. Block diagram of TFTS

How depicted in the block diagram of Fig. 1, the instrument is made up of a vapour rubidium oscillator (Temex Time: LPFRS 01), by a 12-channel GPS single frequency receiver (Motorola: M12T) [2] with external antenna, by a control and measurement system, by a rubidium temperature regulating system and by a PC card supervising the system and performing the general management of the measurement data. The control and measurement system is in turn composed of a time interval counter, a Phase Locked Loop (PLL), a frequency synthesizer and a time interval generator. The TFTS is also equipped with a telephone modem that allows the ILC pilot laboratory to configure remotely its operational specifications, as well as to remotely transfer its internal parameters and the measured data collected so far.

By analysing in details the various elements depicted in the block diagram, and starting from the left side, one can firstly highlight that the temperature of the rubidium oscillator is controlled by thermally stabilizing its package to a value by few degrees higher than that which would reach without an external heater; this allows to control this parameter simply by using an heating element. The rubidium oscillator provides a 10 MHz output signal which is the time base of the control board. This board also feeds to the rubidium the control voltage necessary to keep its frequency locked to the GPS signals mean frequency.

The GPS receiver can be controlled from the internal PC through a serial interface and provides an output reference signal every second, namely 1PPS(GPS), sent to the time interval counter of the control unit to compare it with a similar signal derived from the rubidium oscillator. The time interval counter (30 ps resolution single shot), provides every second the time difference between 1PPS(Rb), generated from the 10 MHz of the rubidium clock, and the 1PPS(GPS) signal from the receiver.

The control board, in addition to the divider generating the signal 1PPS(Rb), includes a high-resolution ($4 \cdot 10^{-14}$) Direct Digital Synthesizer (DDS) to implement the frequency corrections to the rubidium output signal, either fixed or variable with a defined rate, that produces an output signal, 10 MHz + $\Delta\nu(t)$, simulating an oscillator with frequency deviation (y) and frequency drift (d) suitable for the planned assessment. In principle $\Delta\nu(t)$ can be an arbitrary function or set of data. The card also allows to generate reference time signals, either pulses with programmable width and repetition period, in the field from 50 ns to 10^6 s (resolution 100 ps), or pairs of pulses (Start / Stop) whose time interval and repetition rate can be programmed in a similar way. Even if the nominal frequency of the device is ν_0 = 10 MHz, thanks to the use of a DDS, the sinusoidal output frequency value can be programmed in a range between 1 MHz and 20 MHz. Moreover, using the direct reference time signal output (square wave), it is possible to generate repetitive pulses with a period covering the range between $T = 0.1$ µs ($\nu = 10$ MHz) and $T = 10^6$ s ($\nu = 1$ µHz).

The telephone modem, controlled by the internal PC and connected to a normal telephone line, allows the reference laboratory to remotely plan the operation of the travelling standard adapting its working parameters to the metrological capabilities of the calibration centre and also to get all the measurement information stored inside the instrument. These will be used for the computation of the inter-laboratory comparison results.

The whole equipment is controlled simply by a mouse meanwhile the operational status is visible on a video screen (6.4'' display). At the instrument start-up, some internal configuration files are automatically loaded and used to control the whole process, following a chosen measurement program. Only a privileged user (Administrator) can access the whole control of the equipment using an external keyboard, or connecting via telephone modem and supplying an appropriate password.

III. CONSIDERATIONS ON HOW THE SYSTEM WORKS

When using the GPS signals to control the frequency of a rubidium oscillator, the approach is always to keep the good short-term stability of the latter (in our case up to 20 000 s) and the long-term stability of GPS (for times higher 20 000 s), choosing the most suitable time constant for the phase locking.

To investigate on this matters, some measurement were performed on the rubidium at the INRIM Time and Frequency Laboratory to evaluate its frequency instability in terms of MDEV (root mean square of the Modified Allan variance) [3], using a high resolution phase meter, versus a hydrogen maser reference standard. The results of this survey are presented in Fig. 2 (green line).

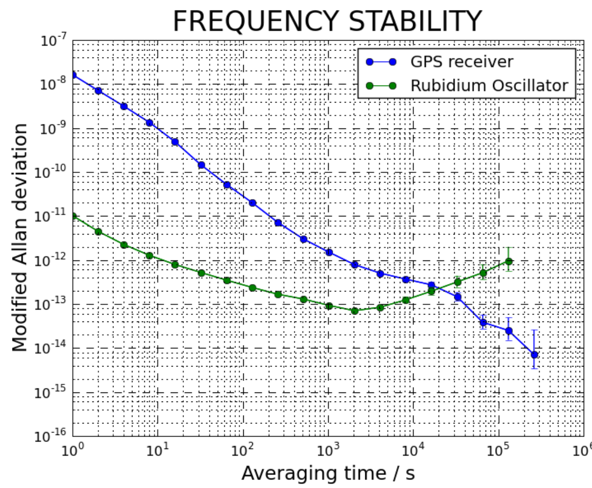

Figure 2. Instabilities of the rubidium and of the GPS signals

Similar instability measurements were carried out on the GPS receiver 1PPS(GPS) signal output versus the reference time scale UTC(IT), always generated by a hydrogen maser, using an electronic counter, and the results are reported in the same Fig. 2 (blue line).

As regards to the configuration of the GPS receiver, it was initially setup to determine the position of its receiving antenna, as suggested by the manufacturer, and the mean value of the position data computed from the measurements collected for about 6 hours, was then used as a reference, forcing the receiver to operate in the "Position Hold" mode, which ensures a better stability of the 1PPS output signal.

By analyzing the two experimental curves shown in Fig. 2, it was chosen the time constant to lock the rubidium oscillator. We set 10 000 s, a factor two less the optimum one, in order to privilege the long-term behaviour.

IV. Installing the travelling standard in a calibration laboratory

The TFTS system set up requires the GPS antenna to be installed in a position where the horizon is free from obstacles and connected to the receiver with the cable supplied. The steps described here below will then be automatically performed by the instrument.

Within 15 minutes after switched it on, the rubidium oscillator locks onto the atomic resonance line, provides the 10 MHz signal output and triggers on the “lock” indicator light. The thermal equilibrium of the rubidium oscillator and of the equipment itself is reached after about 2 hours. At this point, the TFTS control system starts the external thermal stabilization of the rubidium, measuring the temperature of its package, warming it to a temperature some degrees higher than the steady-state one and keeping it stable at 0,1 K level.

The GPS receiver, who has regularly tracked all the available satellites in the meantime and reached the thermal balance, automatically acquires for six hours the position fix. Afterwards, the internal PC computes the average position value and sends it as a reference to the GPS receiver, enabling it to operate in the "Position Hold" mode.

After about eight hours from the switch on, the phase locking algorithm of the rubidium oscillator to the GPS signals begins to operate. This algorithm uses, as error signal, the results of the phase measurements between the 1PPS(Rb) and the 1PPS(GPS) signals, and calculates the frequency correction to be applied to the rubidium. To smooth the process, the time constant of the PLL increases regularly until the selected final value is reached, to maintain the phase/time error next to zero. To complete the oscillator locking process, in order to reach the wanted performances, a time of about three time constants are needed.

About one day later, the system has completed the initialization cycle and has reached the operating conditions suitable to perform the frequency and time interval comparisons, according to the agreed ILC protocol.

The schedule for the different initialization phases above can also be changed, if necessary, by an authorised operator. The typical measurement programs suited to the periodical assessment of the calibration centres accredited, imply that the system is designed so as to emulate the characteristics of either a quartz or rubidium oscillator of known specifications, namely a device having a defined frequency deviation and drift. The accuracy of these features is guaranteed by the fact that the reference oscillator inside the TFTS is phase locked to the GPS signal and, with the current rubidium, has an uncertainty below 10^{-11} for 1 s < τ < 10 s, below 10^{-12} for 10 s < τ < 100 000 s and below 10^{-13} for τ > 100 000 s.

Starting from these characteristics an authorized operator, via a predefined configuration file or by sending appropriate commands even in remote mode via a telephone modem connected to the TFTS, can program the internal synthesizer to generate arbitrary frequency deviation and drift, typically scheduled in the range from 10^{-7} to 10^{-12} for the frequency deviation, and from 10^{-7} /d to 10^{-12} /d for the daily drift. In the same way the time reference pulses, with programmable width, repetition rate and time interval can be set. Since these configurations are directly controlled by the reference laboratory, or by an authorized operator, the measurement parameters are known only to the controller, avoiding that prior knowledge of the expected values can affect the assessment results.

By means of a remote connection, one can also monitor the system downloading the “sensitive” data on the TFTS performance, in particular the time differences 1PPS(GPS) - 1PPS(Rb) between the reference GPS and the rubidium clock, that will be used for the remote traceability of the travelling standard by comparison with similar data collected from the reference laboratory.

V. Evaluation of the TFTS performances

The experimental prototype of the TFTS (see Fig. 3), has reached a consolidated hardware and firmware configuration. Concerning the software of the internal PC, written in Microsoft C#, it is in a “beta testing” evaluation phase, implementing all the main features suitable to perform the full experimental tests.

Figure 3. Picture of the TFTS prototype

Fig. 4 reports a screenshot of the TFTS, showing the information available to a “normal” operator (not an Administrator).

Some preliminary assessments on the characteristics of the generated signals were carried out and the results are presented in the followings. A first test was made to evaluate the temperature stability at which the rubidium container is maintained, obtaining, in different conditions, values within a range of few tenth of a degree.

The following test consisted in analyzing the 10 MHz output of the TFTS versus the national time and frequency standard UTC(IT), using a high resolution phase comparator after the warm-up procedure described above, the frequency instability of this signal in term of MDEV, with the system configured with no frequency offset and drift, is reported in Fig. 5. During this test, the time constant of the PLL was of 10 000 s and the position of the receiving antenna was that evaluated by the receiver during the preliminary automatic survey.

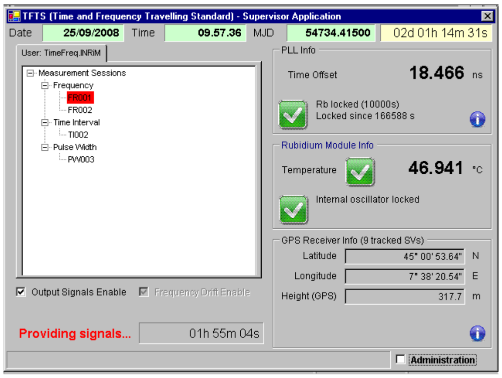

Figure 4. Image of the of TFTS screen

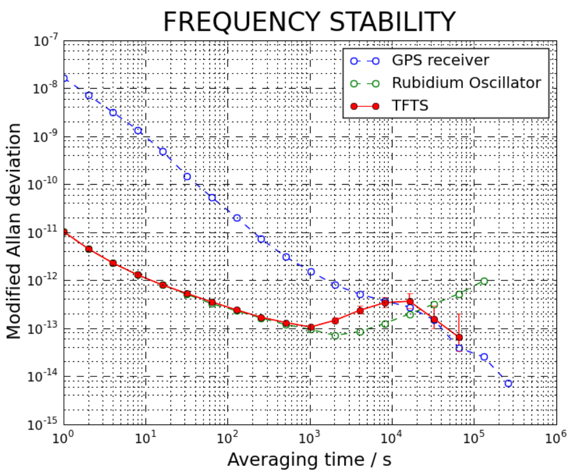

Figure 5. Instability plot of TFTS (February 2009)

Looking at the graphs in Fig. 5, it can be observed that the long-term behaviour (τ>1000 s) is as expected, showing an instability "bump" corresponding to the locking time constant of the rubidium. Besides, on the same graph, the shaded area represents the typical accreditation levels for the calibration laboratories in the frequency field, using electronic counters and the direct frequency measurements technique.

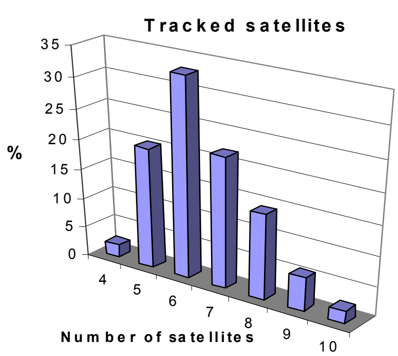

Figure 6. Histogram of the received satellites

Fig. 6 shows an histogram representing the distribution of the number of the tracked satellites used for the disciplining process during these measurements. This number varied between 4 and 10 showing a maximum probability at 6.

Some additional tests on the 10 MHz signal generated by the TFTS were performed. One of these concerned the application of known frequency deviations and drifts, analyzing the output signal versus UTC(IT).

Table 1 reports the results of these investigations. Every measurement, using UTC(IT) as a reference for the phase meter. In the table, y_0 and d_0 represents the nominal frequency deviation and daily frequency drift applied to the TFTS, y and d the mean measured values, while Δy and Δd are the errors between the measured and the nominal value.

TABLE I. RESULTS ON FREQUENCY MEASUREMENTS

Measurement time [s]	282 530	200 000	235 251
y_0	0	$1\cdot10^{-12}$	$1\cdot10^{-10}$
y	$(0.3\pm0.5)\cdot10^{-13}$	$(10.2\pm1.0)\cdot10^{-13}$	$(999.4\pm1.1)\cdot10^{-13}$
$\Delta y = y - y_0$	$(0.3\pm0.5)\cdot10^{-13}$	$(0.2\pm1.0)\cdot10^{-13}$	$(-0.6\pm1.1)\cdot10^{-13}$
d_0 [/d]	$5\cdot10^{-13}$	$5\cdot10^{-12}$	$5\cdot10^{-10}$
d [/d]	$(4.8\pm0.3)\cdot10^{-13}$	$(49.6\pm0.7)\cdot10^{-13}$	$(4998.9\pm1.4)\cdot10^{-13}$
$\Delta d = d - d_0$ [/d]	$(-0.2\pm0.3)\cdot10^{-13}$	$(-0.4\pm0.7)\cdot10^{-13}$	$(-1.1\pm1.4)\cdot10^{-13}$

Concerning the pulse and time interval generation facility, some tests were performed to evaluate the stability and the uncertainty of different time and time interval values generated in the range between 100 ns and 100 s.

Fig. 7 reports the results of this investigation when the TFTS is generating time intervals between A and B output channels. On the x-axis is given the nominal time interval T_0 requested to the TFTS, while the y-axis reports the measured time error T-T_0 and jitter. In this case the error is less then 200 ps while the jitter is less then 300ps.

The same has been done for the pulse width generation and the results are reported in Fig. 8. In this case the jitter is comparable, while the error is a little higher.

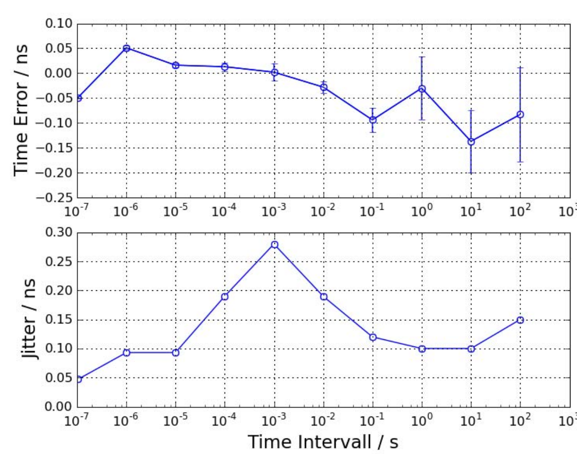

Figure 7. Results on time interval measurements

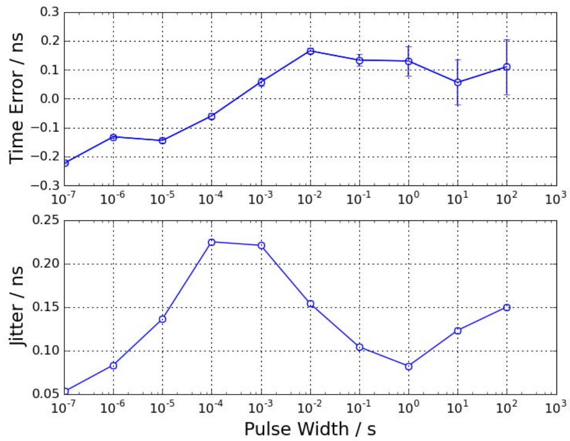

Figure 8. Results on pulse width measurements

VI. FUTURE ACTIVITIES

To complete the assessment of the TFTS performances, the following work program is in progress at INRIM:

- temperature dependency of the time interval and pulse width generation;
- verification of the remote operability of the TFTS by installing the instrument in SIT calibration centres;
- organization of a first ILC for frequency and time within a significant number of Italian calibration laboratories, selected in a way that takes into account their geographical distribution and the diverse CMC levels.

The last two points are planned to take place in the second half of 2009 and will serve to qualify the instrument also in view of its use in international inter-laboratory comparisons eventually promoted by EA.

VII. CONCLUSIONS

A prototype of a travelling standard for inter-laboratory comparisons in the frequency and time field was designed and realized at the INRIM Time and Frequency Laboratory. The characterizations of the prototype main features performed to date showed the validity of the approach followed and its suitability to assess the CMCs in the time and frequency fields of most accredited calibration laboratories in Europe.

The activity will continue in 2009 with the aim to test the instrument in the field by organizing a first national inter-laboratory comparison among a selected number of accredited laboratories to verify the reliability of the instrument and the reproducibility of its performances in the remote use.

If the results will be positive, the exercise could be extended to the assessment of others calibration laboratories accredited in Europe.

REFERENCES

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[3] International Telecommunication Union – Radiocommunications: Recommendation ITU-R TF.583-3, "Measures for random instabilities in frequency and time (phase)". ITU-R recommendations – TF Series, 1997.