Development Of A Ku Band Satellite Simulator For TWSTFT Applications

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***Abstract*— LNE-SYRTE has developed a satellite simulator for the monitoring of the delay difference of its earth station used for the two-way satellite time and frequency transfer (TWSTFT) applications. Such a device is more and more recommended by the CCTF working group on TWSTFT in order to better evaluate the time transfer uncertainty component related to the variation of the earth station delay difference between two calibration campaigns with a portable station. Besides few simulators commercially available based on the VSL design [1], our laboratory has realized a new calibration device with at least two different concepts from those currently in use: a faster delay calibration process and a characterization of its internal delays using a microwave vector network analyzer (MVNA).**

The key component of this simulator is the use of a double-balanced microwave mixer and its characterization in terms of absolute delay requiring a specific measurement system such as an MVNA allowing a vector mixer calibration technique using a characterized mixer/filter as a through standard. The measurements done with the MVNA completed by those giving with the SATRE modem during calibration sessions, involving the earth station -which is driven by UTC(OP)- and the satellite simulator, are described in this paper.

Moreover, the study of the time stability of the whole system including the earth station and the simulator shows a time deviation below 20 ps at 1 s, giving an excellent measurement noise. For the long term, a time deviation below 50 ps is reached between 0,3 d and 3 d averaging time [2]. The next step is the implementation of the simulator into measurement regular sessions permitting the computation and the monitoring of the earth station differential delay as well as the study of the time stability over one year period.

I. Introduction

The TWSTFT technique is used to compare atomic clocks located at different metrology institutes in the world (Europe, United States and the Asia Pacific region) contributing to the TAI computation calculated by the BIPM, which is the international time reference for all the scientific community. The clock signals of two remote earth stations, located at geographic places 1 and 2 (Fig. 1), are simultaneously transmitted through the geostationary satellite used for the comparison, and then received by stations at both sides. Each station measures, with a Time Interval Counter (TIC), the delay between the one pulse per second (1pps) transmitted signal and the 1 pps received signal, noted ΔT_1 for station 1 and ΔT_2 for station 2.

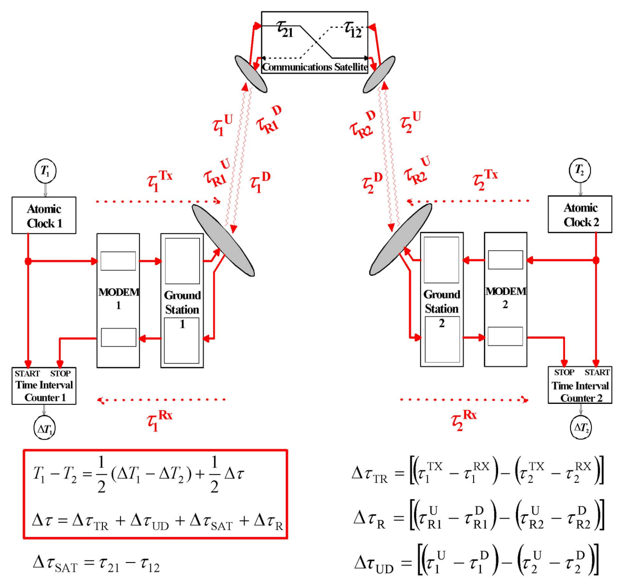

Figure 1. Principle of the TWSTFT technique

The time difference $T_1 - T_2$ between the two atomic clocks is given by (1) [3]:

$$T_1 - T_2 = \frac{1}{2}(\Delta T_1 - \Delta T_2) + \frac{1}{2}\Delta\tau \qquad (1)$$

Where:

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$$\Delta\tau = \Delta\tau_{TR} + \Delta\tau_{UD} + \Delta\tau_{SAT} + \Delta\tau_{R} \quad (2)$$

The TWSTFT technique eliminates the first-order effects due to path reciprocity of signals. The $\Delta\tau$ parameter represents non reciprocal residual effects to be determined. It includes the delay differences due: i) to the propagation in the atmosphere for up and down links ($\Delta\tau_{UD}$); ii) to the transponder path in the geostationary satellite ($\Delta\tau_{SAT}$); iii) to the earth rotation (Sagnac effect: $\Delta\tau_{R}$ parameter); iv) and inside each earth station including transmission and reception paths ($\Delta\tau_{TR}$). The last parameter seems to be the most important source of error which is developed in (3):

$$\Delta\tau_{TR} = \left[\left(\tau_1^{TX} - \tau_1^{RX}\right) - \left(\tau_2^{TX} - \tau_2^{RX}\right)\right] \quad (3)$$

Therefore, this delay difference is to be determined for an earth station, as $\tau_1^{TX} - \tau_1^{RX}$ for station 1 and so on… Some calibration methods already exist. Two main calibration techniques are strongly recommended: using a portable station and a satellite simulator respectively, in relative and absolute mode calibration. The latter is considered in this paper.

II. Design of The Satellite Simulator

The goal of LNE-SYRTE is to develop a rigorous calibration method in absolute mode, which takes into account all the delays inside both station and satellite simulator. In particular, LNE-SYRTE has developed an original calibration method using the satellite simulator technique and coupled with a precise measurement procedure. The configuration of this new method is given in Fig. 2:

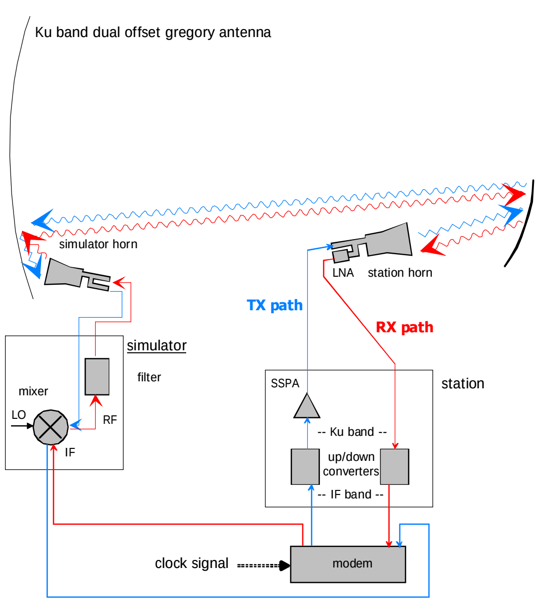

Figure 2. Design of the two-way satellite simulator of LNE-SYRTE

The earth station includes both indoor (modem and external TIC installed in a temperature controlled room) and outdoor (up and down converters, dual offset antenna) equipments. The satellite simulator is designed for outdoor use and, a part of it is placed in a temperature regulated box, having a temperature of (25 ± 5) °C and less than 50 % relative humidity (Fig. 3). It contains a microwave local oscillator driven by an active hydrogen maser, a double-balanced microwave mixer, two RF and IF filters, four electromechanical switches, a conical R120 waveguide horn with linear cross polarization, two flexible waveguides, two coaxial to waveguide adaptors, coaxial cables and connectors.

Figure 3. View of the two-way station and satellite simulator of LNE-SYRTE (Observatoire de Paris)

III. Principle of Measurement

The measurement of the delay difference between transmission and reception paths inside the TWSTFT station relies on two successive measurements:

The first measurement setup illustrated in Fig. 4 (bold path) is used to measure the whole delay in transmission mode, $\delta t_1 = \tau_1^{TX} + Cal_1$, where:

$$\tau_1^{TX} = d_{modemTX} + d_{int1} + d_{c4} + d_{up} + d_{c2} + d_{sourceTX} \quad (4)$$

τ_1^{TX} represents the delay of the transmission path inside the earth station, including the internal transmission delay of the modem, and:

$$Cal_1 = d_{t1} + d_{corRX} + d_{g1} + d_{a1} + d_{c5} + d_{int4} + d_{mix1} + d_{int3} + d_{f2} + d_{int2} + d_{modemRX} \quad (5)$$

Cal_1 represents the extra transmission path including the satellite simulator and the internal reception delay of the modem.

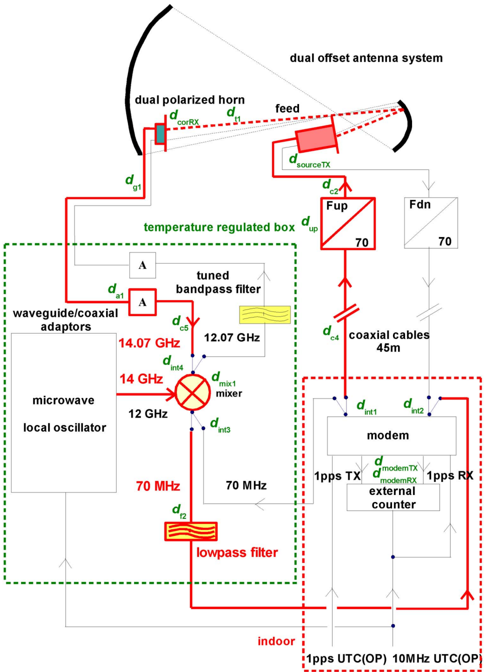

Figure 4. Diagram of the global transmission path delay $\tau_1^{TX} + Cal_1$ in measurement

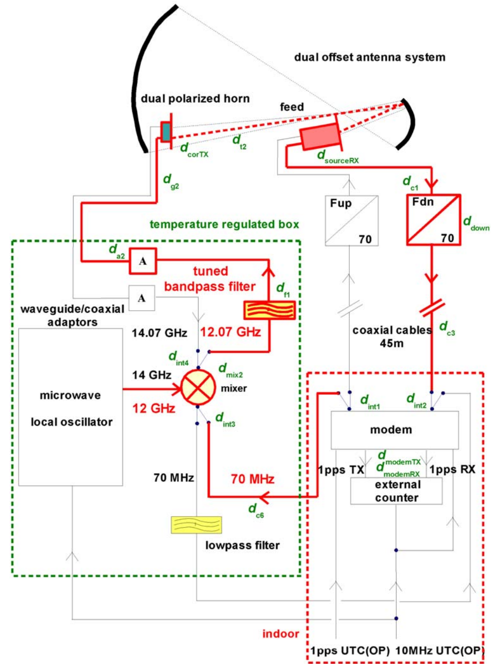

Figure 5. Diagram of the global reception path delay τ_1^{RX} + Cal_2 in measurement

The second measurement setup illustrated in Fig. 5 (bold path) is used to measure the whole delay in reception mode, $\delta t_2 = \tau_1^{RX} + Cal_2$, where:

$$\tau_1^{RX} = d_{sourceRX} + d_{c1} + d_{down} + d_{c3} + d_{int2} + d_{modemRX} \quad (6)$$

τ_1^{RX} represents the delay of the reception path inside the earth station, including the internal reception delay of the modem, and:

$$Cal_2 = d_{modemTX} + d_{int1} + d_{c6} + d_{int3} + d_{mix2} + d_{int4} + d_{f1} + d_{a2} + d_{g2} + d_{corTX} + d_{t2} \quad (7)$$

Cal_2 represents the extra reception path including the satellite simulator and the internal transmission delay of the modem.

Then, by difference calculation between these two measurements, we obtain the required delay $\tau_1^{TX} - \tau_1^{RX} = \delta t_1 - \delta t_2 - (Cal_1 - Cal_2)$. The parameters Cal_1 and Cal_2 are to be determined precisely by measuring the time delay components forming the satellite simulator using a TIC and an MVNA.

IV. TIME STABILITY OF THE SYSTEM

Time stability of the whole system including two-way station and satellite simulator has been studied at first. Time delay was measured over a period of 20 days, with respect to twelve measurement sessions per day (every two hours) recording 2x120 measurement points (1s data) during a session. It was observed that the fluctuations in time for TX and RX paths do not exceed 1,3 ns over the whole measurement period, while the received power at the modem were less than 1,1 dB and 1,9 dB, respectively [2].

The time stability calculated from these measurements is plotted in Fig. 6.

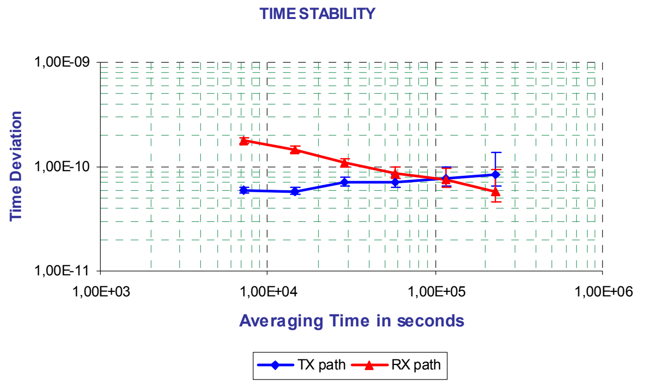

Figure 6. Time stability of the system on the TX and RX paths

The results shown that the TX path is characterized by a Flicker Phase Modulation noise (τ^0 slope) with a level stills below 90 ps for averaging times from $\tau = 2$ h to $\tau \approx 3$ d, and the RX path is characterized by a White Phase Modulation noise ($\tau^{-1/2}$ slope) attaining 60 ps noise level at 3 d averaging time.

Moreover, from these data, it is easy to determine the time stability of the delay difference 0,5.(TX–RX), as it is shown in Fig. 7.

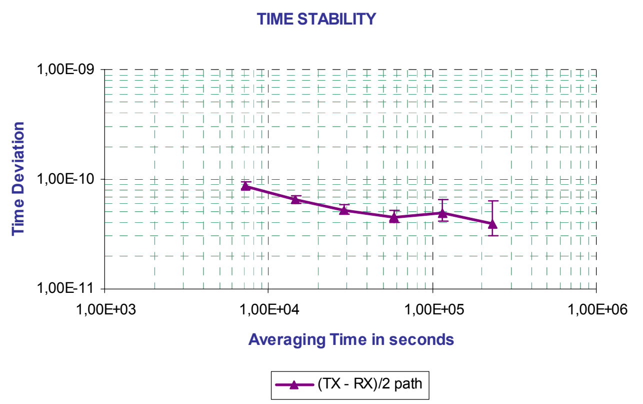

Figure 7. Time stability of the system's delay difference

A time deviation below 50 ps is achieved between 0,3 d and 3 d averaging time, which is a very promising result in comparison with other few existing systems.

Now, in order to determine the lowest noise level which can be reached with our two-way satellite simulator system, additional experiments have been done showing that more effort can be realized on the RX delay in optimizing the position of the simulator horn, as can be seen from measurements plotted in Fig. 8.

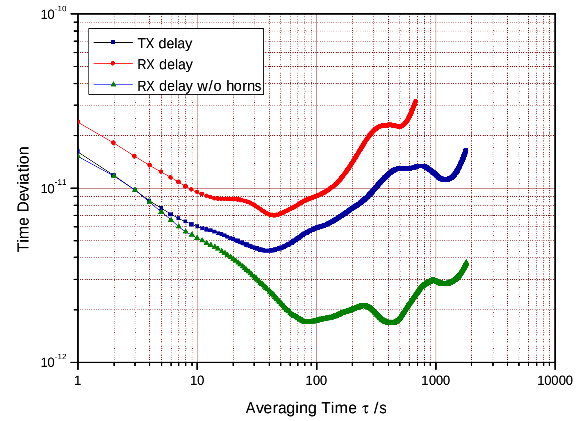

Figure 8. Time stability of the system TX and RX path delays, with and without horns

In this study, the measurements of the system are done, with and without horns, in order to evaluate the impact of the microwave radiated propagation in terms of measurement noise. From Fig. 8, it is clearly shown, that this impact is canceled for the TX path while it is 20 ps higher for the RX path. The time stability of the whole system including the earth station and the simulator achieved a time deviation below 20 ps at 1 s, giving an excellent measurement noise on our two-way station.

V. Use of a Microwave Vector Network Analyzer

The design of LNE-SYRTE two-way satellite simulator requires the knowledge of its internal delays. This can be achieved using a high accuracy performance method provided by a microwave vector network analyzer.

The relationship of the two-way station's delay difference and the satellite simulator's internal delays is given (see §-III):

$$\tau_1^{TX} - \tau_1^{RX} = \delta t_1 - \delta t_2 - (Cal_1 - Cal_2) \qquad (8)$$

After some calculations, the parameter $Cal = Cal_1 - Cal_2$ can be expressed as:

$$Cal = [d_{modem,\,Rx} - d_{modem,\,Tx}] + Cal_0 \qquad (9)$$

Where Cal_0 is determined using the MVNA. It includes the internal delays of the satellite simulator and the path delay in between the two horns.

A. Characterization of the satellite simulator's linear components

The MVNA model Agilent 8510C has been used (Fig. 9). Two calibration methods were applied [4] according to the different frequency bands operated in the two-way station:

- The TRL (Thru Reflect Line) method applied in the frequency band 10 – 15 GHz, using a precision calibration kit with 3,5 mm precision connectors;

- the SOLT (Short Open Load Thru) method applied in the frequency band 50 – 90 MHz, using a standard calibration kit with 3,5 mm precision connectors;

In addition, precision adaptors (N – 3,5 mm) and cables have been used.

Figure 9. The MVNA of LNE used for the characterization of the satellite simulator's linear components

The characterization concerned the different elements constituting the satellite simulator (coaxial cables, switches, adaptors, waveguides, satellite simulator waveguide horn, attenuators and filters), based on scattering parameter measurements, using both reflection (1-port) and transmission (2-port) configuration modes (Fig. 10).

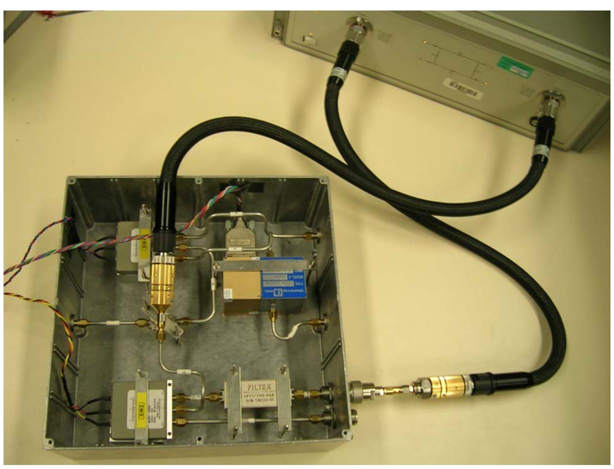

Figure 10. S-parameter measurements of the satellite simulator using an MVNA

Depending on the configuration of each ensemble within the system, the delay measurements have been done at three convenient frequencies: 70 MHz, 12,518200 GHz and 14,013200 GHz. The relating results obtained are illustrated in section C below.

B. Absolute delay of the microwave mixer

Usually, the MVNA is currently used to characterize linear components with frequency. When non linear components are requested (e.g. mixer in the satellite simulator), a completely different concept of measurement is necessary to use since a change of frequency is required, between input and output of the device under test.

With the support of Agilent Technologies France, a new process was applied that provides a vector corrected measurement solution for measuring the satellite simulator mixer, where LO/RF frequency must be swept. This measurement technique uses standard network analysis instrumentation with frequency offset capability and can be fully vector corrected using the vector mixer characterization method [5].

The measurement results of the satellite simulator mixer (Miteq DM0416LW2) in terms of absolute delays are given in Fig. 11 and Fig. 12:

Figure 11. Delay measurement of mixer when the signal is down-converted: a value of 1,2 ns is found

Figure 12. Delay measurement of mixer when the signal is up-converted: a value of 0,5 ns is found

From these results, it's clearly shown that accuracy of a few hundred picoseconds can be easily achieved. The corresponding results are reported in section C below.

C. Absolute delay difference of the LNE-SYRTE station

The satellite simulator has been tested with the OP01 station, over a period of twenty days, during odd hours, outside the BIPM TWSTFT schedule. Measurements were done, on a basis of twelve times per day, with 2x120 measurement data (1 s data) per time, using the code 0 of the SATRE modem at 2,5 MChips/s. The carrier to noise ratio C/N_0 received by the station, when transmitting through the station or through the simulator, was 68 dBHz.

Table I reported the delay budget of the whole parameters required:

- Parameter No. 1 determined by the SATRE modem;
- Parameter No. 2 to 9 determined from measurements done with the MVNA;
- Parameter No. 10 assumed that paths are reciprocal;
- Parameter No. 11 to 12 calculated;
- Parameter No. 13 measured by the internal TIC of the modem;
- Parameter No. 14 to 18 calculated.

Table I. Delay budget of the TWSTFT station and satellite simulator

Prameter No.	Delay budget parameter	Delay difference /ns
1	$d_{modem,Rx} - d_{modem,Tx}$	14 062,9
2	$d_{int2} - d_{int1}$ (70 MHz)	0,0
3	$d_{int3} - d_{int3}$ (70 MHz)	0,0
4	$d_{int4} - d_{int4}$ (Ku band)	0,0
5	$d_{f2} - d_{f1}$ (IF - Ku band)	241,9
6	$d_{mix1} - d_{mix2}$ (Ku/IF - IF/Ku)	0,7
7	$d_{c5} - d_{c6}$ (Ku band - IF)	-237,3
8	$(d_{a1}+d_{g1}) - (d_{a2}+d_{g2})$ (Ku band)	-0,8
9	$d_{cor,Rx} - d_{cor,Tx}$ (Ku band)	-9,2
10	$d_{t1} - d_{t2}$ (Ku band)	0,0
11	$Cal_1 - Cal_2$ (without modem)	-4,7
12	$Cal_1 - Cal_2$ (with modem)	14 058,2
13	$dt_1 - dt_2$ (from [2])	24,0
14 ⇨	$t_1^{Tx} - t_1^{Rx}$ (OP01)	-14 034,2
15	*CALR(OP01) from TUG calibration report 2005*	*-14 014,2*
16 ⇨	$t_2^{Tx} - t_2^{Rx}$ *(TUG portable station)*	*20,0*
17	*CALR(OP - VSL) from TUG calibration report 2005*	*-14 036,2*
18 ⇨	$t_2^{Tx} - t_2^{Rx}$ *(VSL01)*	*-2,0*

From the delay budget, the absolute delay difference of OP01 station is obtained as -14034,20 ns. By taking into account the results of the last calibration campaign results [6], one can deduce the absolute delay difference of either the portable station of TUG or other calibrated links/stations (e.g. VSL01 station, etc …) as reported in Table 1. The related results need to be validated by TUG and VSL with their satellite simulator system.

VI. CONCLUSION

A satellite simulator has been developed and implemented into the LNE-SYRTE earth station. It will be used for the two-way satellite time and frequency transfer applications (absolute delay difference calibration and monitoring). The first measurements obtained for the determination of the station delay difference are very promising and accuracy measurements at a level of few hundred picoseconds can be reached.

This work will be continued with the followings tasks:

- Optimization of the position of the simulator's horn;
- Implementation of the simulator into two-way regular sessions permitting the computation and the monitoring of the earth station's delay difference;
- Study of time stability at long term (ideally for a period covering two successive calibration campaigns with a portable station).

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