High performance of DMTD system used in a composite clock.

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1 Abstract

We present the DMTD (Dual Mixer Time Difference) results with its ZCDs (Zerro Crossing Detectors) use in the composite clock. This composite clock is based on servoing a VCO by both a cesium beam clock and a hydrogen maser. We obtain an output signal which combines the long term stability of the cesium clock, the middle term stability of the H maser and the short term stability of the VCO. The DMTD system contribution at 100 MHz to the frequency instabilities is expected to be around $10^{-15}@1s$*. This paper describes the DMTD system used to obtain the information necessary for the oscillator control.*

2 Introduction

The system of the composite clock is based on the DMTD principle (Dual Mixer Time Difference) [1, 2]. We realize three comparisons, for comparing each standard clock with the same shifted oscillator. We obtain three signals which inform us on the stability and the frequency deviation of each clock. Then, thanks to the FPGA, we measure the period of the signals coming from the DMTD in order to realize the digital processing. Finally a digital to analog converter allows the correction of the VCO. Figure 1 presents the whole system. The whole system works at 100 MHz which imposes the presence of many frequency multipliers. Only the H-maser clock provides a 100 MHz output frequency, the CS clock output frequency is 10 MHz and the VCO output frequency is 5 MHz.

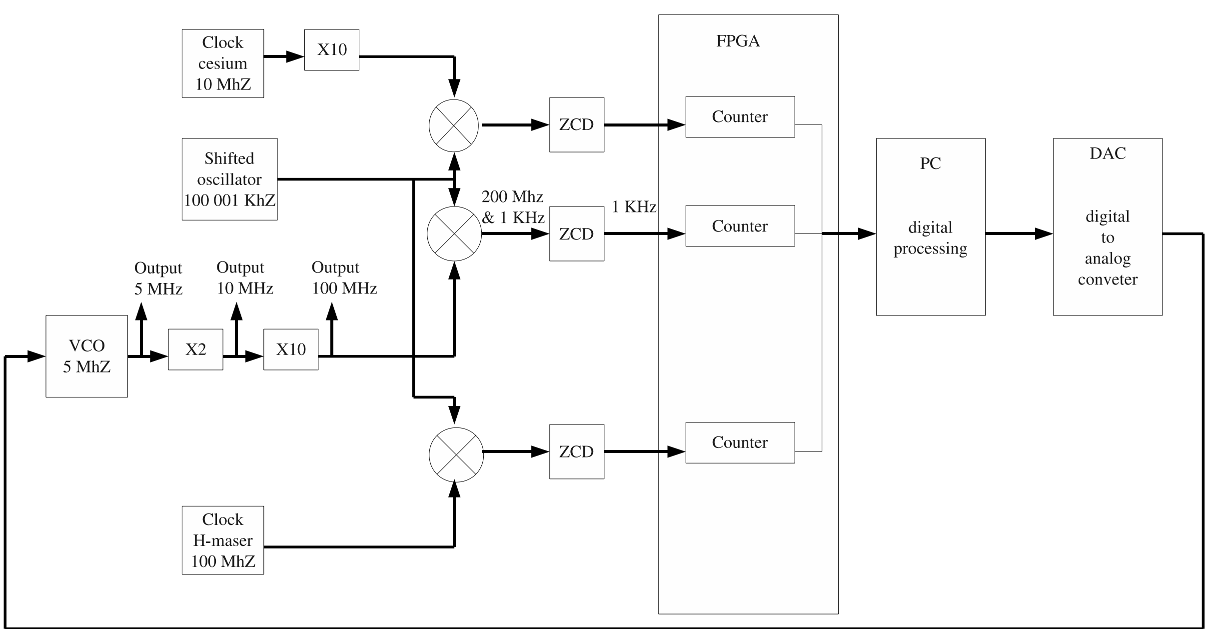

Figure 1: General diagram

We wish to have three outputs, one at 5 MHz, one at 10 MHz and another one at 100 MHz. The shifted oscillator frequency is 100 001 kHz in order to obtain a mixer output signal which is composed of a beat frequency at 1 kHz.

3 The hardware

3.1 Dual Mixer Time Difference (DMTD)

3.1.1 Principle

The DMTD [3] consists of comparing 2 clocks at the same oscillator in order to know frequency deviation of these clock. In most of the system the DMTD is used to compare an oscillator which is the reference to another oscillator to measure the frequency deviation of this oscillator. In our case it's different; we use a DMTD system to make a clock and not a measurement system, moreover in this system we make 3 comparisons and not 2 like in a mesurement system. Each mixer receives 2 signals: one at 100.001 MHz, which comes from the shifted oscillator, and another one at 100 MHz which comes from one of the standard clocks. we obtain in the mixer output the following signal:

$$V_M(t) = V_1 cos(\omega_1 t + \phi(t)) \times V_2 cos(\omega_1 t + \Delta_\omega) \quad (1)$$

where $\omega_1 = 2\pi f_1$ with $f_1 = 100MHz$, and $\Delta_\omega = 2\pi f_b$ with $f_b = 1kHz$. We obtain:

$$V_M(t) = \frac{V_1 V_2}{2} \times$$

$$[cos(2\omega_1 t + \Delta_\omega t + \phi(t)) + cos(\Delta_\omega t + \phi(t))] \quad (2)$$

We note that this signal is composed of two components: the frequency sum at 200 MHz and the frequency difference at 1 kHz. Each of three signals informs us about the frequency deviation of each clock because they were compared to the same oscillator.
To make the three comparisons, we use a second oscillator: the shifted oscillator. Two reasons impose this choice, firstly in a DMTD we must have a shifted oscillator to generate a beat frequency, so if we do not use a shifted oscillator, we must shift the VCO, and the 3 output signals become 5.00005MHz, 10.0001MHz and 100.001MHz. Secondly the noise of the cesium clock is much higher than the VCO noise and we can not obtain any information concerning the short term. With the cesium comparison we obtain an information only for the long term.

3.1.2 The ZCD

Then each signal, which comes from the mixers, is sent to a Zero Crossing Detector [4]. Each ZCD has 2 roles. Firstly the ZCDs eliminate the component in $2\omega_0$ with the first stage of the ZCD: the low pass filter (fig. 2). Secondly the ZCDs transform the sine signal of 1 kHz into a square signal of 1 kHz with a very sharp rising edge, and a minimum noise. We must increase the sharpness of rising edges and keep the noise as low as possible. In fact, we must find the best compromise between the highest gain and the lowest noise possible. We use four stages to increase the slope of the signal. The four stages after the first one are composed of a high gain and a low pass filter for the first two amplifier stages. To generate the lowest noise possible, it is advised to respect the following conditions:

$$B_i < B_1 \Pi_{n=1}^{i-1} G_n^2 \quad (3)$$

$$G_i < \frac{2\pi B_i V_{max}}{S \Pi_{n=1}^{i-1} G_n} \quad (4)$$

where B_i is the filter bandwidth, G_n the filter gain (dimensionless), V_{max} the maximum output voltage (V), S is the slope of the input signal (V/s). The noise spectrum density equivalent N_{eq} to four amplication stages is :

$$N_{eq} = KT \times F_{eq} \quad (5)$$

with

$$F_{eq} = (F_1 + \frac{(F_2 - 1)}{G_1^2} + \frac{(F_3 - 1)}{G_1^2 \times G_2^2} + \frac{(F_4 - 1)}{G_1^2 \times G_2^2 \times G_3^2}) \quad (6)$$

where K is the Boltzmann constant, T the temperature in Kelvin, F the noise factor, G^2 the power gain. With the last formula we note that the noise mainly depends on the first amplifier stage. That is why we apply the conditions only to the first 2 amplifier stages. We must decrease the bandwidth of the first 2 amplifier stages but we must be sure that this filter do not alter the signal phase.

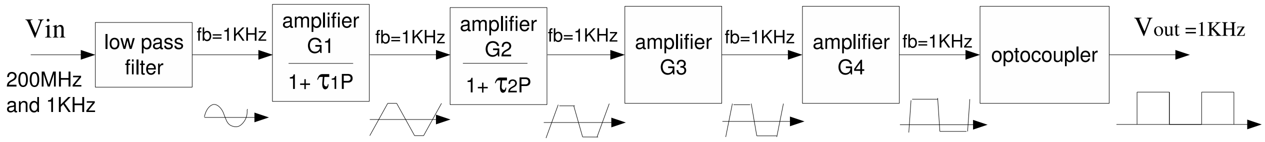

Figure 2: ZCD diagram.

3.1.3 Test

To test the ZCD, we perform 2 tests. In the first one we generate a beat frequency, we split it and send it into two ZCDs and we measure the time difference between the rising edge of these two ZCDs. The time difference between the two ZCDs is not important but the time stability and the jitter are significant.

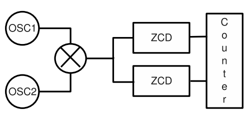

Figure 3: diagram of test 1

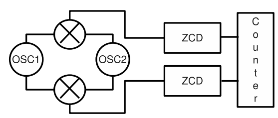

Figure 4: diagram of test 2

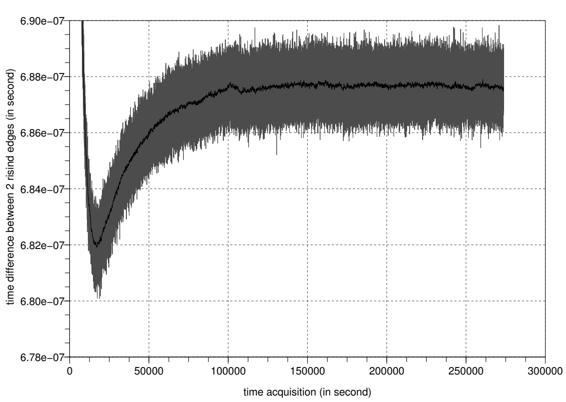

Figure 5: result of test 1.

With the first test (fig. 5 grey curve) after about 3 days of measurement we note that the ZCDs needs a heating time of about 1 day. It is due to polystyrene which covers the ZCDs. The measured jitter is about 3.5 ns peak to peak, with a standard deviation $\sigma = 5.5 \times 10^{-10} s$. We will explain later how to improve the obtained result with the appropriate processing.

Next we perform the second test (fig. 4), we replace the beat frequency by 2 beat frequencies which are identical because they are made by the same oscillators. We observe the result on figure 6.

We can see many variations with a period of 9 minutes. In fact, we observe the air conditioning variations. It is the ZCDs that are sensitive to the temperature variations [5]. We must do other tests but we tend to think that these variations come from either the power supply variations or the phase variation due to the filter of the first 2 amplifier stages.

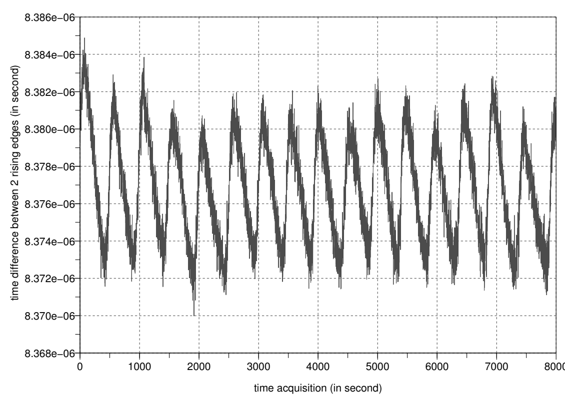

Figure 6: result of test 2.

The temperature variations are not visible in the first test result but they have an effect. When we trace the modified Allan deviation of the first test result we note that this signal is composed of 2 noises (fig. 7): the white phase noise and the Flicker phase noise. The cut off frequency between these 2 noises is about 600 s, and 600 s is the period of the air-conditioning. However we must establish the relationship between the Filcker noise and the temperature sensitivity to verify that the Flicker noise is due to the temperature variations.

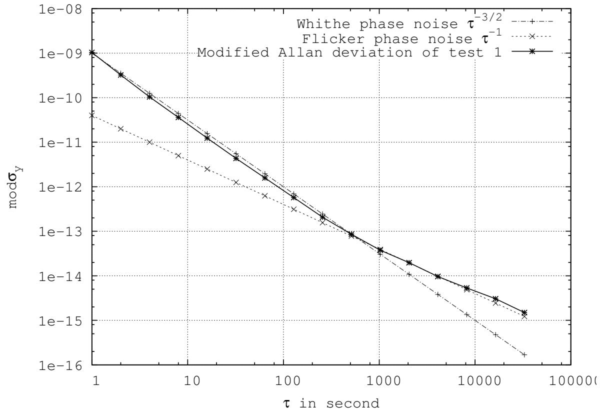

Figure 7: modified Allan deviation of test 1.

4 Software

4.1 Principle

It is more difficult to satisfy the limit conditions (equations (3) and (4)) using a DMTD with a beat frequency of 1KHz than with 1Hz. But we can correct the VCO more often and keep the same performances with the appropriate processing. We have chosen to use the triangular averaging as estimator in order to improve the ZCDs results.

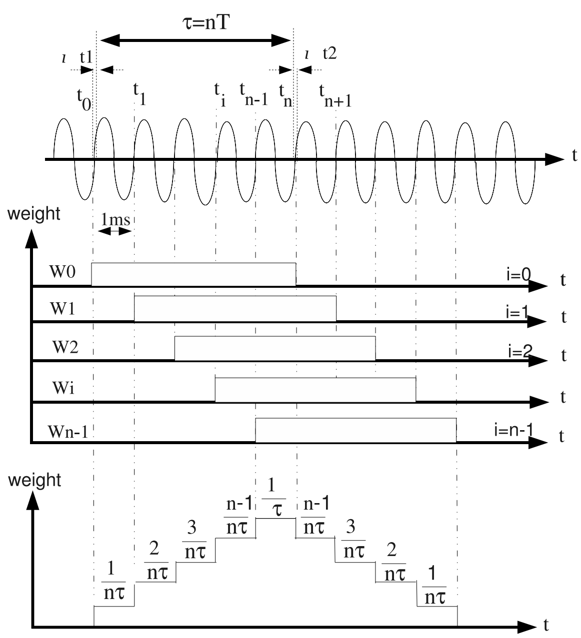

Figure 8: making of triangular averaging estimator.

We measure the beat frequencies with a 1 second gate and we shift this gate of 1ms every 1 ms during 1second, thus we generate 1000 gates of 1 second, i.e. 1000 averages . Then we sum these averages in order to obtain the triangular averaging function figure 8. By realizing a measure with a triangular averaging estimator we can decrease the white phase noise effect. The modified Allan deviation algorithm is related to the triangular averaging function [6].

4.2 Relationship between modified Allan function and triangular averaging function

Now we will explain the relationship between the modified Allan deviation and the triangular averaging. Figure 9 shows the weight function of the 2 triangular averaging functions.

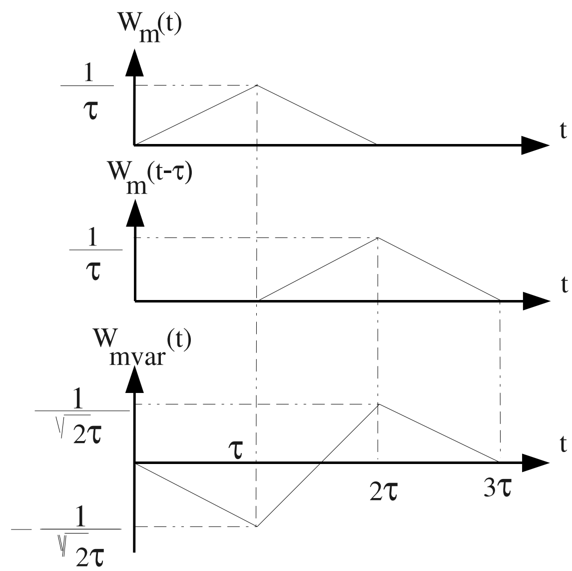

Figure 9: modified Allan function from 2 triangular averaging functions.

W_m represents the triangular average and W_{mvar} the modified Allan deviation. In fact if we have two triangular averaging functions shifted of τ and if we realize the subtraction between the 2: $-W_m(t) + W_m(t-\tau)$, we observe that we obtain the same function as the time sequence of the modified Allan deviation. With 2 triangular averaging functions we do a modified Allan deviation, only the coefficient of weight is different of a factor $\sqrt{2}$. This principle is used in some counters [7]. It yields a $\tau^{-3/2}$ behaviour for the white phase noise and then decreases much more quickly than with the classical Allan variance (τ^{-1} behaviour) without eliminating the phase jumps or the frequency jumps.

4.3 Processing results

When we apply the triangular averaging estimator on the result of test 1 (grey curve fig. 5), we obtain the black curve on figure 5. After the heating time we obtain a $\sigma = 6 \times 10^{-11}$. With a moving average estimator we have a $\sigma = 6.8 \times 10^{-11}$, the difference between these 2 estimators is little because we had noted that the signal is composed of 2 noises. If the signal were composed only of white phase noise, the difference would be higher and the σ of the black curve better. However in this condition (test 1) we can obtain mod $\sigma_y(1s) = 6 \times 10^{-11}$ @ 1KHz So we can obtain:

$$\text{mod}\,\sigma_y(1s) = 6 \times 10^{-16} \text{@100 MHz}$$

5 Conclusion

Even if we must do again many tests we notice that the obtained results are encouraging.

The obtained results on the short term are sufficient to use the ZCDs. We can obtain mod$\sigma_y(1s)$ lower than 1×10^{-15} but we must fix the problem concerning the temperature sensitivity. In fact we can not use the ZCDs in this project if we not decrease or not eliminate the temperature sensitivity of the ZCDs. We must do other tests in order to locate the source of this variations. However we think that they come from either the power supply variations or the phase varitions of first 2 amplifier stages in ZCDs, which have a low passs filter. In the case of power supply variations we could use voltage references to eliminate the variations. But if the sensitivity comes from the phase variation it is more complex. We will have to increase the bandwidth in order to move the signal frequency (1 KHz) away from the cut of frequency of the low pass filter, but we will increase the noise. However even if we increase the noise, the ZCDs noise are sufficiently low on the short term not to alter the stability of the output signal. We must find the best compromise between the temperature sensitivity and the noise.

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