Thermal sensitivity of a DMTD used in a composite clock.

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1 Abstract.

We present the thermal effect on the DMTD (Dual Mixer Time Difference) and its ZCDs (Zerro Crossing Detectors) used 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 stability of the DMTD system and its ZCDs at 100 MHz must be about $10^{-15}@1s$ for the system. The stability of the output signal depends on the VCO stability. This paper describes the effect of the thermal variations on the DMTD and the ZCDs. We explain how to decrease or eliminate the thermal sensitivity of the DMTD system.

2 Introduction.

The system of the composite clock is based on the DMTD principle [1, 2]. We compare each standard clock with the same shifted oscillator. We obtain three square signals which inform us on the stability and the frequency fluctuations of each clock. The choice of the beat frequency has an impact on the whole system. 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.
This system has 3 outputs, one at 5 MHz, one at 10 MHz and another one at 100 MHz.

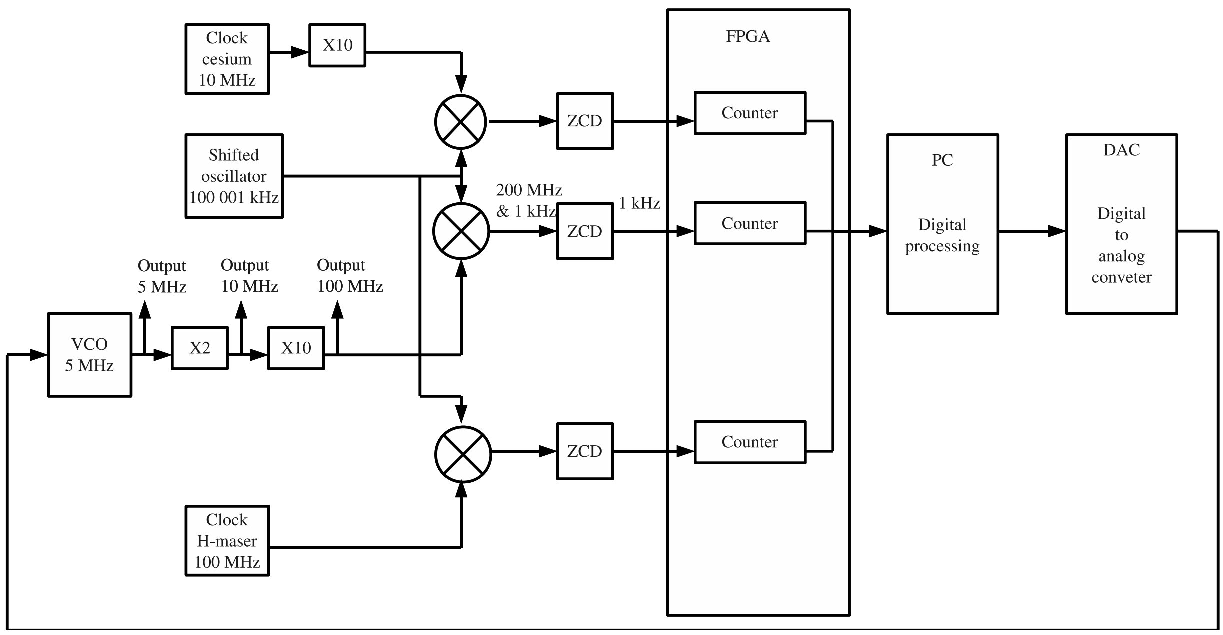

Figure 1: General diagram

The system works at 100 MHz and the beat frequency issued from the ZCDs is about 1 kHz. The DMTD system often works between 1 Hz and 10 Hz, allowing a high rate between the system frequency and the beat frequency. However we get a new data only every 1 s or 100 ms following the beat frequency. Working with a beat frequency of 1 kHz increases the data number by second but it decreases the rate between the system frequency and the beat frequency. So we need to determine the period of the beat frequency with more precision. To attain a relative stability of 10^{-15} with a beat frequency of 1 kHz we must measure the preriod of this one with an accuracy of 0,1 ns. However we must verify that the fluctuations of the beat freaquencies comes from the standard clock and the shifted oscillator, and not from environmental effect or other.

3 Principle of the DMTD and its ZCDs.

The DMTD [3] consists of comparing 2 clocks to the same oscillator in order to know the frequency fluctuations of these clocks. In most cases the DMTD is used to compare an oscillator which is the reference to another oscillator to measure the frequency fluctuations 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 but the principle is the same. 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:

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

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

$$V_M(t) = \frac{V_1 V_2}{2} \times [cos(2\omega_1 t + \Delta_\omega t + \phi(t)) + cos(\Delta_\omega t + \phi(t))] \tag{2}$$

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 the three signals informs us about the frequency fluctuations 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 or another standard clocks. In our case modifying the frequency of the maser or the cesium cannot be considered. Indeed these clocks contribute to other systems and the first problem could decrease their stability. In this way only the VCO can be shifted but the 3 output signals should become 5.00005MHz, 10.0001MHz and 100.001MHz and we do not want it. Secondly the noise of the cesium clock is much higher than the VCO noise and we can not obtain information concerning the short term. A comparison beetween the VCO and an oscillator (or anorther frequency source with a good stability on the short term) is necessary to get an information on the short term.

Then each signal, which comes from the mixers, is sent to a Zero Crossing Detector [4]. Each ZCD has 2 roles (fig. 2). Firstly the ZCD eliminates the component in $2\omega_0$ with the first stage of the ZCD: the low pass filter. Secondly the ZCDs transform the 1 kHz sine signal into a 1 kHz square signal 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 amplifier stages to increase the slope of the signal. The first 2 stages are composed of a high gain and a low pass filter, the next 2 amplifier stages are used only to increase the slope and not to limit the noise. The noise in this configuration (cascade amplifier) mainly depends on the noise of the first stage amplifier as proven in the friis formula. The noise spectrum density equivalent N_{eq} to four amplication stages is :

$$N_{eq} = KT \times (F_1 + \frac{(F_2 - 1)}{G_1^2} + \frac{(F_3 - 1)}{G_1^2 \times G_2^2} + \frac{(F_4 - 1)}{G_1^2 \times G_2^2 \times G_3^2}) \tag{3}$$

where K is the Boltzmann constant, T the temperature in Kelvin, F the noise factor, G^2 the power gain (not in dB).

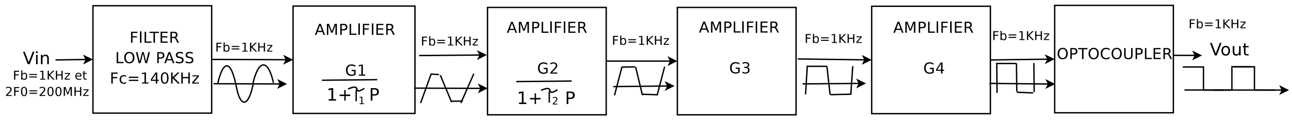

Figure 2: ZCD diagram.

To generate as low noise as possible, it is advised to respect the following conditions:

$$B_i < B_1 \Pi_{n=1}^{i-1} G_n^2 \tag{4}$$

$$G_i < \frac{2\pi B_i V_{max}}{S \Pi_{n=1}^{i-1} G_n} \tag{5}$$

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). With this 2 conditions we obtain 2 limits for the bandwidth : a high limit and a low limit. To minimize the noise of the first 2 stages we use a low noise amplifier LT1028 and it is necessary for this one to not saturate. So the first stage is realised with a low gain about 7, and the bandwidth is about 3 kHz. From the previous formula, we choose a cut off frequency for the second amplifier stage between the calculate high limit and low limit but close to the low limit. To avoid the saturation of this stage and the next stages we place 2 diodes head to tail on the amplifier feedback. The last stage of the ZCDs is an optocoupler which allows to shape the signal entering the FPGA.

4 A thermal sensitivity.

To test the DMTD with its ZCDs we realise the test on figure 3. We generate 2 beat frequencies, send them into two ZCDs and we measure the time difference between the rising edges of these two ZCDs.

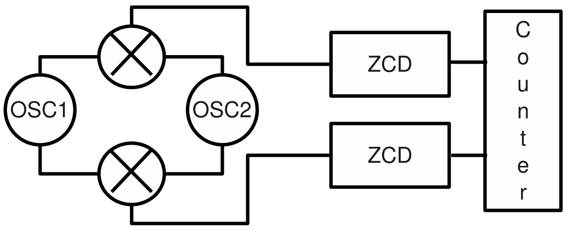

Figure 3:
Diagram of test 1

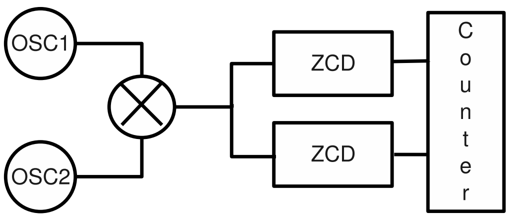

Figure 4:
Diagram of test 2

The time difference between the two ZCDs is not important but the time stability and the jitter are significant. The time difference between the 2 rising edges should stay constant because the beat frequencies are the same for the 2 ZCDs because they are realised from the same oscillator.

Figure 5 shows the result of test 3 where we observe many variations. we notice that the period of the variations of the signal corresponds to the period of the air-conditionning. We conclude that the system is sensitive to the thermal variations [5] but we can not identify which element is sensitive with this test.

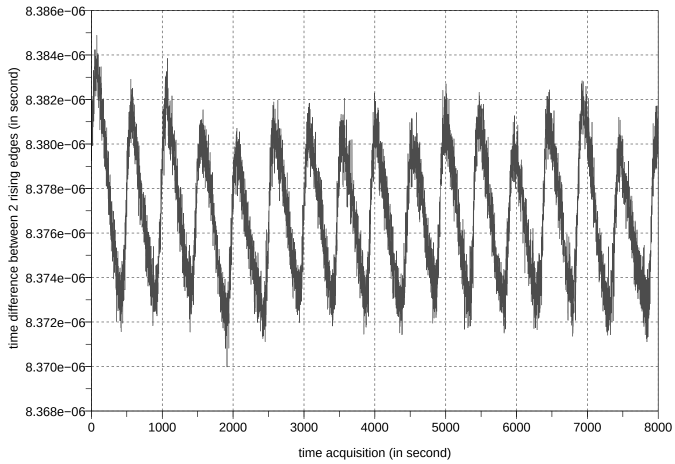

Figure 5: Result of test 2.

We use the test 4 to determine which element is sensitive.We realise only one beat frequency, and we send it on the both ZCDs. After treatement of data we note that the thermal sensitivity is still present but lower than previously. We conclude that both the mixers and the ZCDs are sensitive to the thermal variations. However the thermal sensitivity of the ZCDs is less important than the thermal sensitivity of the mixers.
To obtain a stability of $10^{-}15$ @1s it is necessary to eliminate or decrease the thermal sensitivity. The variatons of the signal, due to the thermal sensitivity, must be inferior to 1ns. In a first time we study the different solutions for the ZCDs and after we will search the solutions for the mixers.

To decrease the thermal sensitivity of the ZCDs the first step consists in using components with a low thermal sensitivity. We choose resistors with a thermal sensitivity of 5 ppm and capacitors type COG with a thermal sensitivity of 30 ppm. These capacitors have filtering capacity worse than the capacitor of type X7R, that is why we associate a low X7R capacitor at the COG capacitor. We can find capacitor X7R with a low thermal sensitivity but not in CMS.
The thermal sensitivity is decreased but not sufficiently. We note that the thermal sensitivity is due to the filter of first amplifier stage. We explain previously that the bandwidth of this filter is reduced thanks to a capacitor on the feedback. the temperature variations modify the value of the capacitor and change the cut off frequency. The cut off frequency variations have a direct impact on the phase of the signal because the cut off frequency and the signal are close. To reduce this effect we need to move the cut off frequency away from the signal frequency (1 kHz), thus increasing the signal noise.

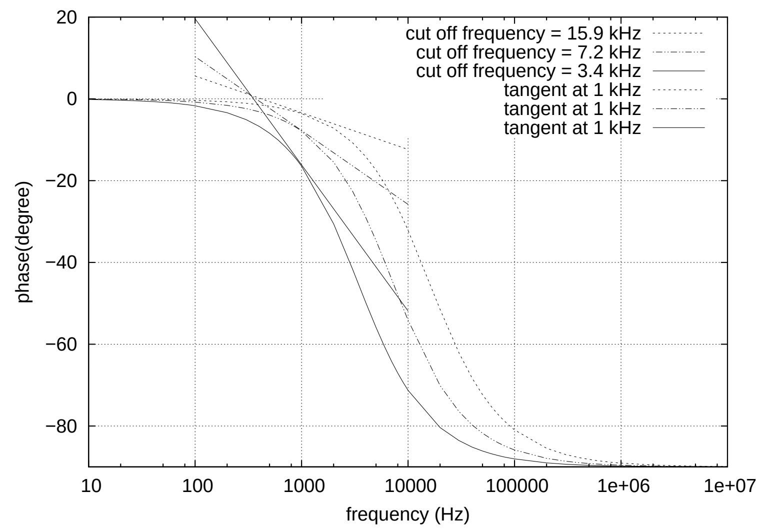

Figure 6: Phase variations for different cut off frequencies of the first amplifier stage.

The curves on figure 5 show bode phase plot for different cut off frequencies of the first stage filter. The tangent at 1 kHz prove the influence of this cut off frequency. We must find the best compromise between decreasing the thermal sensitivity and not adding too much noise. When we realise again the test 2 (figure 4) with components with a low thermal sensitivity and with a cut off frequency of the first stage amplifier of 7.2 kHz, we obtain the curve on figure 7.

We note we have nearly eliminated the thermal sensibility. The White curve on figure 5 is a moving average through 100 data of the black curve, which decreases the effect of white noise without changing the variation of signal. This signal is close to a straight line with a null slope. Thanks to this signal we can affirm that we have nearly eliminated the thermal sensitivity of the ZCDs. We obtain for the black curve $\sigma = 1.88 \times 10^{-9}$ without the heating time (about the first 20000 s), and $\sigma = 1.88 \times 10^{-10}$ for the white curve. The rate between the 2 sigma in presence of only white phase noise should be of $\sqrt{100} = 10$. We note that this one corresponds to our value, so it confirms that we have eliminates the thermal sensitivity. With a thermal sensitivity the rate should be lower.

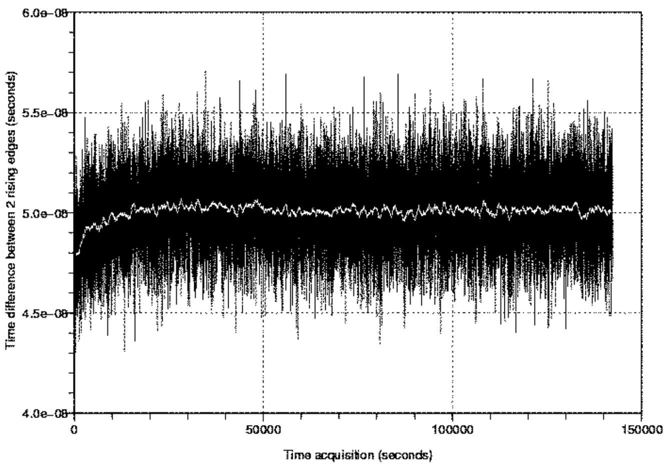

Figure 7: Result of test 2 with a cut off frequency of the first amplifier stage of 7.2 kHz.

We note that with the moving average we have sigma inferior to 2×10^{-10} at 1 kHz, we deduce that we obtain a relative instability of about 2×10^{-15} at 100 MHz. With this approximation we conclude that the result corresponds to our expectancy. However in our system to determine the period of the ZCD signals we use an estimator based on Allan modified deviation [6,7] in order to decrease more the white phase noise effect. The modified Allan deviation has a $\tau^{-3/2}$ behaviour for the white phase noise, while the classical Allan deviation has a τ^{-1} behaviour.

For the thermal sensitivity of the mixer 2 solutions are possible.The first consists in adapting the power level at the mixer input. We know that the curve which plots the thermal sensitivity of the mixer versus the power level of mixer imputs passes by an invert point. By choosing a input level which corresponds to the invert point of the mixer we decrease the thermal sensitivity. However with this solution we must use amplifiers, thus adding some noise. Moreover each mixer is different so each mixer must be adapted one per one in function of the invert point of the studied mixer. This solution needs many time and every system must be developped separately.

The second solution consists in regulating the temperature of mixer case. all mixers of the DMTD are mounted in the same case. So by regulating the case of the mixers, these ones are not affected by the temperature varation of the ambient air. This solution is more expensive than the previous but we can apply it easily and fastly. Moreover it does not require an indivudual study. Even if we did not yet test these solutions, we have found them. The second solution seems the most adapted for our system but if it is not sufficient to eliminate the thermal sensitivity of the mixer, we will apply the first solution, and if necessary we can associate the 2 solutions.

5 Conclusion.

The obtained results on the short term are sufficient to use the ZCDs. We can obtain a sigma lower than 2×10^{-15} by using an appropriate estimator. Even if we have increased the signal noise, the temperature sensitivity has been eliminated. In fact we can not use the ZCDs in this project if we do not decrease or 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 off 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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