High Stability Microcontroller Compensated Crystal Oscillator

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Abstract

Microcontroller Compensated Crystal Oscillators (MCXO) are described which use an ARM type processor embedded in field programmable grid array (FPGA).
Crystal oscillators are used for frequency generation due to very good stability capability. The main instability contributor is the temperature variation. Two main technologies are employed: manage the temperature environment of the crystal resonator or compensate for the effect of temperature on the crystal resonators. The first technique is widely used in Oven Controlled Crystal oscillator (OCXO). Compensation techniques are well known through analog Temperature compensated crystal oscillator (TCXO), digital temperature compensated crystal oscillator (DTCXO) and MCXO. This document will describe the technology for high end MCXO.

Introduction

MCXO technology were developed in the past using dedicated ASIC (application specific integrated circuit). This technology is costly and can't offer flexibility. The Memory size was limited too.

OCXO is widely used in infrastructure systems but this technology has major need of high power consumption and require a long warm up time. These issues are critical in some systems operational condition such as battery operated or instantaneous signal establishment.

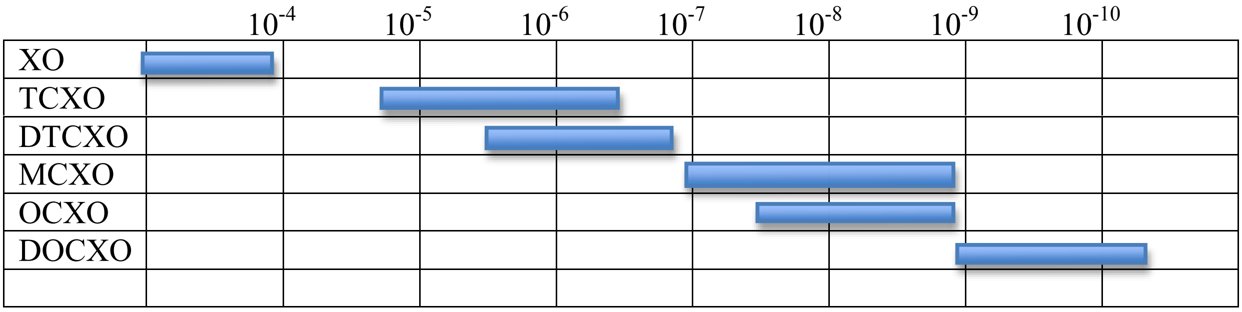
Compensation techniques are superior to OCXO in energy consumption domain due to the fact that OCXO uses heating element to control the temperature of the crystal and its associated oven at 70 to 80°C typically.
OCXO needs 1 to 3 watts at steady state when the thermal regulation is stable and at room temperature. Considering the consumption at low temperature, an additional 500mW is necessary the heat an OCXO at -20°C. The 500mW are to be added to the consumption at room temperature.
The warm up phase will use full available power in the range of 2 to 8 watts. The shorter the acceptable is warm up time for the host system the higher is the power need. The management of the warm up time is sometime tremendous technical compromise at the system level. MCXO consumption is below 100mW; at least one twentieth of the comparable miniature OCXO.

MCXO has naturally a very fast start up time compared to OCXO. MCXO start up is bellow 1 second while OCXO about 5 minutes

Stability vs. temperature comparison

From basic crystal oscillator (XO) up to the Double oven crystal oscillator (DOCXO), the stability versus temperature range is compared in the below table for each technologies.

TCXO requires thermistor with resistor compensation network. The circuitry is set to compensate the 3rd order polynomial AT cut crystal variation. TCXO requires manual tuning of the passive resistor network to reach 10^{-6} typically.
DTCXO improves this calibration process due to automated calibration. So DTCXO mass production can achieve stability in the range of 10^{-7}.
MCXO uses a microcontroller to increase its compensation capability. While compensation is brought to high level; the temperature sensor should provide accurate information.



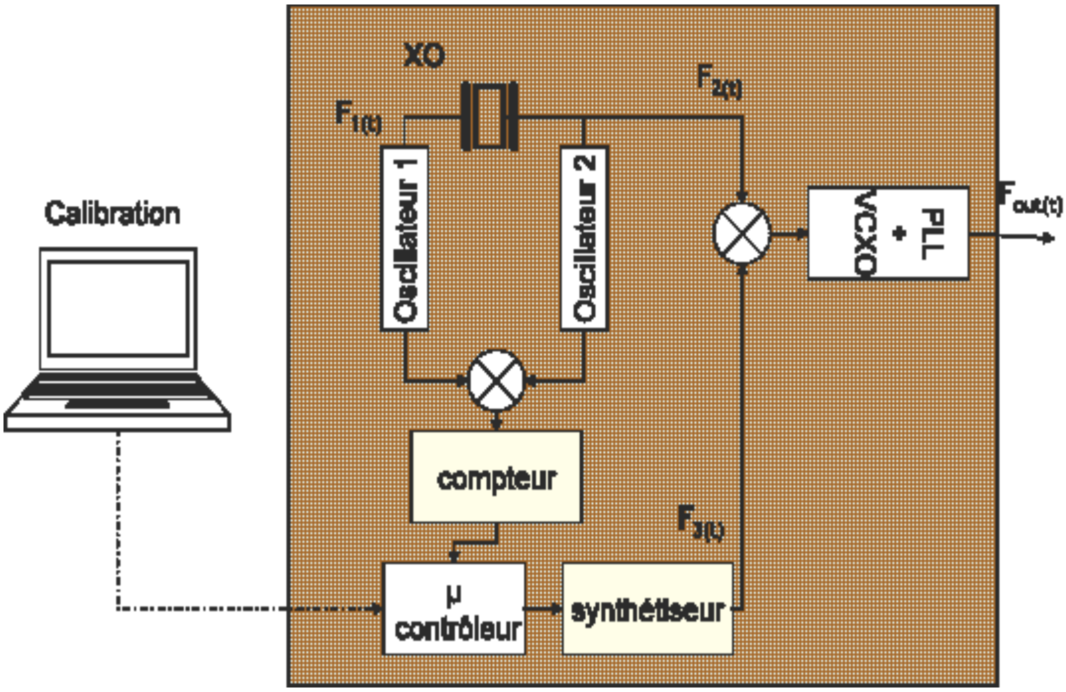
The temperature magnitude considered for the above table is 140°C.

Nowadays, most MCXO are limited to few 10^{-8} performance. We will see the important technical prerequisite to achieve few 10^{-9}.

MCXO block diagram

The simplified block diagram of the MCXO is shown hereunder. The double oscillator circuit is using a SC cut crystal resonator. The oscillator 1 is generating the 10MHz signal while oscillator 2 is providing the temperature information. The frequencies are compared in order to send the shift to the controller.
The controller read the information and applies the corrected value known from the previous calibration process.
The Controller synthesise a 10 MHz using DDS block to create the compensated 10MHz output signal.
The output signal is generated with a VCXO locked on the stabilized DDS. The VCXO is filtering the noise from digital activity.

The accuracy of the temperature sensing and the data correction are critical to reach the stability of few 10-9 in the temperature range.
Temperature sensor and calibration treatment are elaborated topics in this documents.



The accuracy challenge

The tremendous challenge is to get accurate calibration data.
The measurement chain including precise 12 digits counter locked to reference frequency such as GPS systems. This test system shall have a resolution better than 100 times the objective of 10^{-9}.
Then the error from measurement system is declared negligible. We use a test system with a resolution of 1 pico seconde (1.10^{-12}).
Once this measurement chain is set, you obviously need a temperature sensor providing repeatable, accurate and high-resolution data.

Temperature sensor

The TCXO, OCXO and some MCXO are using thermistor to get the temperature information. Thermistor is a cost effective solution to design TCXO with few 10^{-7} deviation in temperature. This proven technology is suitable to OCXO design to monitor the temperature of the oven. The oven is creating a stable environment in temperature. It also prevent the humidity sensitivity thanks to high temperature setting (usually 60 to 80°C)

Thermistor shows some non-linearity especially in wide temperature range. The MCXO challenge is to adapt the thermal environment and extend the operational temperature range. Obviously, the humidity has to be taken into account to with the temperature variation.

In addition, measuring the temperature of the thermistor has an offset error due to transmission through many different materials: metal can, copper, FR4 (PCB), glue, air and/or nitrogen (see Figure 2 below).
This thermal resistance of these material could change with humidity very rapidly or due to out gazing on a long term. The hysteresis phenomenon is also sensitive to humidity variation.

The temperature is transmitted through different mode: conduction mode, convection mode and radiation mode. Mode of transmission and material involved occurred a variation of the thermal resistance.

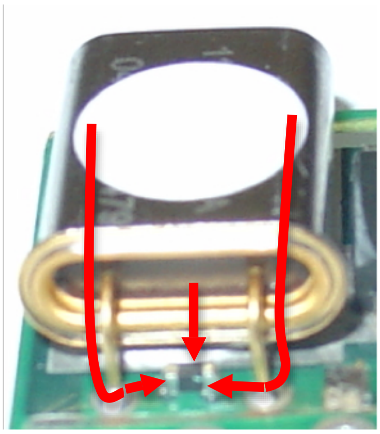


Figure 2 shows an example of temperature sensor in an OCXO. Red line shows the way temperature is transmitted through to the thermistor.

Accurate compensation needs a better sensor to be in the situation to apply the right correction.
The High Stability MCXO is using a dual mode oscillator.
The fundamental crystal resonator frequency (f_1) and third overtone (f_3) frequencies are excited simultaneously and a beat frequency f_β is generated such that $f_\beta = 3f_1 - f_3$ (or $f_\beta = f_1 - f_3/3$).
The f_3 has a great dynamic in temperature range compare to f_1
The f_β is a monotonic and nearly linear function of temperature, as is shown above for a 10 MHz 3rd overtone (3.3. MHz fundamental mode) SC-cut resonator
For temperature compensation purposes, the f_β vs. T need not be used; the calibration can consist of f vs. f_β only.
The dual mode oscillator provides then the crystal temperature directly without the offset error due to the material involved in temperature transmission. The crystal are hermetically sealed in nitrogen atmosphere, the f_3 information is then less sensitive to environment.
In the calibration process of the COLD series MCXO we have a resolution of few mili-degree Celsius.

Digital signal analysis

Using the dual mode temperature sensor, MCXO has the correct architecture to acquire accurate data. The measured data contains noise. Also noise from collected data shall be reduced to get the maximum benefit in accurate compensation. This section review the data processing studied to "average" the raw data.

Polynomial function

The optimum polynomial function is given with the best ratio of accuracy of polynomial / data entry resolution.
We compute an original frequency f_n in a temperature range T_n
We obtained a number of computed points called n_p.
Random noise is added to the frequency and to the temperature data.
The noise level is obtained by multiplied typical deviation factor in temperature σ_T as well as in frequency σ_f
Obtained points are then interpolated in a polynomial of degree d in order to compute again the Frequency versus temperature from the created polynomial.
Finally we calculate the error by comparison of polynomial and the original frequency versus temperature.

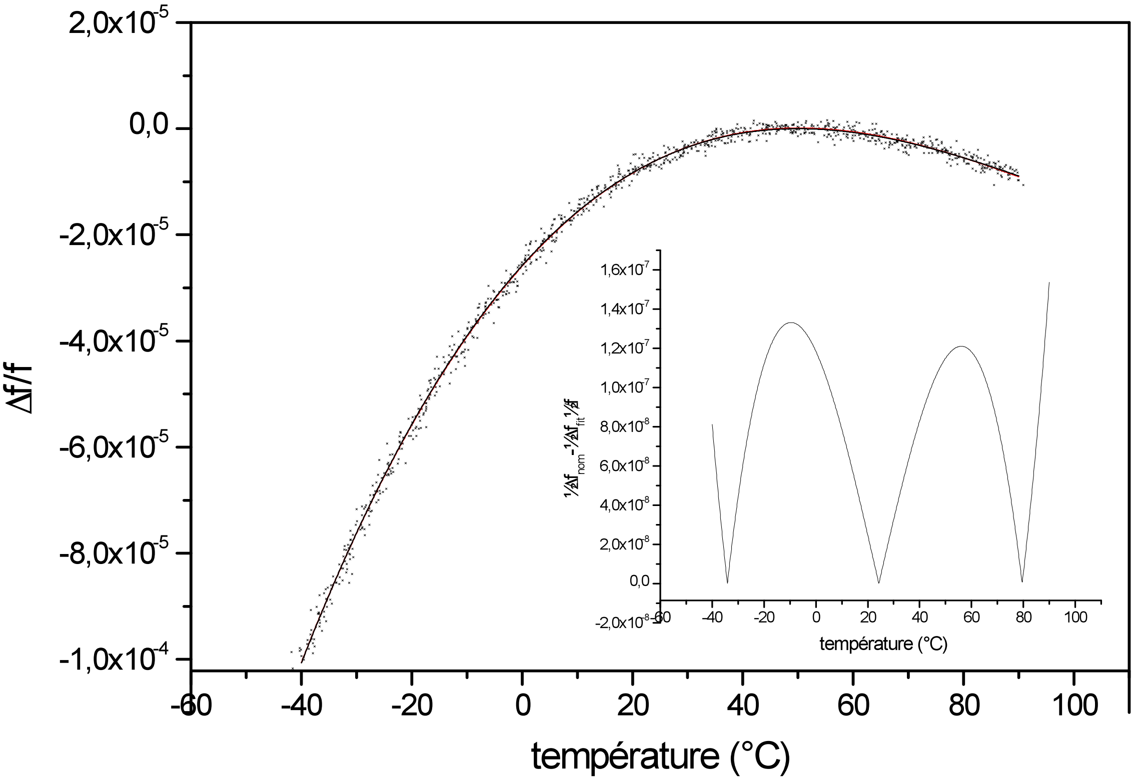


Figure 3 shows an example of comparison between noised curve with a noise level of 10σ and the polynomial function.
Inserted graph shows the error between original data and data obtained with the computed polynom. This error is displayed din absolute value .

The study shows that optimum polynomial is 5th order : d=5.

Frequency & temperature error contribution

We define σ as the noise in temperature and frequency as follow:

$\sigma_T = 0.1°C$

$\sigma_f = 1\ .10^{-7}$

We define the k as noise level as follow: $k\sigma_T$ and $k\sigma_f$

Noise level	Error (average / maximum)
No noise (rounding computation)	$3,2\ 10^{-11}$ / $1,549\ 10^{-10}$
$\sigma_T = 0$ °C $\sigma_f = 1.\ 10^{-7}$	$4,87\ 10^{-9}$ / $1,877\ 10^{-8}$
$\sigma_T = 0.1$°C $\sigma_f = 0$	$5,91\ 10^{-9}$ / $1,79\ 10^{-8}$
$\sigma_T = 0.1$ °C $\sigma_f = 10^{-7}$	$8,19\ 10^{-9}$ / $2,10\ 10^{-8}$

Table 1 : Using a polynomial function of degree 3 the contribution frequency and temperature noise is computed for 500 points.

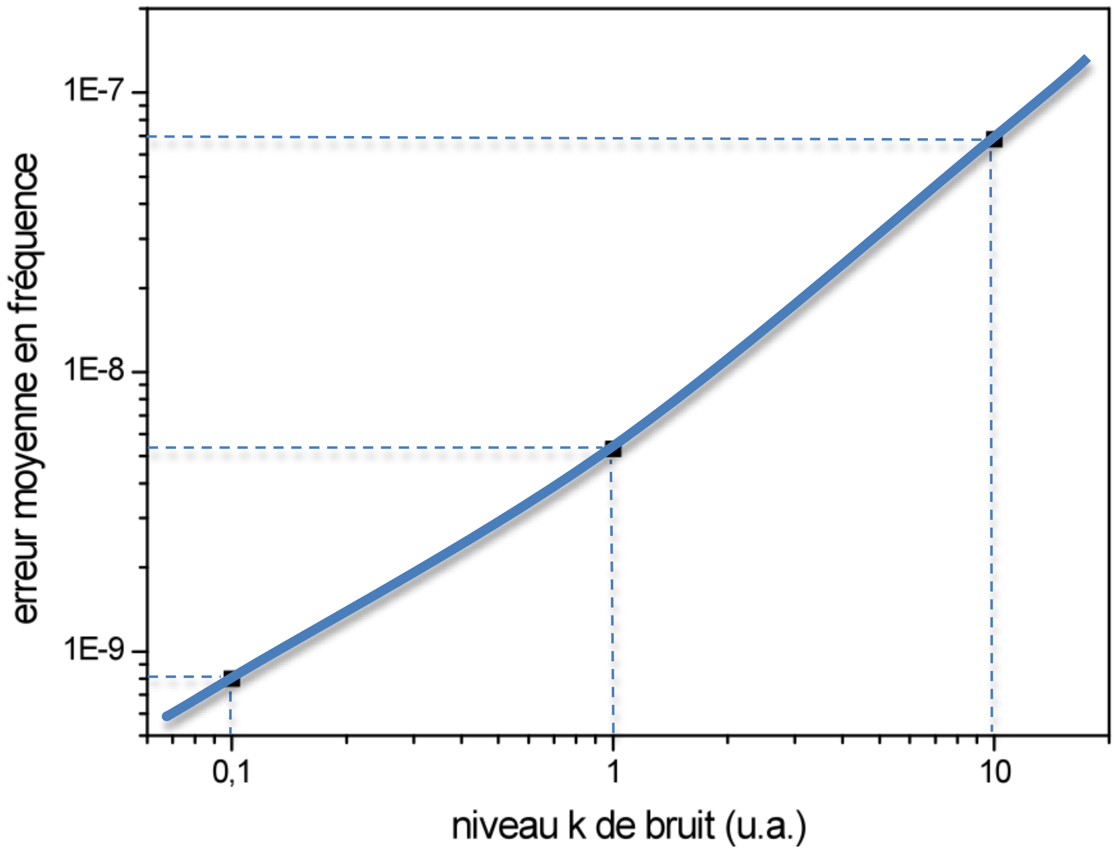


Figure 4 shows the average error (vertical axe) variation of the frequency by changing the k level. (Polynomial degree d= 3 / number of computed points n_p=500)

The study of the Frequency error contribution an d temperature error contribution show no ceiling nor floor effect. In principle every gain obtained in both temperature and frequency accuracy will potential provide a benefit in the global stability.

Contribution of the number of sampled points

In order to review the impact of the amount of collected data from the calibration process, we study the influence of the number of point on the error. Therefore, the noise level is a fixed value and the temperature range is limited to 10°C.
We review n_p = (100, 200, 500, 1000, 2000).
For each value of n_p, several randomized noises have been generated.

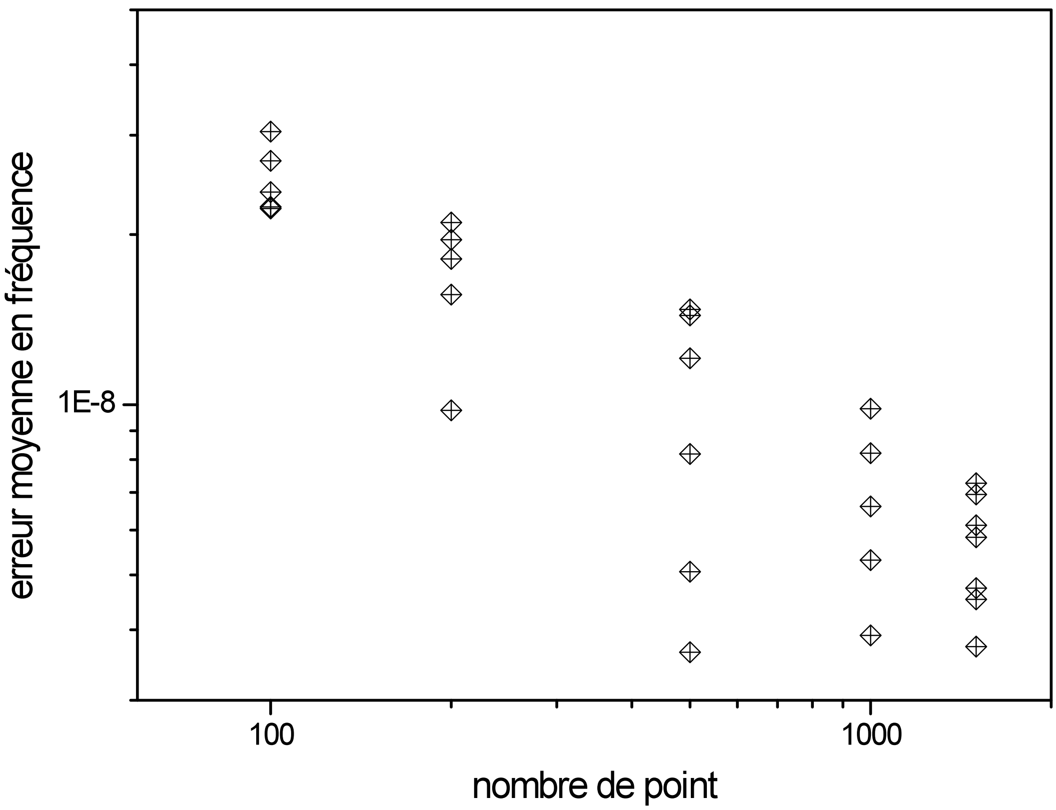


Figure 5 shows the error (vertical axe) variation of the frequency depending on the number of computed points.
(Polynomial degree d= 3 / σ_T=0.1°C / σ_f=1 10-7)

At the level of 1000 points-samples we reach a precise result.
Increasing the samples to 2000 contribute in reducing the result's dispersion with a low impact on the accuracy.

This chapter shows that large quantity of data is necessary. With sufficient data in collected, the polynomial analysis will provide accurate data for compensation purpose. For a temperature range of 150°C, 30 000 samples are correct volume data.

Outcomes: Stability versus temperature range

FPGA technology provides features required to design High Stability MCXO with a good level of flexibility. Manufacturers of FPGA have on the shelves solutions, which suit this application.
The memory size is no longer an issue nowadays 1 Mbytes onboard a frequency control device is economically reasonable.
So the "entry ticket" of the ASIC could be avoided. The R&D effort can be focus on performances and functionalities that are direct benefits for MCXO users.

Europa Electronics has developed an MCXO platform at the state of the art of the compensation technique; the COLD series. The production of COLD series shows equivalent performance compared to OCXO in term of stability versus temperature, Allan variance and long-term stability (aging).

New benefits of the dual mode oscillator and the digital processing of the calibration data is the stability in temperature range as good as OCXO: **few 10^{-9}**

The temperature range is then no longer limited to the turn over point of the crystal.
The extended temperature range depends on the quality level of the component used in the design.

The power consumption is divided by 20 compared to miniature OCXO to reach: **50mW** typically. This helps the integration in system without a pick current to manage during the warm up phase.

Application require

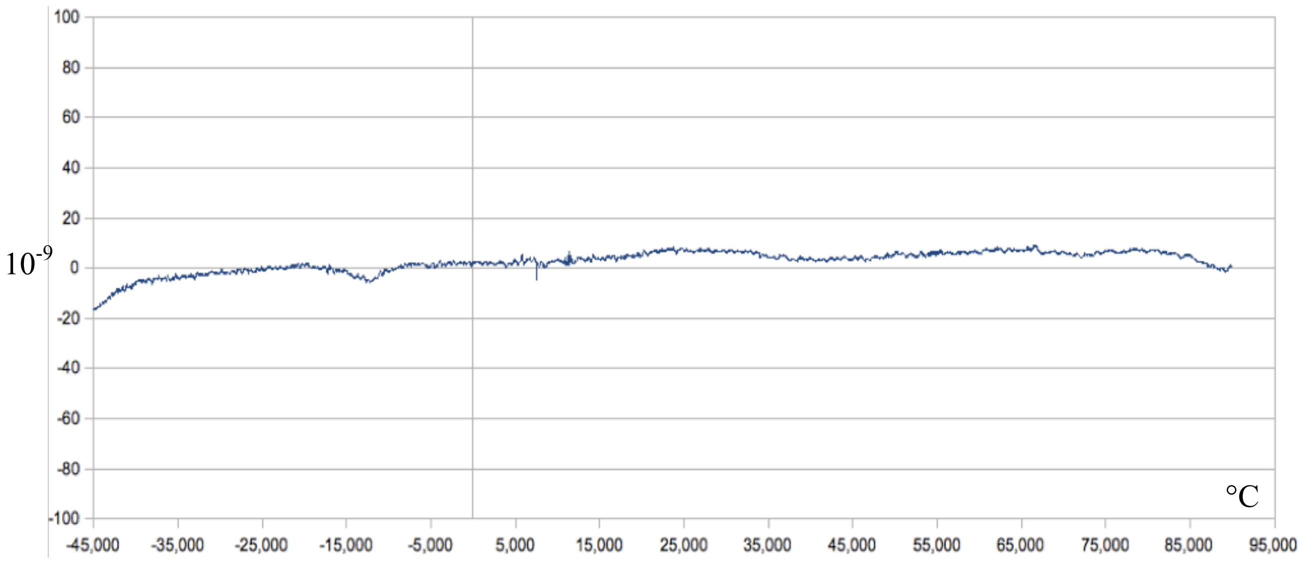


Figure 6 shows stability versus temperature range