

Investigation of Long-Term Drift of NTC Temperature Sensors with less than 1 mK Uncertainty

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Abstract— Long-term drift of temperature sensors is critical to applications requiring high reliability. However, documentation and knowledge regarding long-term stability is limited. Usually manufacturers promulgate drift margins down to 10-20 mK/year, while the performance of the sensors might be much better. For some advanced industrial applications, which demand drift rates down to a few mK/year, this information is inadequate. In this paper, we present our investigation of the long-term drift of a few sets of small footprint, off-the-shelf NTC (negative temperature coefficient) temperature sensors, based on an extremely stable test setup guaranteeing stability of better than 1 mK between two calibration intervals. The results show that the SMD type sensor from Murata manufacturing (NCP15XH103D03RC), intriguingly, is the most stable sensor among the sensors tested with a drift rate of 0.492 mK/year peak-to-peak. Most of the other sensors tested have drift rates of lower than 1 mK/year, making them suitable for temperature sensing applications requiring long-term stabilities in the mK range.

Keywords—Drift, NTC temperature sensors, Thermistors, Long-term stability in mK/year range, Sub-mK resolution

I. INTRODUCTION

For temperature sensing applications requiring sub-mK resolution, semiconductor oxide (ceramics) based temperature sensors with high sensitivities are preferred. However, there is a gradual change in resistance from the initial value over time. This is known as “drift” and is more evident in high sensitivity NTC sensors. Hence, for applications requiring higher resolution, long-term stability usually has to be compromised.

The reasons for drift are ambiguous and include migration of cations in the material due to oxidation, process conditions (e.g: sintering temperatures), thermal cycling, humidity, stress, self-heating, material compositions and manufacturing techniques [1]-[8]. Few studies on sensor drift performance of temperature sensors have been conducted in the past [9]-[14]. Some have been able to reach measurement setup stability in the mK range [11], [12]. Other than the performance reported in the literature, manufacturers also measure drift rates and report them in datasheets [14]. However, their measurement setups feature drift margins larger than 10 mK/year, and therefore they cannot measure drift in the mK/year range accurately. Yet, for certain high-end industrial applications like

lithography, optical radiometers, and space applications, long-term stability along with high resolution are required and are critical to device performance.

In this paper, we present long-term drift results with a few state-of-the-art temperature sensors. The results are obtained using a measurement setup with less than 1 mK uncertainty. The tested sensors are of the following types: glass bead, probe and SMD (Table 1). Since all the sensors in our experiment have a negative temperature coefficient, we will refer to them as NTCs in the remainder of the paper.

Table 1: Details of the type, manufacturers and excitation voltages applied to the sensors being tested for drift performance

	Amt	Supplier	Type	Name	Operating conditions
1	10	Murata	SMD	NCP15XH103D03RC	0.6V AC
2	5	Meas Spec	SMD	SMD410KF38H	0.6V AC
3	5	Meas Spec	Probe	10K3MCD1	0.6V AC
4	5	Meas Spec	Bead	46036	0.6V AC
5	5	Meas Spec	Bead	55036	0.6V AC
6	5	Meas Spec	Bead	46036	0.6V DC
7	5	Murata	SMD	NCP15XH103D03RC	1.2V AC
8	5	Panasonic	SMD	ERTJ0EG103FA	0.6V AC
9	2	Vishay	Foil	Ref resistors[8]	0.6V AC
				Total = 47 Samples	

Some studies specify that the NTC packaging is one of the factors that limit their stability [13]. For example, glass-encapsulation provides better protection than epoxy encapsulation, which leads to better long-term stability. In order to keep the measurement environment uniform and to avoid temperature fluctuations, all the test sensors are enclosed in hermetically sealed, stainless steel tubes. In addition, each set of NTCs have been taken from the same fabrication batch, with no pre-aging applied.

The paper starts with a description of the measurement setup, followed by the methodology used for the drift measurements. Next, the measurement results and the error minimization techniques employed are presented. Finally, the obtained results, processed for error minimization, are

discussed and analyzed. Based on the results, the sensor with the best long-term stability which can meet the requirement for applications in mK/year range is identified.

II. MEASUREMENT SETUP

The NTCs are inserted in a water bath and maintained at 22 °C (room temperature) by 16 Peltier elements. This is the temperature at which we intend to do the measurements for drift. Primarily, the drift in the resistance of the NTCs is measured and recorded. Later, this will be translated into equivalent drift in temperature. IPRTs (Industrial Platinum Resistance Thermometers) are used as reference sensors to measure the change in resistance of the NTCs (Fig. 1a). They are calibrated using a Triple Point of Water (TPW)¹ cell (Fig. 1b). In addition to measuring drift, IPRTs are also used to regulate the temperature of the bath.

The drift of the NTCs is measured with IPRTs using an F17 automatic resistance (AC) Ratio Bridge^[15]. The AC Bridge is calibrated by two fixed reference resistors^[16]. Additionally, a Digital Multimeter (DMM) from Keithley^[17] is used to measure the absolute values of impedance of the reference resistors and the sensors (Fig. 2).

III. METHODOLOGY

A. Calibration procedure

To maintain a setup with 1 mK/year stability, the blocks being calibrated during every measurement are: the waterbath, IPRTs and the AC resistance ratiometric bridge. Firstly, the short-term temperature fluctuations within the bath are kept below 50 µK. The water in the bath is circulated at the rate of 0.6L/second and the temperature of the water bath is recorded continuously. Next, IPRTs are calibrated each time they are used, using a TPW cell (Fig. 1b). This cell is used to define the ITS 90 temperature scale. Its uncertainty contribution is considered to be 20 µK/year, although drift rates of a triple point of water cells are reported to be much less^{[18] [19]}. Each of the IPRTs is inserted into TPW cell and their resistances are logged for 15 minutes at the TPW. The values are translated into room temperature (22°C) using the Callendar-Van Dusen equation^[20]:

$$R_t = R_0 (1 + A * t_n + B * t_n^2) \quad (1)$$

where R_t is the resistance measured at 22°C; Nominal Values of Coefficients according to IEC 751 (1995): $A = 3.9080 * 10^{-3} \text{ } ^\circ\text{C}^{-1}$; $B = -5.775 * 10^{-7} \text{ } ^\circ\text{C}^{-2}$; $R_0 = 100\Omega$ at 0 °C; and t_n is the measured temperature. The coefficients A and B are multiplied by t_0 and t_0^2 , respectively, ($t_0 = 273.15 \text{ K}$) to make them dimensionless to ease calculation and inverse use. Coefficients A and B were calculated for each thermometer before the experiment was initiated, in order to match the thermometers at 0 °C and 22 °C. If the slope of the curve of a

thermometer needs adjustment, only the linear component A will be recalculated, leaving B unchanged.

Any deviation from the last value measured larger than 100 µK at the TPW, leads to recalculation of the value of R_0 . Next, all sensors (Table 1) are placed in the water bath at 22°C. After complete stabilization, the IPRTs are inter-compared. If the total spread is larger than 200 µK, then the sensors are checked again for correctness at 22°C. The linear coefficient A of the sensor which does not match the other will be recalculated.

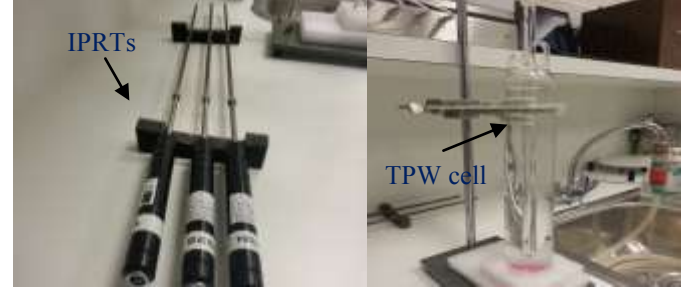


Fig. 1. a) IPRT sensors; b) Triple point of water cell.

The accuracy of the AC ratiometric bridge is ensured by using a set of fixed resistors. The resistors are placed in a bridge configuration. Next, they are swapped in their positions to obtain exactly the reciprocal of the previous value. This procedure is repeated with several resistor pairs. The bridge should be able to reproduce to at least 1 LSB (least significant bit), which corresponds to 255 µK for a Pt 100 sensor.



Fig. 2. Readout set-up used to measure drift of NTCs, which includes AC ratiometric bridge and Keithley DMM.

B. Drift measurement of NTCs

Initially, the stability of the water bath was measured. Later, the same procedure was repeated for drift measurement of the NTCs. To measure the temperature of the water bath, a fixed resistor and a Pt100 sensor (IPRT) are inserted into the bath. It is assumed that both register the same temperature in the water bath. The ratio in resistance values is measured using the AC resistance ratiometric bridge. Since the measurement range of the AC Bridge is only 0-400 Ω for 100 Ω resistors, a Keithley Multimeter is used to measure the

¹ The surface where all three phases of water co-exist in thermal equilibrium is called the triple point of water (TPW). As per definition, this occurs exactly at 0.010°C.

absolute values of impedances which are of the order of 11.5 k Ω .

After complete stabilization of the water bath, the NTCs being tested are measured for drift. Three Pt100 resistors are kept in the water bath together with different sets of NTCs enclosed in tubes made of stainless steel (Fig. 3).



Fig. 3. NTCs enclosed in tubes along with three Pt100 sensors.

The tubes are placed in the same position each time the measurement is done. A software program ensures that the measured resistance of each NTC is recorded in the same order every time so that any offset or uncertainty is translated into a systematic error and can be disregarded later. Each measurement consists of the temperature of the water bath measured with the calibrated Pt300 sensor and 20 measurements of the NTC resistance, spread over 20 seconds. The mean and standard deviation of 2σ of the 20 measurements are calculated along with the slope, which represents the probable drift during a series of 20 measurements. All raw data as well as the calculated data are recorded.

The next step is to convert the raw data of resistance drift into equivalent temperature drift. The Steinhart-Hart method, which characterizes non-linear NTCs, is widely used for this step. Using a fitting equation with only three coefficients, temperature can be derived from the measured NTC resistance. However, nowadays accurate NTCs which reproduce within millikelvins are available. A curve-fit over larger temperature ranges may be less accurate than the accuracy of the measurements gathered by calibration. Once characterized, the total uncertainty in the temperature, determined with a calibrated NTC using the Steinhart-Hart method, can be unacceptably large. This point was noticed, thus an alternative characterization was developed. It is based on a polynomial using the natural logarithm of the measured resistance divided by the resistance at 0 °C (or any other temperature within the calibrated range versus the temperature in °C) (2).

$$t_{bn} = \sum_{m=0}^i b_m \ln \left(\frac{R_{tn}}{R_0} \right)^{m+1} \quad i = 3; m = 0 \dots i; \quad (2)$$

A restriction of the Steinhart-Hart method is that only three coefficients can be used. With enough data available, more coefficients can be added to the alternate fitting method. Experimentally obtained calibration data was used to test this alternative characterization. For example, a comparison of the two methods for YSI 55033 NTC yielded the following results. The uncertainty in the curve using Steinhart-Hart equation with three coefficients was found to be 0.0122 °C. With (2), (four coefficients) the differences and uncertainties in °C were reduced to 9×10^{-4} , an order of magnitude of more than 10 times compared to the Steinhart-Hart equation. For each NTC type, a set of parameters was calculated from the resistance versus temperature tables, as published by the respective manufacturers.

Now, we can summarize all the uncertainties mentioned. The temperature fluctuations allowed within the bath are kept below 50 μ K. The TPW cell has a defined reproducibility of 20 μ K. The margin of error during calibration of Pt100 sensors at the TPW is 100 μ K. When the IPTs are inter-compared for deviation, 200 μ K of margin is allowed. Finally, for the AC resistance ratiometric bridge, a margin of error of 255 μ K is allowed. This corresponds to a total margin of error for the measurement setup of less than 1 mK. Note that this is the worst case estimation. In reality, the uncertainty value of the setup is expected to be well below 1 mK, as will be confirmed by the measurement results. As an extra check for the stability claim, two fixed resistors are measured for drift along with the NTCs (Fig 4), which are presented at the end.

IV. RESULTS AND DISCUSSION

A. Measurement results

Drift performance (in mK) of various sets of NTCs, along with two fixed resistors (R08 & R09) for a duration of six months, was recorded and plotted (Fig 4(a)-(i)). The minimum drift of the NTCs observed in the measurement is of the same order as that of the uncertainty mentioned of the measurement setup (less than 1 mK p-p).

B. Error minimization

The measurement results show that all the sets of NTCs follow a certain pattern in drift, indicating the presence of deterministic measurement error in addition to their actual temperature drift. The sources of this kind of error are probably related to the test set up and the measurement conditions which need to be further investigated. Also, the reason for drift of all the sensors in negative direction is unknown and needs further inspection.

To segregate the deterministic error from the actual temperature drift, the following techniques were employed:

1. All data from the same type of NTC were averaged and plotted on one graph (Fig. 5) Each line in represents the average temperature drift including the deterministic error, in each set.

2. The initial phase where the NTCs show a larger variation (Fig 6.) is considered to be a “pre-aging phase” (out of scope). Hence, it is excluded from the final result and no error minimization techniques are applied to this part of the data. No quantitative threshold has been used for setting this phase.

3. The drift behavior of the NTCs over time is equivocal. Some studies report about a few types of NTCs that have exponential behavior over time ^[11], indicating that the drift is higher initially. Gradually, the sensor stabilizes.

In this paper, to predict the sensor behavior over time, either a linear or logarithmic fit was used. Both approximations were applied to the graphs and compared. Since no significant difference was found for the present data sets, the graphs were approximated to a piecewise linear function of offset (deterministic error) and slope (actual drift).

$$\text{Drift, } Y = mx + C \quad (3)$$

m = Actual Drift; C = Deterministic error

The segregated deterministic error is shown in Fig 7. Every line in the graph represents the error in each set of NTCs. Most of the NTCs exhibit an error of about 0.6 mK. In principle this value is the uncertainty of the measurement setup, which is less than 1mK.

4. In the final step, the error values of all the sensors are averaged and subtracted from the actual signal. The outliers present in the graph are not included while averaging the errors. By doing this, we reduce the deterministic error from the results. What remains is the actual drift value.

Hence, through measurements we obtained results with an uncertainty of 1mK. The uncertainty is further reduced by applying error minimization techniques. The final drift performance is shown in Fig 8.

C. Discussion

From the final result Fig. 8, it is evident that by applying the error minimization techniques, we can reduce the measurement uncertainty from greater than 1 mK/year (measurement results) to much less than 1 mK/year peak-to-peak (pp) (results after error minimization). Studies reported in the literature on drift performance have predicted that glass encapsulated bead-type NTCs usually have low drift margins and are most suitable for applications requiring long-term stabilities ^[13]. However, a closer look at the outcome of our experiment shows some remarkable results:

- In contrast with some of the previous studies which predict glass encapsulated bead-type NTCs to be the best for applications requiring long-term stability ^[13], the SMD type NTC from Murata Manufacturing (NCP15XH103D03RC) performs better than the glass encapsulated bead-type NTC. With an excitation voltage of 0.6 V AC, it has a drift margin as small as 0.492 mK/year pp. It exhibits the least amount of drift and the highest stability in our study, and is predicted to be the best sensor to be used in miniature, temperature sensing

applications requiring high sensitivity and long-term stability. It is to be noted that the two outliers present in the measurement data (Fig 4 (a)) are considered deterministic installation errors and are excluded while averaging the set for error minimization. Since 10 samples of the sensor were available, they were used for the tests. However, to maintain fairness in comparison, if we consider only 5 samples in the calculations, the drift rate is found to be 0.49375 mk/year pp. The difference in the results is negligible.

- When the same SMD type sensor (NCP15XH103D03RC) was given an excitation voltage of 1.2 VAC, the drift rate was found to be about 1.704 mK/year pp. With higher voltages the effect of self-heating is more pronounced, the as the overall drift increases. Conversely, at low excitation voltages (0.6 VAC), self-heating does not noticeably affect most of the tested sensors.

- SMD type NTCs from Measurement Specialties (SMD410KF38H) exhibits a drift performance of about 0.638 mK/year pp. Clearly, advances in manufacturing processes of SMD type NTCs has helped in limiting the drift margins to a few mK/year.

- SMD type NTCs from Panasonic (ERTJ0EG103FA) initially had a drift of about 10 mK/year pp. If the initial phase is assumed to be pre-aging and not considered in overall drift calculation, the drift rates reduce to 0.899 mK/year pp, which is less than 1 mk/year pp.

- The glass encapsulated bead-type NTC from Measurement Specialties (46036) exhibits drift rates of 0.546 mK/year pp when supplied with 0.6 VAC. The results are in good agreement with the previous studies presented in the literature that have indicated glass encapsulated bead-type NTCs to be one of the most stable sensor types ^{[11], [13]}. However, when supplied with 0.6 VDC, the drift rate increases to 0.9 mk/year pp.

- A smaller version of the 46036 is another glass encapsulated bead-type NTC from Measurement Specialties (55036). Since it is smaller in size and has a faster response time, it exhibits lower stability and drift rates of about 2.388 mK/year pp.

- The worst performance among the sensors tested is shown by epoxy encapsulated probe-type NTCs from Measurement Specialties (10K3MCD1) with drift rates of 11.307 mk/year pp. Epoxy encapsulation does not provide the NTCs with enough stability and therefore they tend to drift at a higher rate.

- The fixed resistors (R08 and R09) are two foil-type resistors from Vishay. They were measured for drift performance to verify the stability of the measurement setup. The change in resistance is less than 0.24 Ω/Ω /year pp, which validates the claim of an extremely stable measurement setup.

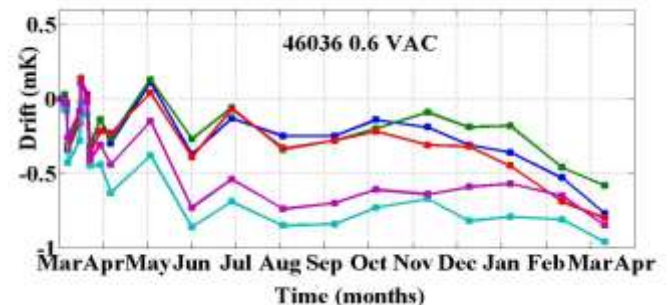
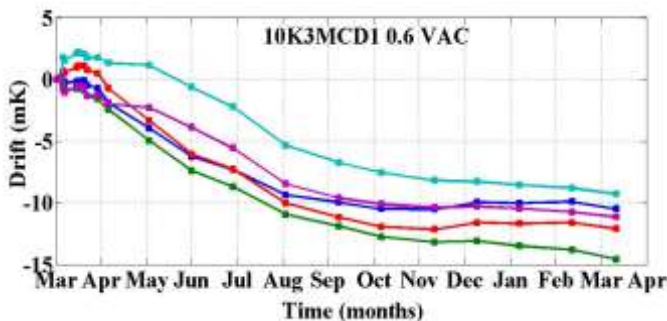
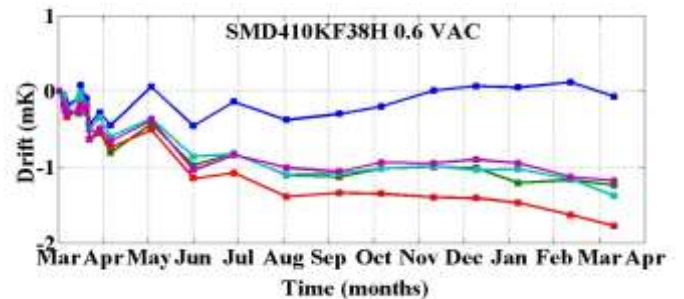
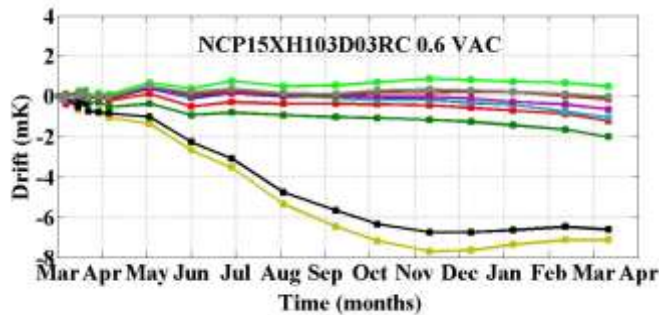
Disclaimer: The validity of the conclusion is based on a limited number of new (without pre-aging) sensors per type, from a single fabrication batch tested at only one temperature (22 °C).

V. CONCLUSION

In the present paper, a few sets of miniature state-of-the-art NTC sensors from different manufacturers were tested for drift performance for six months. A measurement setup with stability better than 1 mK was introduced. After applying techniques to minimize the deterministic error in the measurements, most of the sensors appear to have drift rates of less than 1 mK/year pp. The SMD-type sensor from Murata manufacturing (NCP15XH103D03RC) intriguingly showed the least drift performance of 0.492 mK/year pp. It is predicted to be the best small-size candidate (among the sensors tested) to be used in temperature sensing applications requiring high sensitivity together with long-term stability in the mK range.

REFERENCES

- [1] Feteira, A. "Negative temperature coefficient resistance (NTCR) ceramic thermistors: an industrial perspective." *Journal of the American Ceramic Society* 92.5 (2009): 967-983.
- [2] Feteira, A, and K. Reichmann. "NTC ceramics: past, present and future." *Advances in Science and Technology* 67 (2011): 124-133.
- [3] Fritsch, S., et al. "Correlation between the structure, the microstructure and the electrical properties of nickel manganite negative temperature coefficient (NTC) thermistors." *Solid State Ionics* 109.3 (1998): 229-237.
- [4] Fang, D.L, et al. "Aging of nickel manganite NTC ceramics." *Journal of Electroceramics* 22.4 (2009): 421-427.
- [5] Hosseini, M. "The effect of cation composition on the electrical properties and aging of Mn-Co-Ni thermistors." *Ceramics International* 26.3 (2000): 245-249.
- [6] Castelan, P., et al. "Aging study of nickel-copper-manganite negative temperature coefficient thermistors by thermopower measurements." *Journal of Applied Physics* 72.10 (1992): 4705-4709.
- [7] Varghese, J. M., Seema A., and K. R. Dayas. "Ni-Mn-Fe-Cr-O negative temperature coefficient thermistor compositions: Correlation between processing conditions and electrical characteristics." *Journal of Electroceramics* 22.4 (2009): 436-441.
- [8] Groen, W. A., et al. "Aging of NTC ceramics in the system Mn-Ni-Fe-O." *Journal of Electroceramics* 7.2 (2001): 77-87.
- [9] Lawton, K. M., and S. R. Patterson. "Long-term relative stability of thermistors." *Precision Engineering* 25.1 (2001): 24-28.
- [10] Lawton, K. M., and S. R. Patterson. "Long-term relative stability of thermistors: Part 2." *Precision Engineering* 26.3 (2002): 340-345.
- [11] Wood, S. D., et al. "An investigation of the stability of thermistors." *Journal of Research of the National Bureau of Standards* 83.3 (1978): 247-263..
- [12] Edwards, T. J. "Observations on the stability of thermistors." *Review of Scientific Instruments* 54.5 (1983): 613-617
- [13] Siwek, W. R., et al. "Stability of NTC thermistors." *Temperature, Its Measurement and Control in Science and Industry* 6.Part 1 (1992): 497-502.
- [14] Measurement Specialties, Application Note TD011.
- [15] Automatic Systems Laboratories, " F700 Thermometry Bridge ", F700 Datasheet.
- [16] Vishay Precision Group, " Ultra high precision Z-foil resistor with TCR of ± 0.05 ppm/ $^{\circ}$ C, PCR of 5 ppm at rated power, tolerance of ± 0.005 % and load life stability of ± 0.005 % ", Z201 Datasheet, March 2010.
- [17] Keithley, " Low noise 7½ digit autoranging multimeter ", 2010 Datasheet
- [18] Hill, K. D. "Is there a long-term drift in triple point of water cells?." *Metrologia* 38.1 (2001): 79.
- [19] Yan, X. K., et al. "The long-term drift of triple-point-of-water cells." *International Journal of Thermophysics* 29.3 (2008): 815-824.
- [20] Preston-Thomas, H. "The international temperature scale of 1990(ITS-90)." *Metrologia* 27.1 (1990): 3-10.
- [21] Lavenuta, G. "Negative temperature coefficient thermistors." *Sensors-the Journal of Applied Sensing Technology* 14.5 (1997): 46-55.



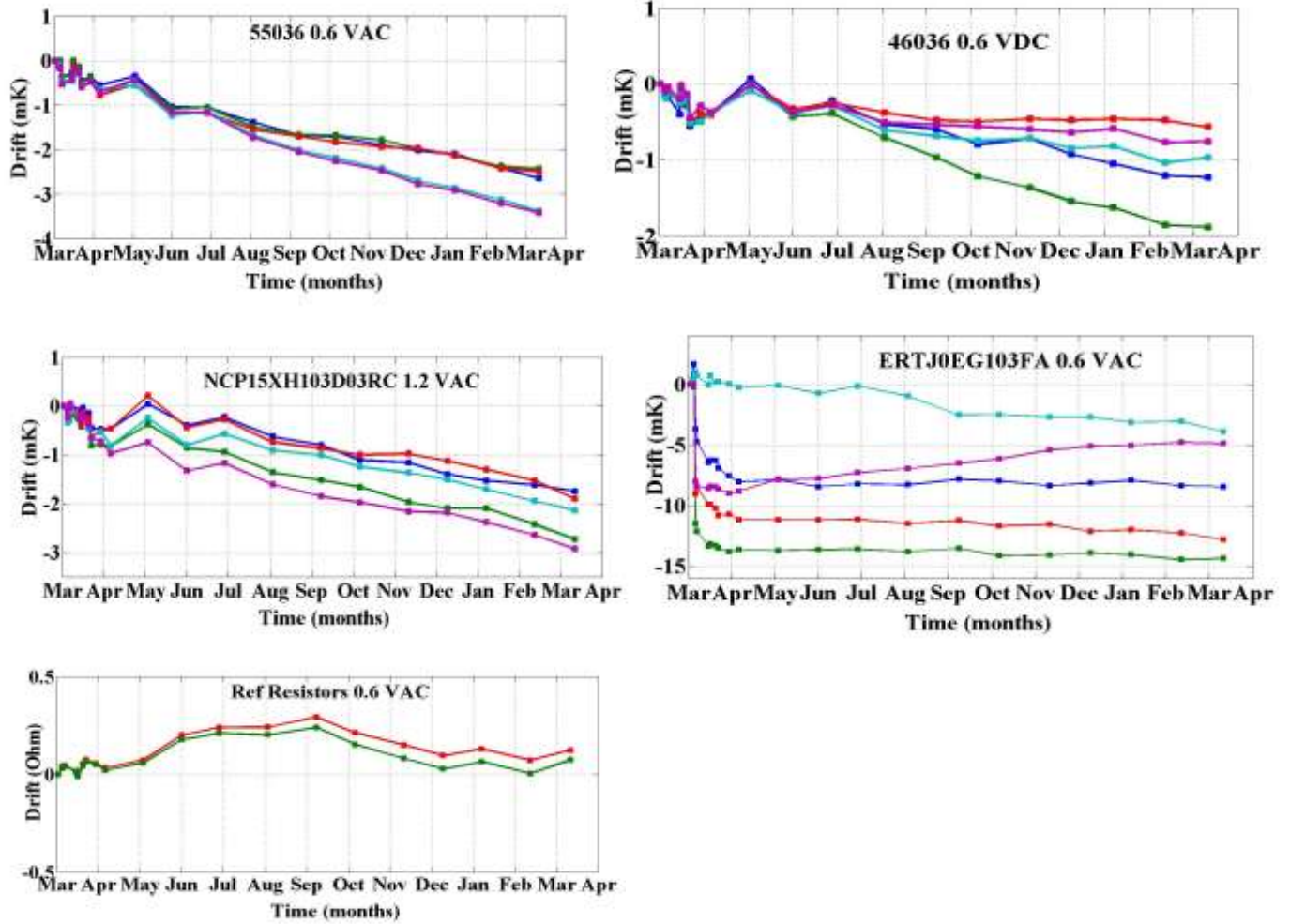


Fig 4 (a)-(i). (In order: NCP15XH103D03RC, SMD410KF38H, 10K3MCD1 ... Ref Resistors) Drift measurement results of various NTCs and fixed resistors, mentioned in Table 1.

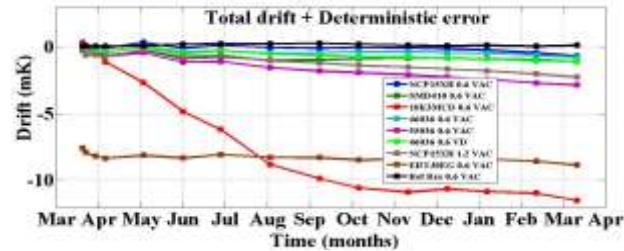


Fig 5. Graph representing the average of each set of NTC

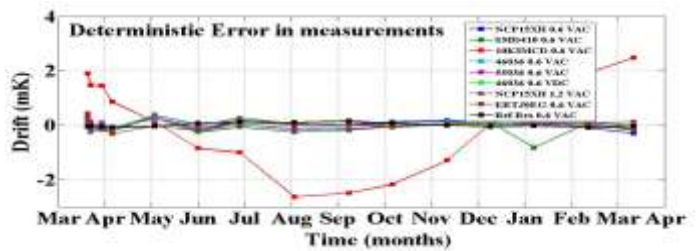


Fig. 7. Deterministic error in each set of NTCs introduced during measurements

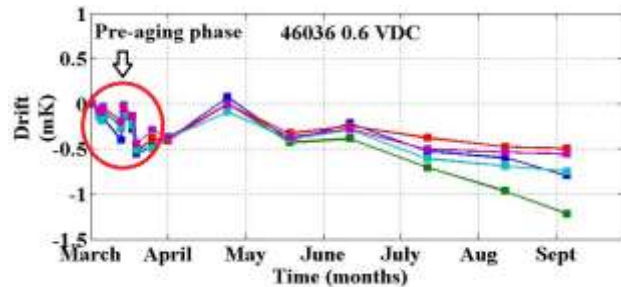


Fig. 6. Example case showing the pre-aging phase

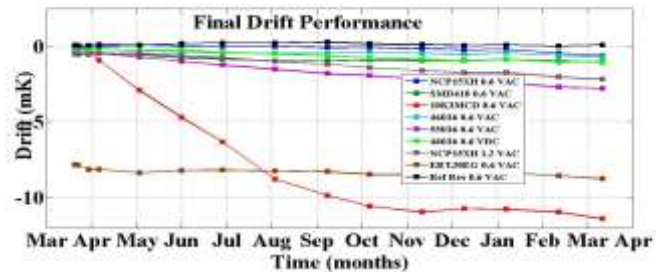


Fig. 8. Final drift results after the removal of deterministic error