HLT1236M : Voltage Reference with temperature-stabilised LT1236-5

DeltaSigmaD, May 2020

In the EEVblog metrology forum references with LTZ1000 and LM399 were discussed in many details. These references use hermetic TO packages, since the long pin wires largely reduce mechanical stress on the reference package. But the TO-package cannot be produced without Kovar or similar alloys for the package feed-throughs, which generate ca. 38 uV/K EMF against the Cu of the PCB. Therefore, the temperature gradients at the LTZ1000 pins must be stable to <0.1 K, while the chip is heated by more than 25 K. This is a demanding task. A further disadvantage is that (in most cases) only the reference, but not additionally required parts are temperature-stabilised. Both disadvantages cause a large size of the complete reference circuit.

For my application, a smaller and less expensive reference circuit is required. But of course, the stability should be as good as possible. I was curios to know what is possible with a 5V reference IC.

To suppress the influence of humidity, a hermetic case of the reference IC must be used. One suitable reference is the LT1236LS8, which was discussed at several places in the metrology forum, e.g. at the „Decapping the LT1236LS8“ thread. Unfortunately, no information (material data sheet) according the materials of this LS8 package are available just now (due to LT acquisition by AD). But this package looks very similar to the Kyocera package KD-VB7955, which uses an alumina base substrate. Kyocera alumina A440 has a thermal conductivity of 14 W/m/K, and the feed-throughs are thin metallic layers, so that thermal gradients at the IC pins are small. Nevertheless, all thermal flows at the IC pins should be as low as possible, since the feedthroughs use W or Mo layers - a low and very constant power consumption of the reference is therefore preferred.

The LT1236-5 offers the relatively rare feature to sense its chip temperature. Reading the data sheet of the LT1236-5LS8, one problem remains with the hermetic package: varying humidity of FR4 PCB material can generate mechanical stress on the LS8 package, which in turn causes instability of the reference voltage. The LT1236-5 has a typical drift with temperature of 2 or 5 ppm/K, and a temperature stabilisation seems to be the only way to suppress this drift.

Having this in mind, a reference circuit should not be mounted on a FR4 PCB material, i.e. a material should be used which has no absorption of water vapour. PTFE can be excluded therefore. Suitable PCB substrate materials are for instance alumina ceramic (Al_2O_3) as used for RF circuit technology, and aluminium as used for power LED and other power electronics carriers. Al substrate PCBs are relatively cheap and easy to get, and therefore this possibility was selected for the first proof-of-concept of the heated LT1236 reference module, since it was not clear whether the temperature sensing of the LT1236-5 chip is reliable. Furthermore, it is assumed (but still to be verified) that the thin isolation layer (thickness 100 µm) on the aluminium substrate does not cause mechanical stress with varying humidity.

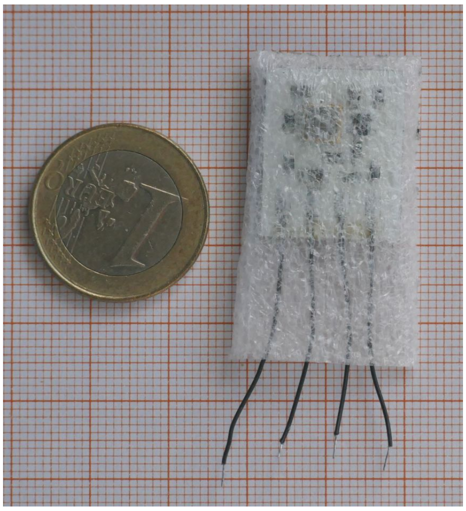
The major idea for a novel LT1236 reference is that the complete circuit is temperature-stabilised and that only Cu-to-Cu material transitions are between the reference module and the non-stabilised PCB. In consequence, the demands on the stability of the thermal gradients are largely relaxed compared to the Kovar-Cu-connections as with the LTZ1000. The reference with controller builds a small module to be mounted on a larger PCB which carries the supporting circuit elements.

The soldering process onto an aluminium substrate is a severe shock for the reference IC. Due to the different thermal expansion coefficients of alumina (7.1 ppm/K, Kyocera A440) and aluminium (23 ppm/K), mechanical stress is frozen at the LS8 package with cooling down, because there are no pins such as gull wing types to reduce mechanical stress. To equalise the stress, it is absolutely essential to use for instance a Sn-Pb-alloy as solder material, but not any lead-free solder. There are leaded alloys which show sufficiently high creepage to obtain low stress after certain days and weeks. A solder alloy containing Cd and Pb would be perfect (melting point ca. 130°C), but tests have shown insufficient wetting of certain circuit elements using suitable flux materials (special fluxes for low temperature are aggressive). A major assumption is now: if the temperature of the aluminium substrate is kept constant, the mechanical stress will be also constant after a certain relaxation period.

In order to reduce the heater power and time constant, the size of the aluminium PCB should be as small as possible (sadly, it must be much larger than with LTZ1000 and LM399 packages). The power consumption of the module should be as low as possible to enable a long period of operation with a backup battery. The Al substrate is slightly larger than needed for the circuit in order to reduce thermal gradients around the LT1236. The temperature controller is a PI type, so that the mean deviation between setpoint and chip temperature is zero. Due to the small SMD circuit size, it is not possible to obtain an equally distributed heating power over the substrate area. The corresponding thermal gradients at the reference location are reduced by the good thermal conductivity of the 1.5 mm aluminium substrate in combination with thermal insulation material, preferably wrapped PE foam foil with at least 2 layers (PE polyethylene: no evaporation of chemical compounds with aging as with other foam materials f.i. PU). The 4 connection wires of the reference circuit have 0.27 mm diameter and 30 mm length to establish a well-defined thermal thermal resistance from the heated reference to the hosting PCB. The according thermal time constant of the reference PCB as thermal block is in the range of minutes, just short enough to enable thermal control. Note: if the thermal insulation is too good, the difference of heating and cooling rate gets too high, and a simple PI controller must show excessive overshot. The PI control parameters are valid only for a particular thermal insulation and wire data. The connection wires start at large solder pads on the Al substrate to direct the thermal flows along the wires well towards the substrate. All connections of the reference circuit to the PCB are pure Cu-Cu transitions. The solder points Cu-solder-Cu will not generate thermal voltages, if there is no temperature gradient inside the solder point itself, also therefore large pads.

Since there are differing thermal expansion coefficients in combination with the creepage of the soldering alloy (and isolation layer of the PCB?), a hysteresis is expected with temperature cycling. But this problem can be avoided if a backup battery bypasses the supply at mains power failure.

The complete reference circuit including PI controller and heaters is on an one-sided aluminium substrate PCB with a size of 22 * 18 * 1.5 mm³, please see picture. With appropriate thermal insulation, the reference module size is 40 * 30 * 7 mm³. The temperature setpoint of the reference is about 38°C depending on the process variations of the LT1236 chip. Other setpoints can be easily selected by changing a single resistor, e.g. a higher temperature setpoint will be necessary for line-powered instruments. The power supply must be a very stable 10V to 15V supply. It is not possible to integrate the voltage regulation on the Al PCB, since the temperature controller must be too slow for the elimination of temperature changes caused by varying power dissipation of the voltage regulator. The current consumption is between 2 mA and 40 mA depending on the surrounding temperature, typically 16 mA at 23°C (38°C setpoint), about 15 mW/K heater power as function of difference setpoint to ambient temperature.



Pic. 1 : Temperature-controlled reference module with LT1236-5LS8 and thermal insulation (only one layer PE foam)

12 references were produced up to now, and no electronic part was damaged by stress of soldering (I had expected more problems). The circuit is working well, the noise voltage is as usual for the LT1236-5, and the temperature control is as good as feasible with a simple analog PI controller. Heating up and coarse settling after switching on needs about 15 min, much more than with LTZ1000A due to the much higher thermal mass.

The temperature setpoint for the controller can be modified even after the soldering process. The module is pre-heated to about 100°C, and an additional trimming resistor is soldered on top of a 0805 resistor to decrease the setpoint temperature. Fortunately, the value of the trimming resistor can be calculated sufficiently precise, so that no iterations are necessary. Setpoint trimming will be made only once shortly after production. A trimpot resistor was omitted due to its size and questionable long-term stability.

The reference module should be soldered directly with Cu wires on the host PCB. The Al PCB substrate can be used as electrical shielding for the reference, so that it can be placed over other electronic parts, provided that there is no varying power dissipation at this place. The mounting of the module is simple due to its low mass (2.4 g) and small size.

Measurements

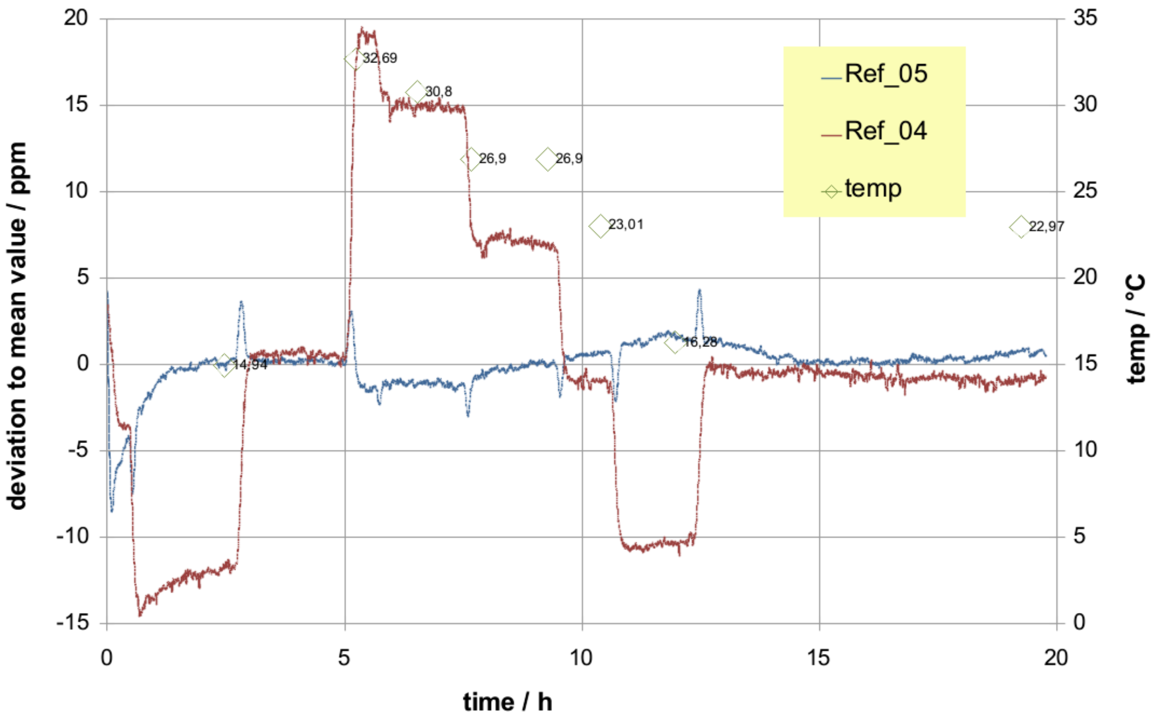
The effect of temperature stabilisation of the LT1236-5 (Ref_05) is shown in Diag. 1 in comparision to the same reference circuit (Ref_04) where the heater is disabled. The reference modules were placed inside a milled box with 5mm aluminium walls. Thermal insulation foam outside around the box reduces the thermal flows along the walls. The box temperature can be controlled by a Peltier module in the range of +5°C to +50°C. The stability and reproducibility of the box sensor temperature is better than 0.02 K, but the thermal homogeneity inside will be much worse (tbd). The diagram was measured with 2 Keysight 34470A instruments with NPLC 100. The box temperature was measured separately by a PT100, indicated by green rhombs, with about 0.03 K reproducibility.

The drifts were measured with a 23 → 15 → 23 → 33 → 31 → 27 → 23 → 16 → 23 °C temperature sequence. After the slopes the test box sensor temperature was constant within ±30 mK. The actual temperature Tref around the reference module is about

Tref = Tbox - 0.03 * (Tbox - Tamb)

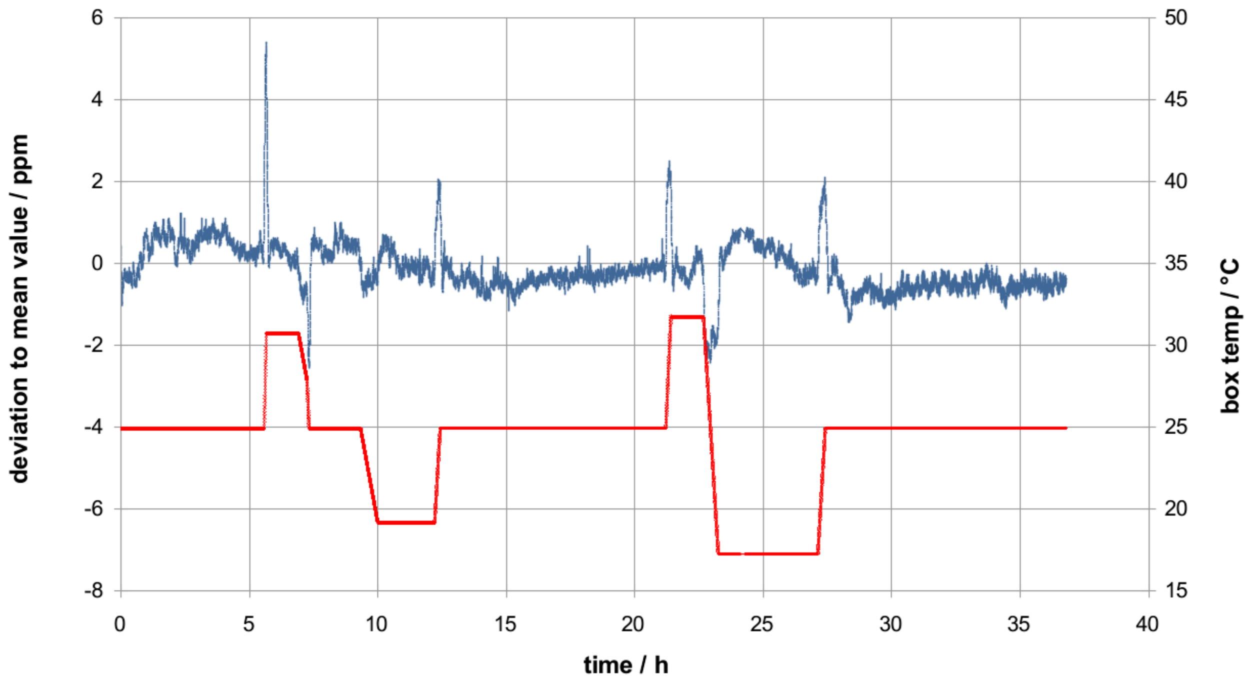
and is therefore also a function of the ambient temperature Tamb, which was about 23°C ±1 °C. Note: there is a small difference between PT100 reading and surrounding temperature of module due to mechanical constraints and heating by module, a precise measurement is hardly possible.

The non-stabilised Ref_04 reflects the box temperature according to its particular drift of +2 ppm/K, which value is within the data sheet specification. The drift of the temperature-stabilised Ref_05 is within a 3.3 ppm range. The peaks of Ref_05 are caused by the 20 mK/s slopes of the box temperature transitions. If we assume that there is only a drift with temperature, the drift of Ref_05 would be about -0.23 ppm/K (this assumption is uncertain). A small hysteresis of Ref_04 might be identified, it would be about 1 ppm with this temperature sequence. Since there were 2 references within the stabilised box, it can’t be excluded that there was a weak interference between the modules. At the first 2 h of this measurement there was a thermal settling of module and cables into box.



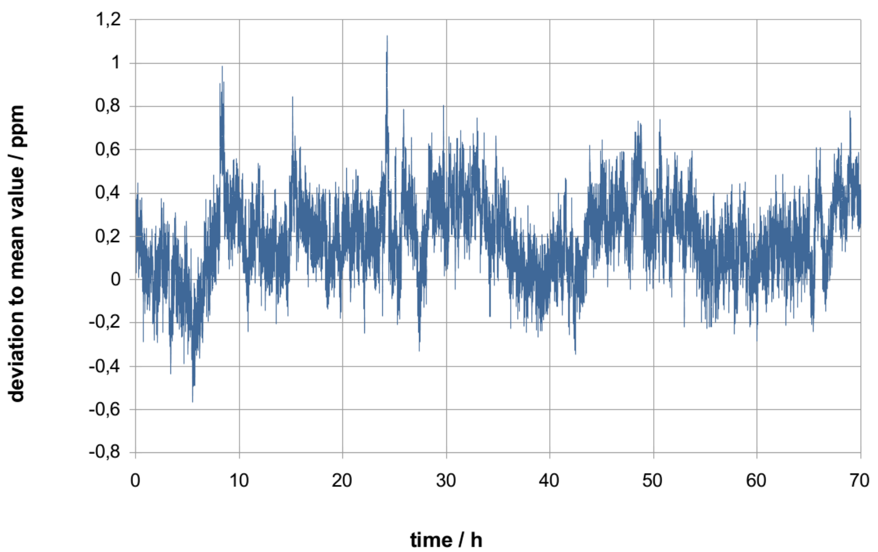
Diag. 1 : drift of 2 reference modules with and without temperature control, box temperature varied in steps

Diag. 2 shows the drift of Ref_07 module. The heights of the deviation peaks correspond to the various rates of the temperature slopes. The reason is the PI controller, which generates a deviation between setpoint and actual temperature proportional to the required slope of the heating power. This temperature deviation causes stress on the reference, however, the resulting hysteresis seems to be less than 0.5 ppm. At low rates <5 mK/s the changes of the reference voltage are lower than the stability limit of about ±1 ppm. The residual temperature coefficient will be anything below 0.15 ppm/K (hard to specify), please assess the diagram yourself.

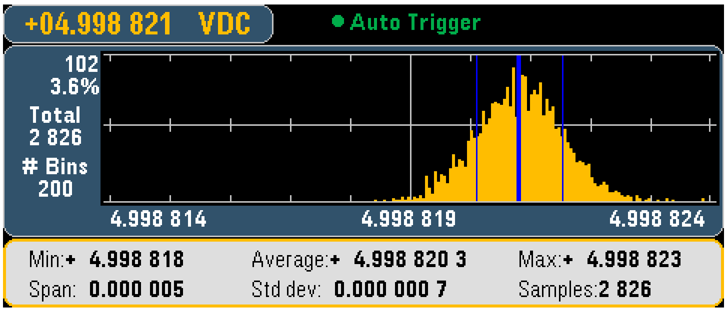


Diag. 2 : drift of reference module Ref_07 (blue) with a test temperature sequence (red)

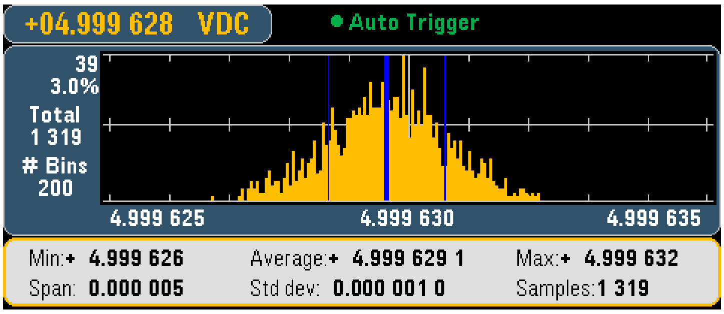
The next diagram Diag. 3 shows the 70 h drift of Ref_05 module while placed in a simple aluminium box with 1 mm walls for EMI shielding. The room temperature and hence the box temperature of about 22°C were not controlled. The reference noise is as expected (measured by 34470A NPLC100). The long term drift is obviously unknown yet, first data please see below.



Diag. 3 : drift of reference Ref_05 under normal laboratory conditions (about ±1 K), NPLC 100



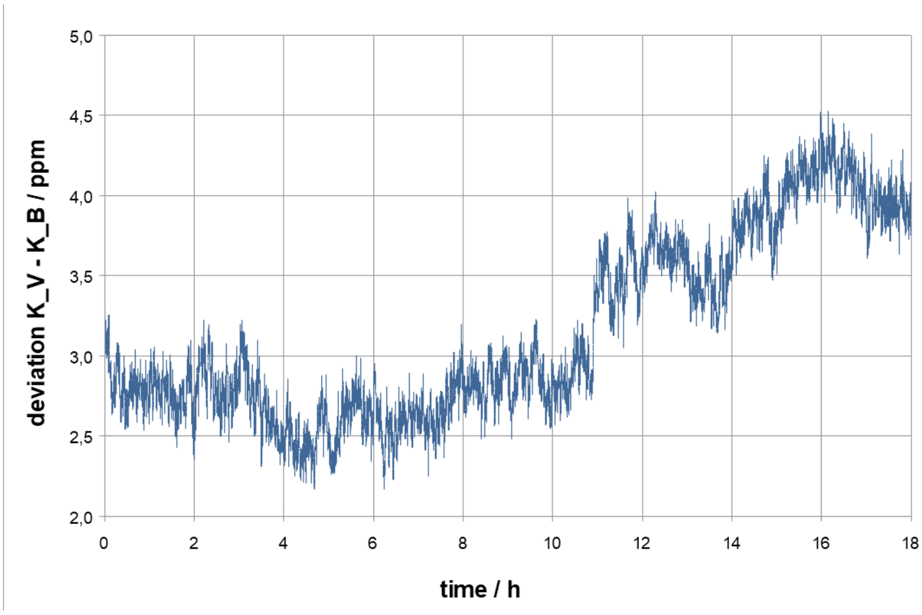
Diag. 4a : histogram of readings with REF_05, NPLC 100



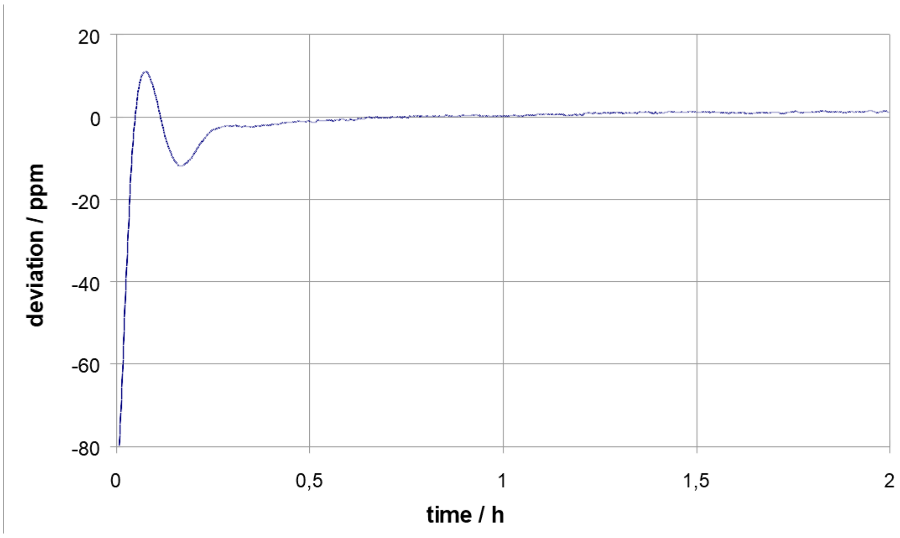
Diag. 4b : histogram of readings with REF_07, NPLC 100

The noise and drift shown in Diag. 3 is close to the drift expected for the KS34470A. The rms noise of the LT1236-5 is about 0.2 ppm for 100 power line cycles integration time measured within a 3 h period, see Diag. 4. Remark: what is the effective bandwidth of NPLC 100 ? Any weighting function?

Diag. 5 shows the difference of readings of two KS34470A which measure the same 5V reference. The difference is within the specifications (8 ppm), maybe the measurement was not made carefully enough (I used no thermal insulation for the input connectors). The according uncertainty of measurement with KS34470A must be considered.



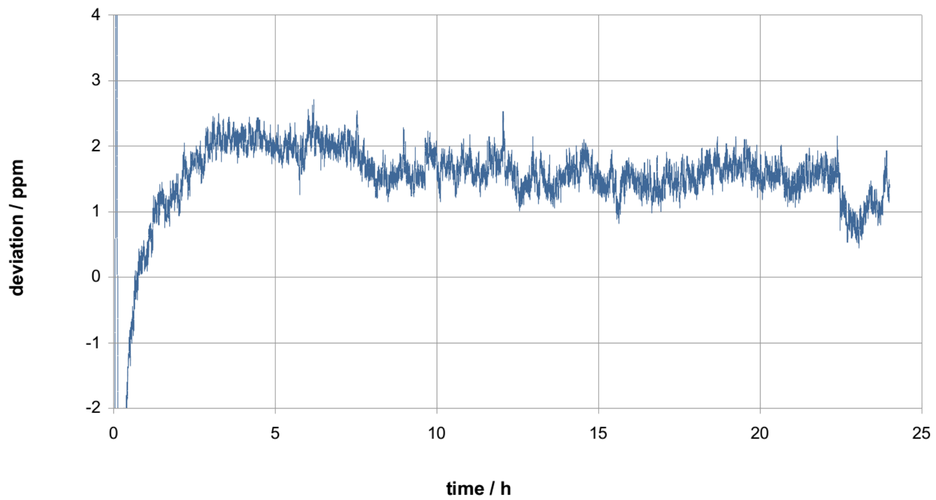
Diag. 5 : difference of the readings of two KS34470A, both connected to the same 5V reference



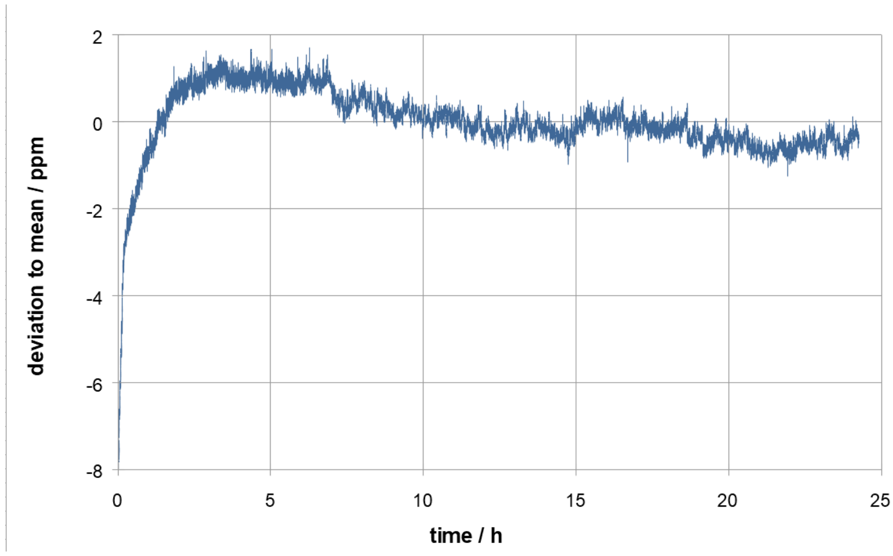
Diag. 6 : power-on drift of Ref_07

When the HLT1236M is switched on, the setpoint temperature is reached after about 15 min with a damped oscillation due to the PI controller (Diag. 6). The non-ideal settling was taken into account to avoid problematic electronic parts. The drift towards the final value can be observed better in Diag. 7. The module was switched off for 12.5 h before this measurement, so that any larger hysteresis as consequence of a power failure should be visible. The deviations are related to the reference voltage value just before switched off.

The hysteresis with an on-off-on cycle could be something like 1.5 ppm, which hysteresis is not unusual (see datasheet LT1236-5LS8 Fig. 2a). According to the data sheet, a hysteresis of (38°C-23°C)*0.5ppm/K = +7.5 ppm would be expected if linear interpolation between datasheet values is applied (other order of dependency, 2nd or 3rd order?). However, this value is already within the uncertainty of the KS34470A, compare with Diag. 5. It can be observed that there is a weak rise and fall of the signal 2 h up to 12 h after starting the measurement. Unfortunately, the KS34470A was switched on only 45 min before measurement of Diag. 6. Such weak signal hump after switching on was reproducible with two different KS34470A, see Diag. 8, where the KS was switched on, but the reference was powered continuously. That's strange, however, fully within the specs. I'm not able to measure these effects correctly with my equipment. Therefore, a reliable interpretation of Diag. 7 is hardly possible, the measurement must be repeated.

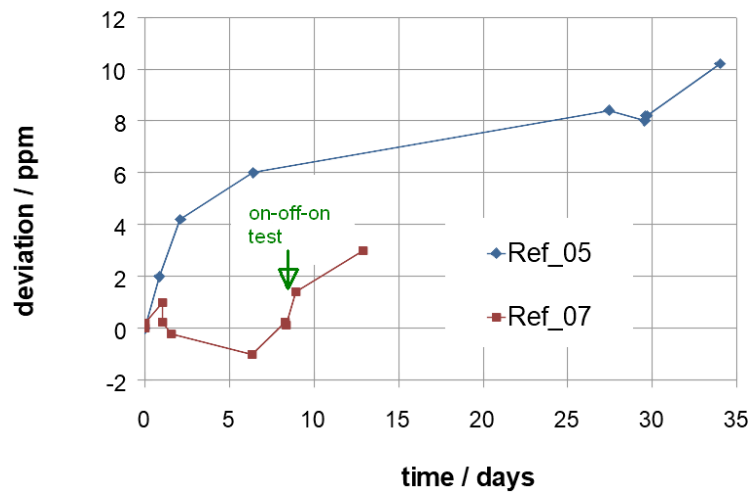


Diag. 7 : power-on drift of Ref_07 within 1 day period, KS34470A powered on 45 min before



Diag. 8 : turn-on drift of KS34470A measuring continuously powered Ref_07

Finally, the first data points of long-term drift are available, see Diag. 9. There are also references which have a negative drift with time. The distribution of drifts is compliant with the long-term drifts shown in Figure 1 of the LT1236-5LS8 data sheet, page 8. The long-term drifts of references on an Al PCB are not worse than those of Fig. 1.



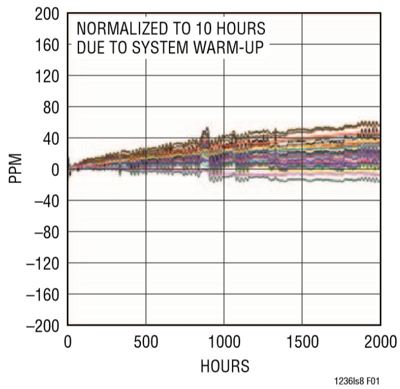


Figure 1. Long-Term Drift

Diag. 9 : long-term drift of Ref_05 and Ref_07

Fig. 1 : drift of LT1236-5LS8

Discussion

The <1 ppm uncertainty level of the LTZ1000 seems to be not available with the LT1236-5, its zener current is just too low. It will be difficult to identify sources of the remaining drifts, and it would take months to do this work while its success is uncertain. The effect of humidity must be analysed next, and the period for final settling for better 5 ppm stability must be determined. First results of long-term drifts are conform with the long-term drifts shown in the data sheet of LT1236-5.

The aluminium PCB induces the problem of differing thermal expansion coefficients. By using an alumina substrate PCB, the thermal hysteresis effect could be avoided, so that there is no reference voltage change if the module was not powered for a longer time. Unfortunately, the thermal conductivity of alumina is more than 10 times lower as of aluminium, so that gradients on the module board due to the heater will be accordingly higher leading to unknown effects. However, the basic uncertainty level of the LT1236-5 can be reached already with an Al PCB if it is powered without interruption.

One important observation was made: the temperature sensing of the LT1236-5 chip was, at least within one month, very stable. Is this statement valid even if we have no temperature stabilisation? If yes, it would be possible to measure the reference voltage as function of the chip temperature, and a suitable fitting function for this relationship is determined. Measurement devices, which use digital data at least at one point of the processing chain, could correct the reference voltage numerically to obtain a temperature drift <0.3 ppm/K without power-hungry temperature stabilisation, for instance for battery-powered instruments. In this case the reference has to be mounted on an alumina PCB to eliminate the effects of humidity and mismatch of thermal expansion coefficients. A PCB layout for first tests is already completed. While looking for a manufacturer, I have found that also alumina PCBs are not free of problems. Cu traces are necessary for low thermal voltages, but it seems to be impossible to place Cu directly on an alumina surface. Therefore, offered technologies use intermediate layers between alumina and Cu layer, possibly a source of further problems. Please consider that the Cu layer has a thermal expansion coeffcient different to that of alumina.

Even if the temperature coefficient could be compensated numerically, one real problem remains: the hysteresis with temperature cycling. Each temperature cycling seems to start a new process of aging, so it is important to avoid this. The temperature stabilisation eliminates this problem. To reduce the effect of power failure, the setpoint temperature should be as low as the system temperature permits.

Summarising, the reference module HLT1236M already satisfies the initial design goals. Important module parameters (e.g. temperature setpoint, maximum heater power) can be easily adapted to the particular application. The LM399 reference, which has higher noise than LT1236, doesn't have this flexibility.

DeltaSigmaD, May 2020