Setting up a SZA263/LTFLU voltage reference

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While voltage references based on LMx99 or LTZ1000CH and LTZ1000ACH are common and lot‘s of information about them is available, there is less knowledge on how to setup a voltage references based on the Motorola SZA263 and the Fluke LTFLU fabricated by Linear Technology.
However, there are reference modules and voltage references available from time to time. Even though noone can say for sure if they are fakes or real world parts, sort out with bad specification or gray market production.
The specimen investigated here were sourced from Walton Electronics from Alibaba.
A teardown of both parts revealed, that SZA263 is a two chip construction in one TO-package with separate silicon and zener diode, while LTFLU is a one chip design, both connected as a refamp with collector, base, emitter of the zener and anode of the silicon diode [EEV01].
Different to LTZ which needs a separate stage to boost the zener voltage to 10 V, the boost of the output on these refamps is part of the zener circuit itself, realized in a bootstrap fashion. However, a 10V output requires an individually trimmed voltage divider for each device from the output to the base of the refamp. As found earlier the t.c. of this divider is rather critical, as it is only dampened by a factor of ~3, while all other resistors of the circuit are less critical and their t.c. is dampened by a factor of 150 ... 500 [EEV02].
The typical zener current is $I_Z = 3$ mA, with the zener voltage varying between $V_C = 6.8 \ldots 7$ V. Operation of this refamp based voltage reference without an oven but somewhat optimized value for R13 can lead to a temperature behavior of < 1 ppm/K over 10..45°C, with a parabolic shape of the t.c. curve. However, for best performance the refamp should be ovenized to achieve 0 ppm/K. To set the zero t.c. for a given temperature the value of R13 needs to be determined, while the range for the current through it is $I_C = 20 \ldots 200$ µA.
This article addresses the findings so far, even though no datasheet is available. Fortunately, circuit diagramms of a lot of Fluke gear can be found using these refamps, which gives a point to start with.

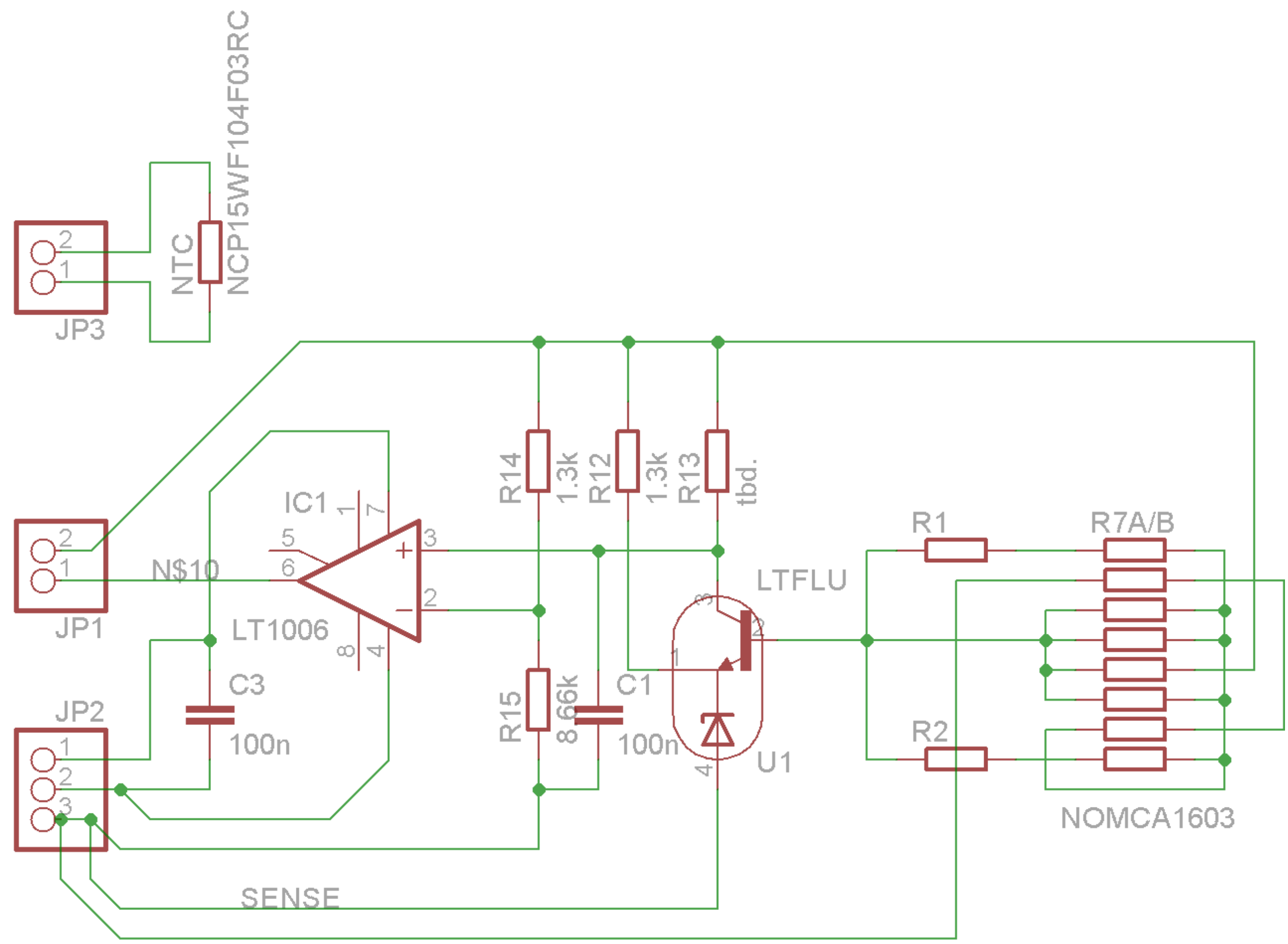

Figure 1: LTFLU circuit

The goal is to build a battery powered, ovenized single supply 10 V voltage reference based on LTFLU1-CH, similar to LTZ1047B designed by Andreas Jahn, a LTZ1000 based portable voltage reference. The oven is planed to use a ceramic or aluminium core substrate mounted on a thickfilm resistor. Preregulation shall be done by LDO LT1763 supplied by a battery pack of 12x 1.2 V Eneloop, a total of 14.4 V.
Based on circuits available a schematic as shown in Figure1 was designed. Therefore a single supply opamp LT1006 (or OPA189, ADA4522-1) comes into play. As for the critical resistor divider R7A/B a NOMCA16035001 is used with additional resistors (R1 and R2) being integrated into the divider to trimm the output voltage to 10.00000 V and to reduce their influence.
The oven temperature is planed to be 45 ... 50°C, which should be enough headroom even in summer. A NTC mounted to the reference board serves as a temperature sensor for the oven. NCP15 series by Murata is said to have good longterm stability, thus it is used here.
Zero t.c. temperature has to be found within the desired temperature range by adjusting R13 respectively. To do so a breadboard was used with R7A/B pretrimmed for a nominal 10V output voltage by arranging the NOMCA resistor network to R7A = 5 kΩ and R7B = 11 kΩ. This is necessary, as the output voltage also influences the current through a given R13.
Measurements of temperature profile inside a temperature chamber while varying R13 with a decade resistor box gave the following values for the zero t.c. temperature:

R13 = 25.343 kΩ: ~30°C
R13 = 24 kΩ: ~35°C

Zero t.c. point is the middle highest point of the flipped parabolic shaped curve, when plotting output voltage over temperature.
Assuming a linear correlation between I_C and zero t.c. temperature point a value of about 22 kΩ for a temperature setpoint of 45°C can be calculated. A repeated temperature profile well agreed with the assumptions, the zero t.c. point is well within 45 … 50°C.
Based on this results a reference board was designed as shown in Figure2. It's 20 x 40 mm² in size. The LTFLU is soldered in a SMT style to the board and the output is realized as a 4 wire connection.

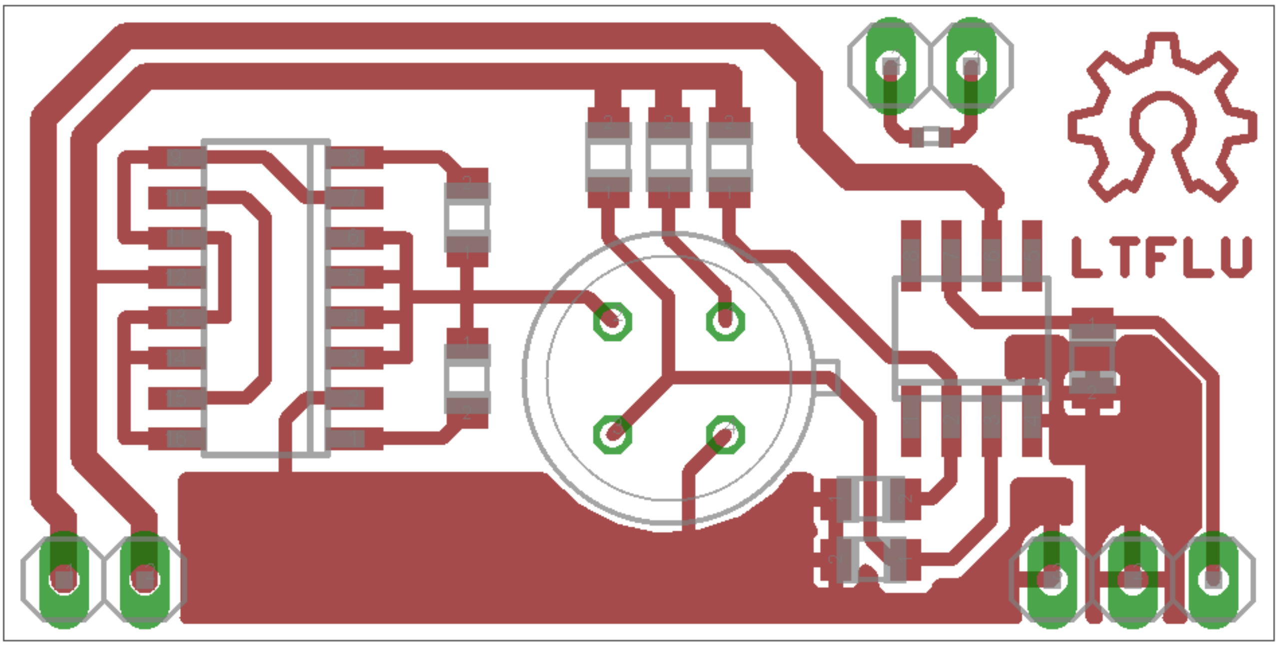

Figure 2: LTFLU reference board

Several temperature profiles were performed with R13 = 22 kΩ and by varying the additional resistors R1 and R2, giving the following results.

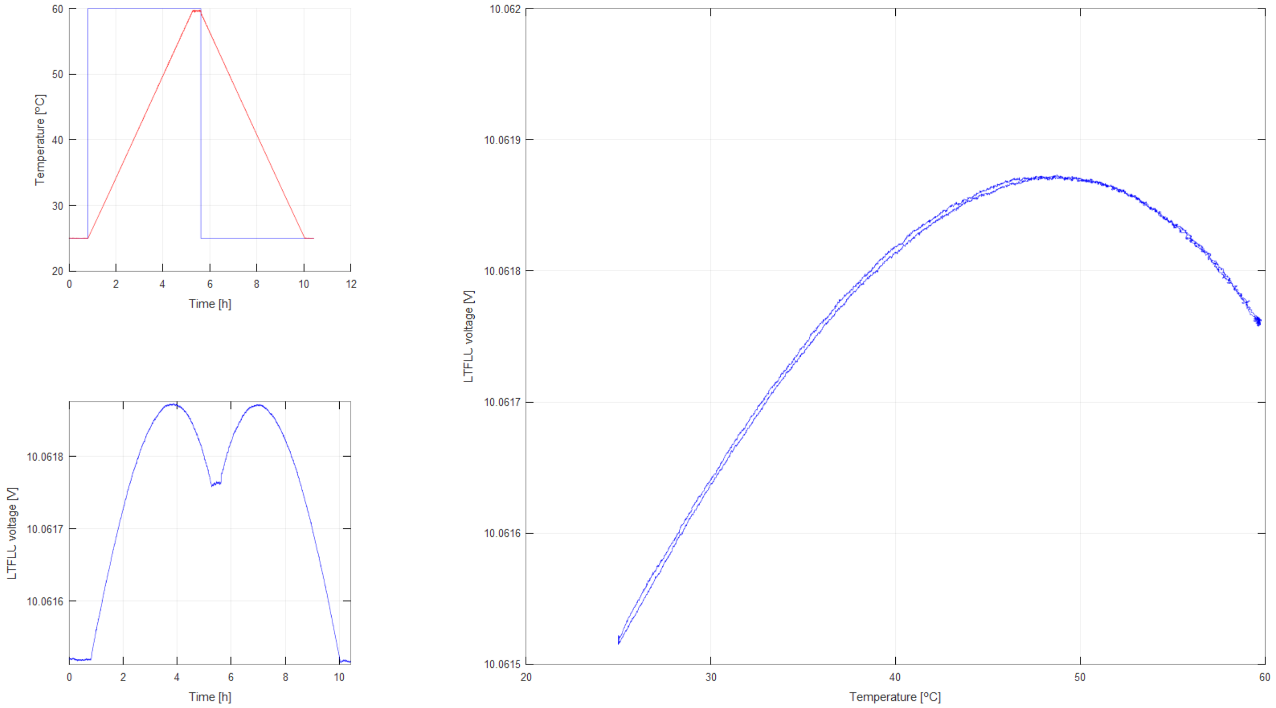

Figure 3: temperature profile 1

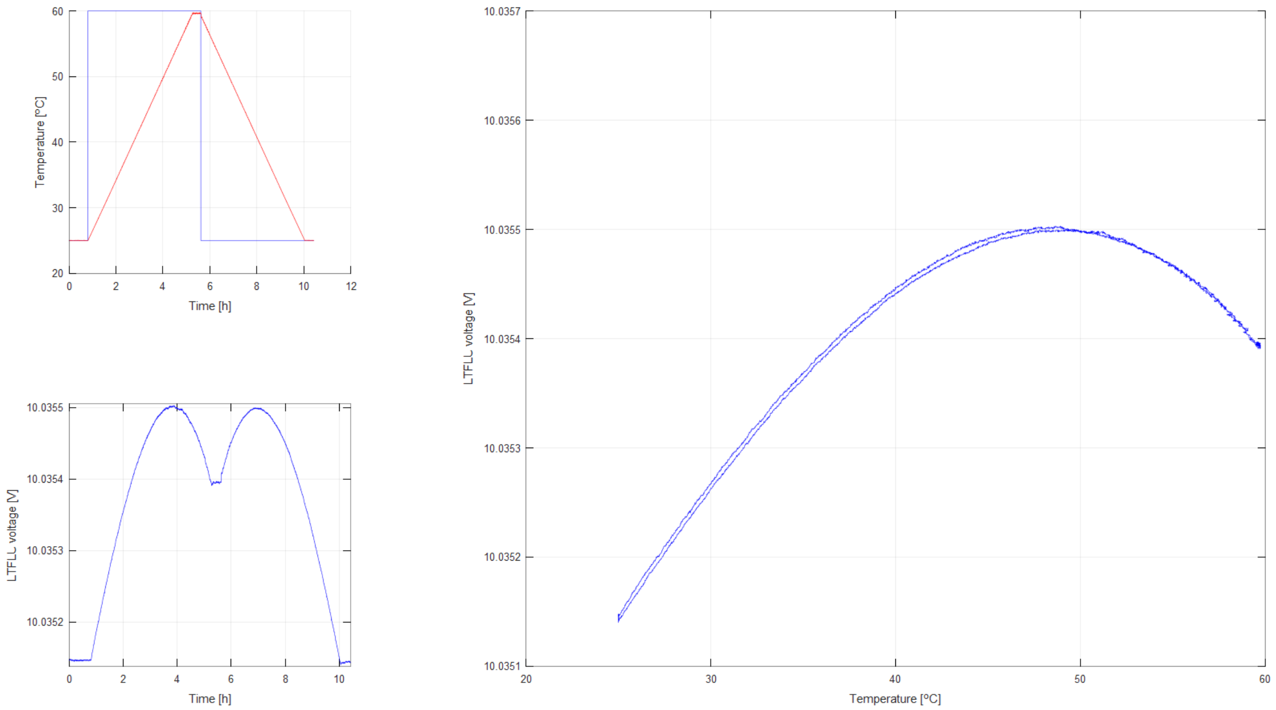

Figure 4: temperature profile 2

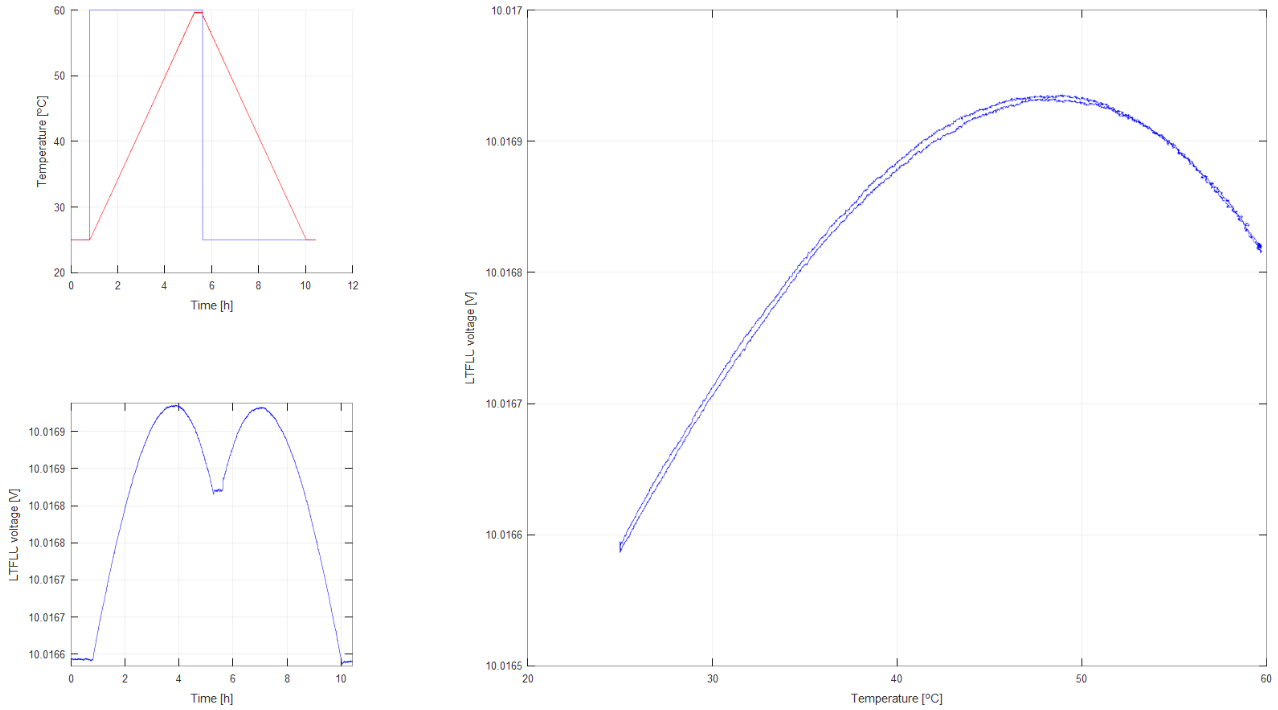

Figure 5: temperature profile 3

	Profile 1	Profile 2	Profile 3
R7A	5 kΩ	5 kΩ	5 kΩ
R7B	10.9091 kΩ	11 kΩ	11.0651 kΩ
Ratio	0.4583	0.4545	0.4519
Voltage @ zero t.c.	10.061870 V	10.035500 V	10.016960 V

With the values given one can calculate the required ratio of 0.4494 as well as the required resistors to trimm the output to 10.00000 V. It turns out that for this specimen R1 = 6.2 kΩ trimms the output to the required range, while R2 = 0 … 10 Ω adjusts the output to the final value.

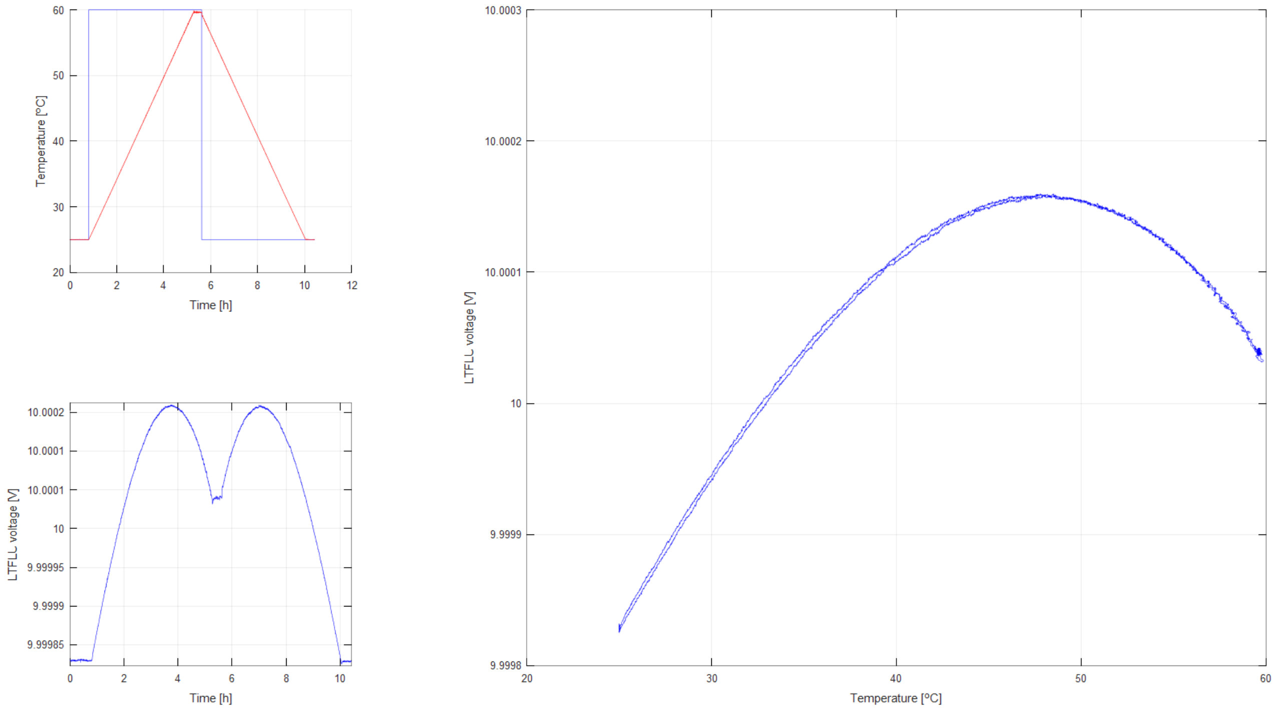

Figure 6: temperature profile 4

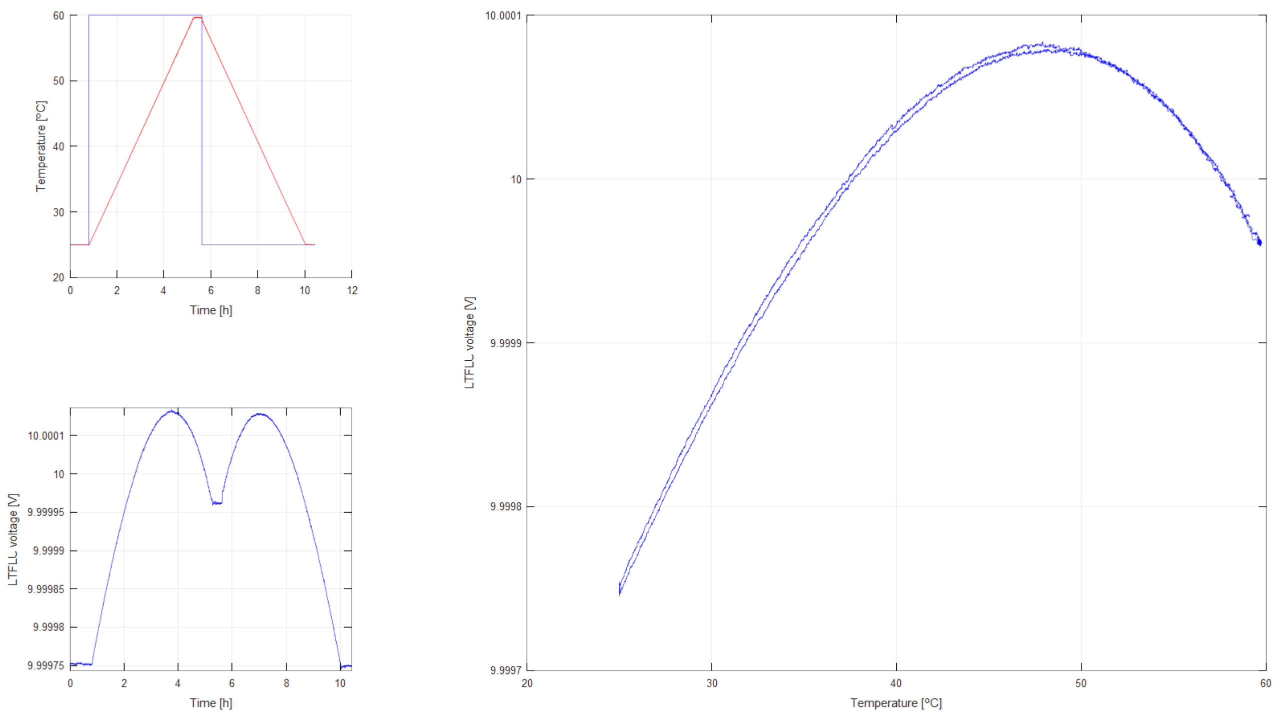

Figure 7: temperature profile 5

Up to this point all the measurements were performed with the aluminum board in a temperature controlled incubator and the temperature sensor used is the one inside the thermal chamber itself, with an Arroyo 5305 temperature controller.

For the final application the aluminum board with the reference circuit and a 10 kΩ NTC type NCP15XH103F03RC with a Beta = 3380 K is assembled with a thickfilm resistor BPR10J101 attached to its back. The whole assembly is located inside a styrofoam box and lined with wadding.

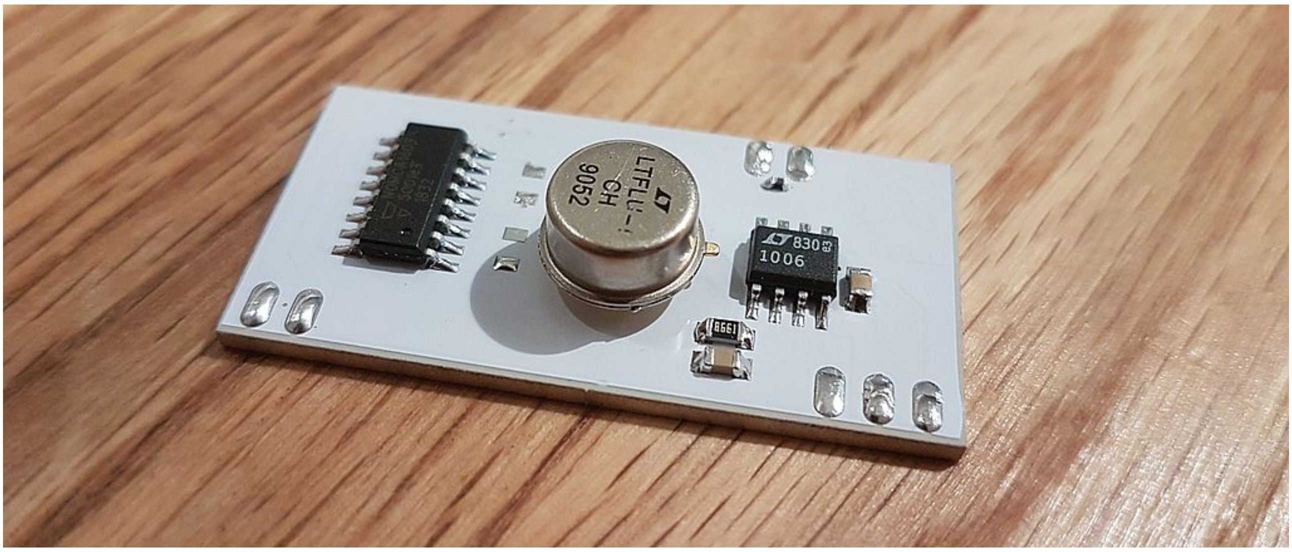

Figure 8: LTFLU on aluminum board

First a W1209 2-point controller was used to stabilize the oven temperature, which is powered by 12 V and uses a 10 kΩ NTCs. It can be set to the required oven temperature with a resolution of 0.1 K. It turned out to create large temperature gradients on the aluminum board and the reference, that resulted in voltage readings with large switching noise. Thus, the idea was discarded and a linear temperature controller approach got in focus.

The resistance over temperature and Beta of the NTC are given in the corresponding datasheet. This values were translated into coefficients for the Steinhart-Hart equation using an online calculator:

https://www.thinksrs.com/downloads/programs/therm%20calc/ntccalibrator/ntccalculator.html

and fed into the Arroyo 5305 TEC controller, that can be configured to heat only modus with output voltages of up to 12 V.

First of all the controller and its autotune function was used to find the optimum PID parameters. Second, a temperature sweep was performed to find the temperature of the oven, at which the temperature coefficient of the voltage reference is zero. It turned out, that the sweet spot was at 47.844°C.

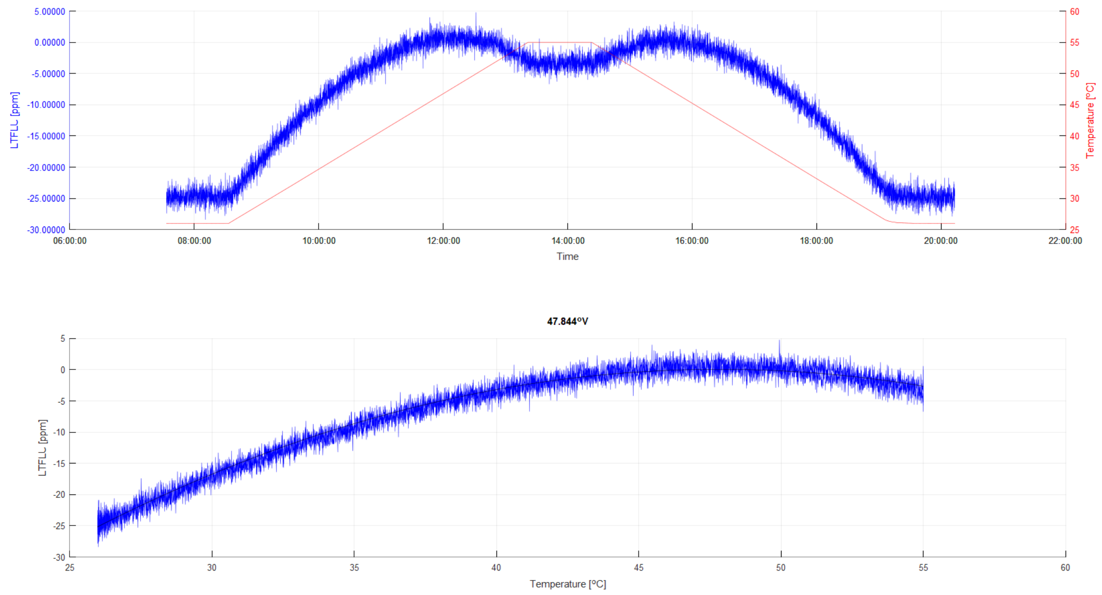

Figure 9: Temperature profile of the oven assembly with Arroyo 5305

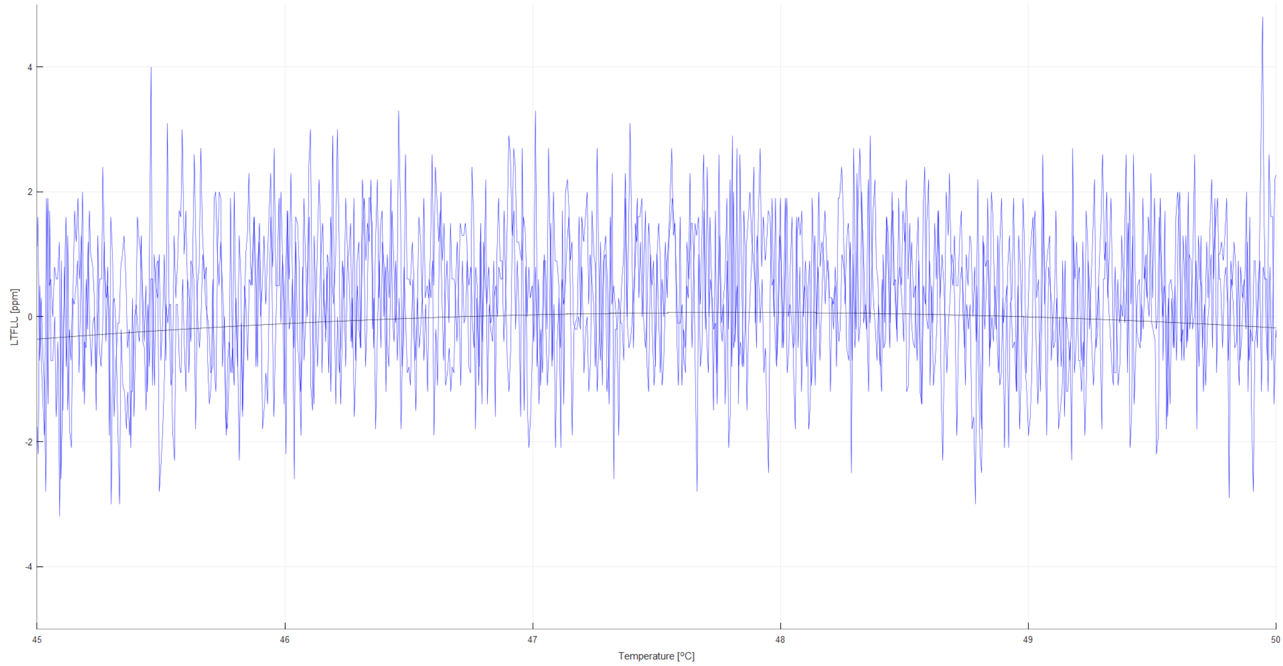

Figure 10: Zoomed area, over a range of ±5 K a change of less than 0.3 ppm can be noticed

A temperature around 48°C appears to be a good choice. Furthermore, the output voltage of the controller at this temperature was determined to be about 7.6 V.

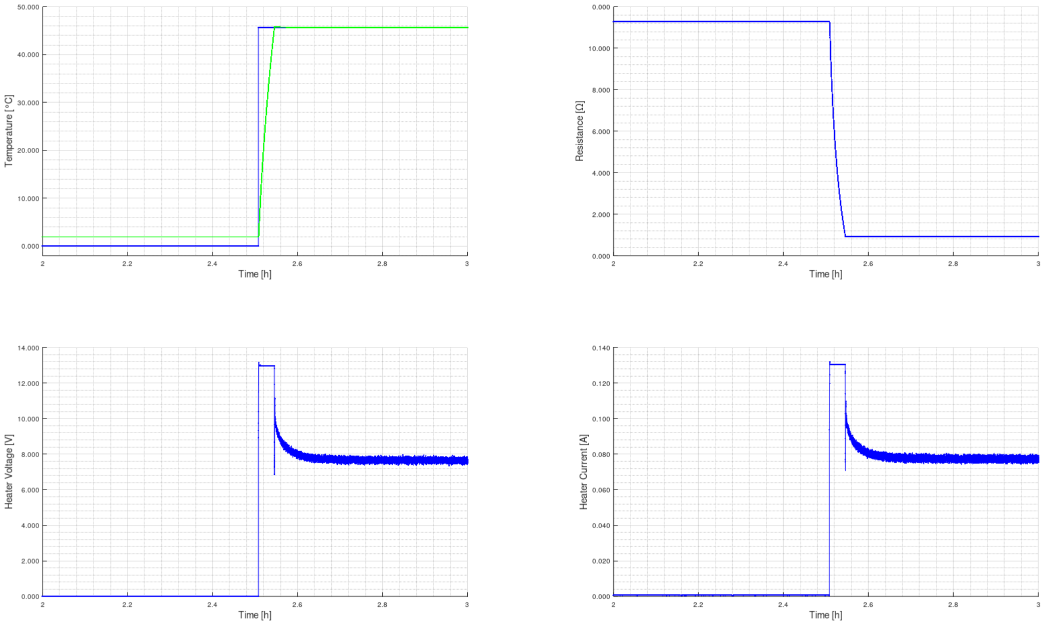

Figure 11: Temperature jump to ztc temperature

To derive the impulse response of the oven assembly alone aka of the open loop a voltage jump from 0V to 7.6 V across the heater resistor was performed using a lab power supply, while the controller was used to sample the NTC resistance as well as the calculated temperature.

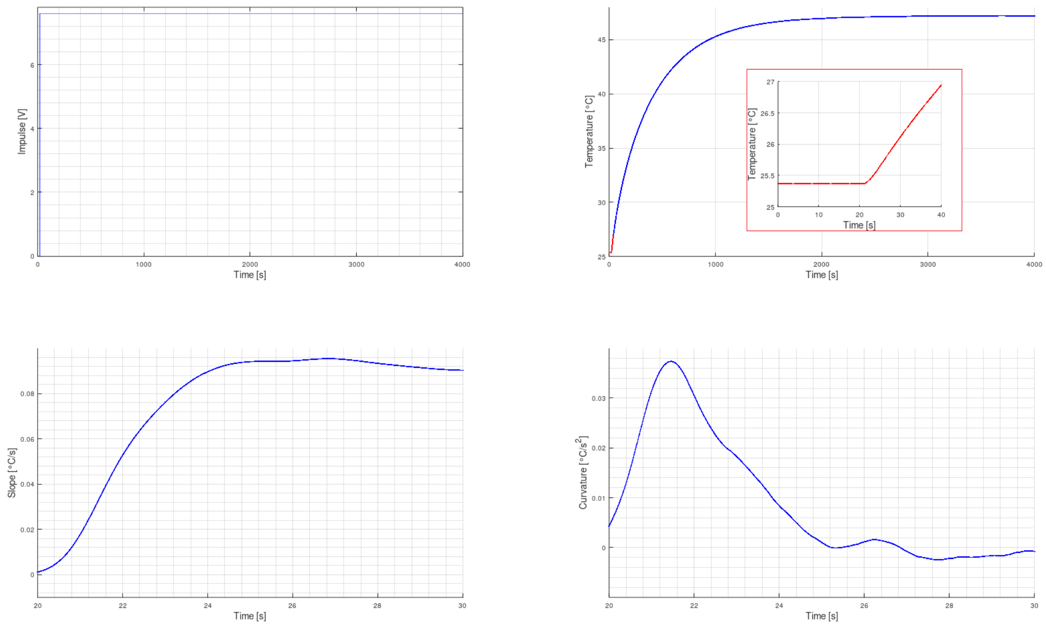

Figure 12: Open loop impulse response of the oven

As shown, the oven assembly acts as a PT2 term. From the second derivative of the measured oven temperature the inflection point can be derived and the slope in this point from the first derivative. From there the tangent of inflection and both the dead time T_u and the compensation time T_g were calculated. This calculation was performed in GNU Octave using the diff command.

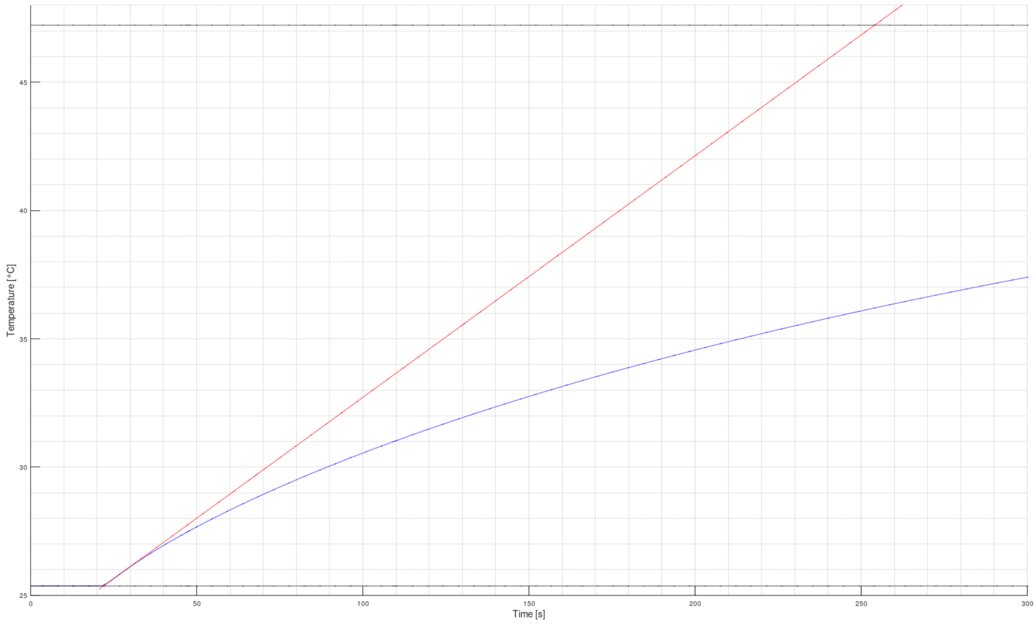

Figure 13: Determination of tangent of inflection and time constants

inflection point at t = 4.753 s

slope m = 0.094185°C/s

T_u = 1.494 s and T_g = 232.0457 s, let's call it T_u = 1.5 s and T_g = 232 s with a controllability T_g/T_u = 155

A controllability of >10 is perfect.

https://www.elektroniktutor.de/regelungstechnik/p_str.html

From here K_S can be calculated to $K_S = \frac{47.22327\,°C - 25.36802\,°C}{7.6\,V} = 2.87569 \frac{°C}{V}$.

The oven draws about 73 mA at 7.6V, which is 550mW.

Now that the behavior of the oven is well known the controller can be designed. It was decided to use a PI controller. With the help of H. Walter and the control_theory1.lib by Helmut S.

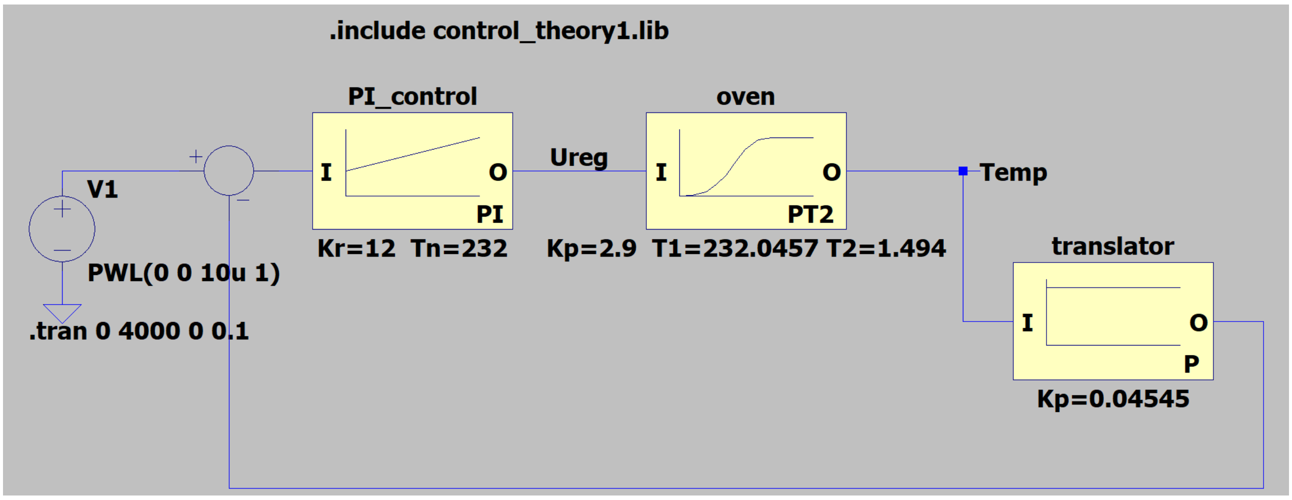

Figure 14: Simulation model as a block diagram

https://www.mikrocontroller.net/attachment/302927/control_theory1.zip

a block diagram of the controller was build in LTspice and simulated.
The block diagram was then translated into an analog circuit and again build in LTspice, including the PI controller as well as a target delay to play with, the oven response as a PT2 term and the coupling with the NTC temperature sensor. The circuit was designed to use a single +12 V power rail for reference and oven only, thus an AD822 was used.

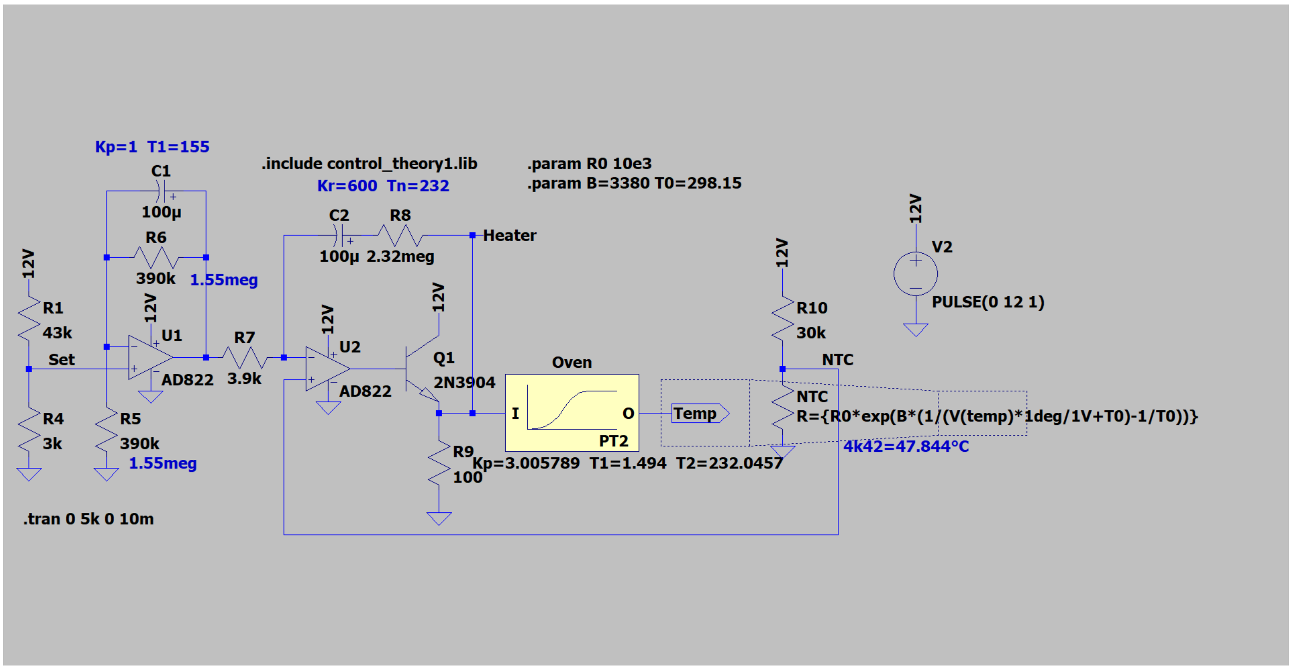

Figure 15: Simulation model of the analog temperature controller

The simulation results prove, that a temperature of 47.59°C should be reached, using standard resistor values without further adjustment, which is close enough to the optimum zero t.c. point of 47.844°C.

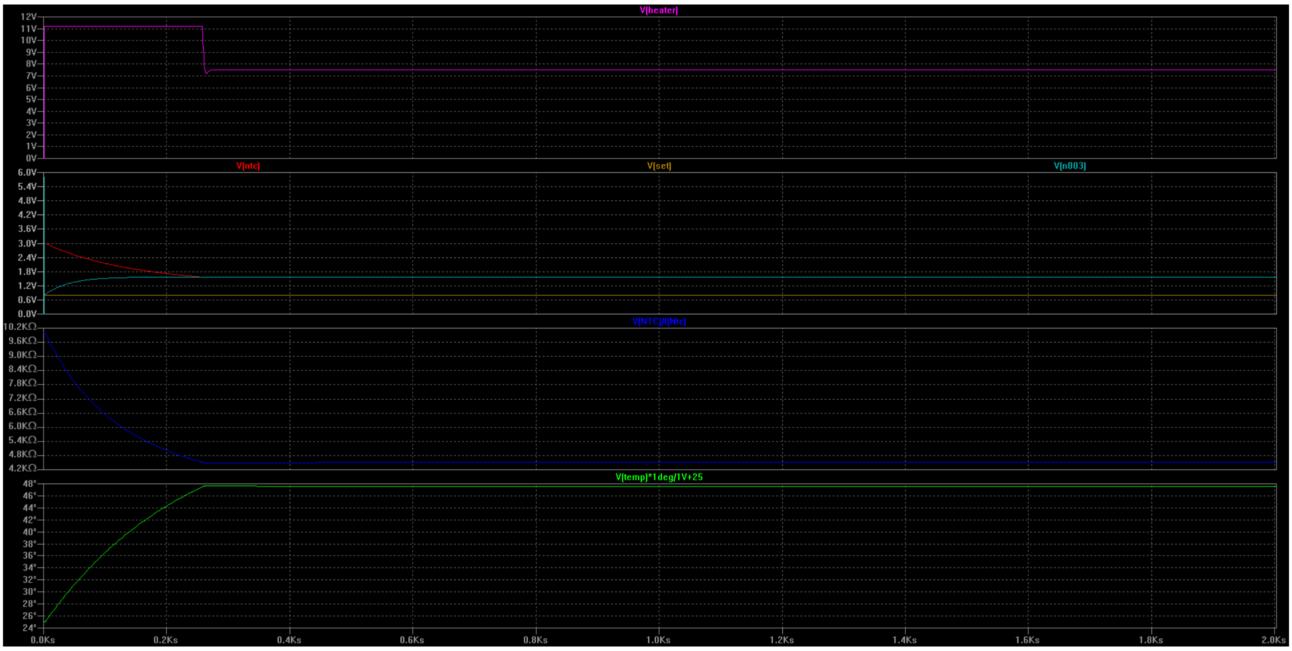

Figure 16: Controller response as per simulation model

Based on this a perfboard for the oven was hacked together and tested for stability.

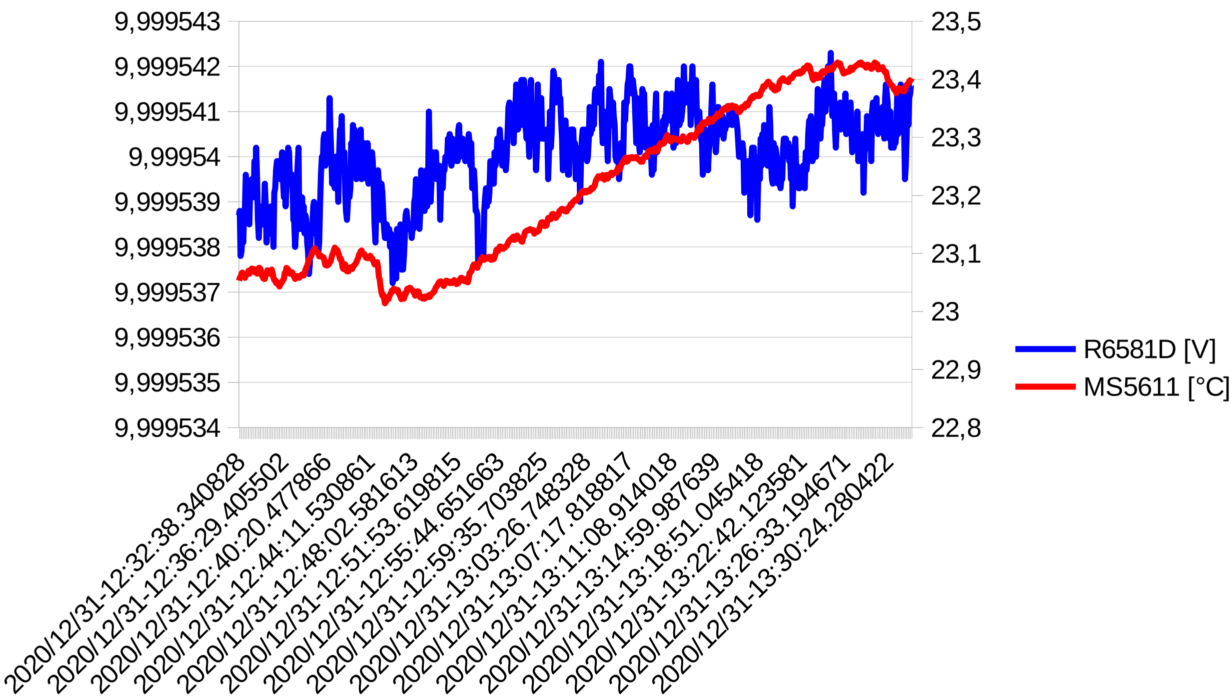

Figure 17: Stability measurement

It was found, that the reference is rather noisy (refer to 1h stability measurement in the figure above). Since it wasn't clear if this is limited by the noise of the NOMCA16035001 network or the reference itself, a new revision with TOMC16031002 network was designed.

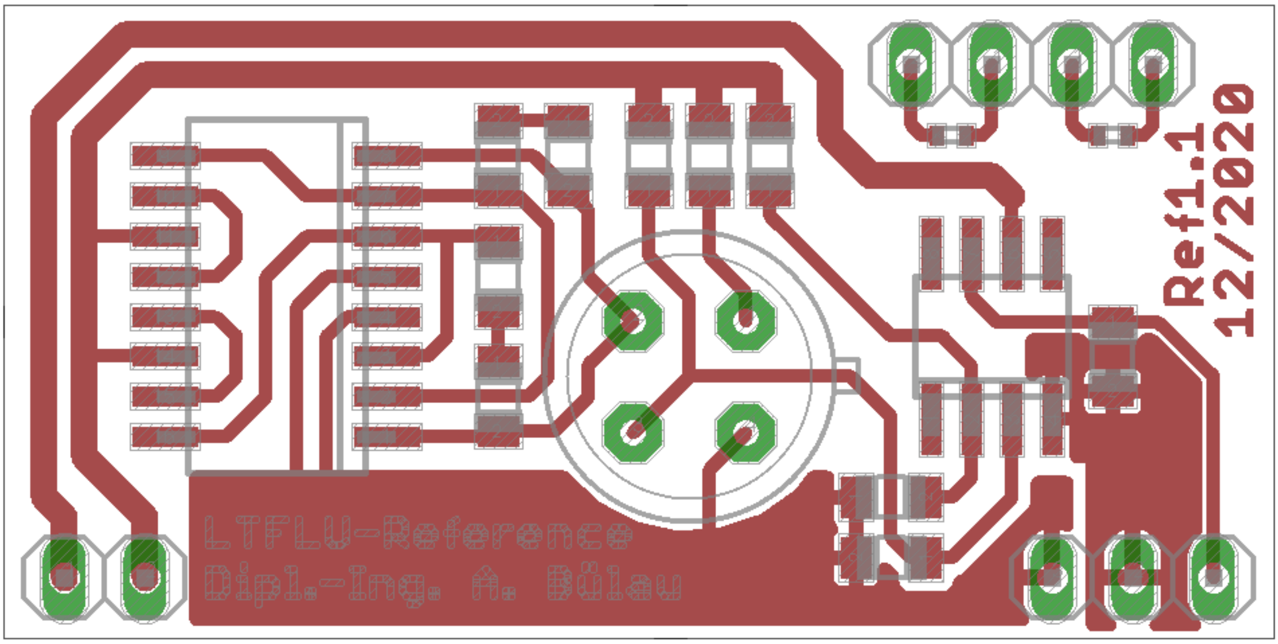

Figure 18: New board design

This network series was chosen, because pre-liminary numbers provided by Nikolai Beev of several resistor networks series noise index:

https://www.eevblog.com/forum/metrology/statistical-arrays/msg3137942/#msg3137942

https://www.eevblog.com/forum/metrology/diy-high-resolution-multi-slope-converter/msg3392180/#msg3392180

NOMCA: 5kOhm -24.9 dB; 10 kOhm -29.5 dB;
TOMC: 10kOhm -52.1 dB;

as well as own measurement indicated, that lower noise - more than a factor of 10 - from TOMC is to be expected.
Unfortunately TOMC comes in a slightly different package than NOMCA, medium SOIC16 instead of narrow SOIC16 and wasn't available in a 5kΩ version but 10kΩ instead, so it couldn't be used as a drop-in replacement.
The modified circuit thus has a slightly different resistor arrangement. Furthermore, the network has a different connection scheme to allow trimming either the upper or the lower part of the network. This way references with different output voltages can be adjusted to 10V. A second NTC was added, to allow observing oven stability with an external measurement device.
The LTFLU reference and other components were transplanted to the new board and the trimming resistors were assembled with shorts in the first place.

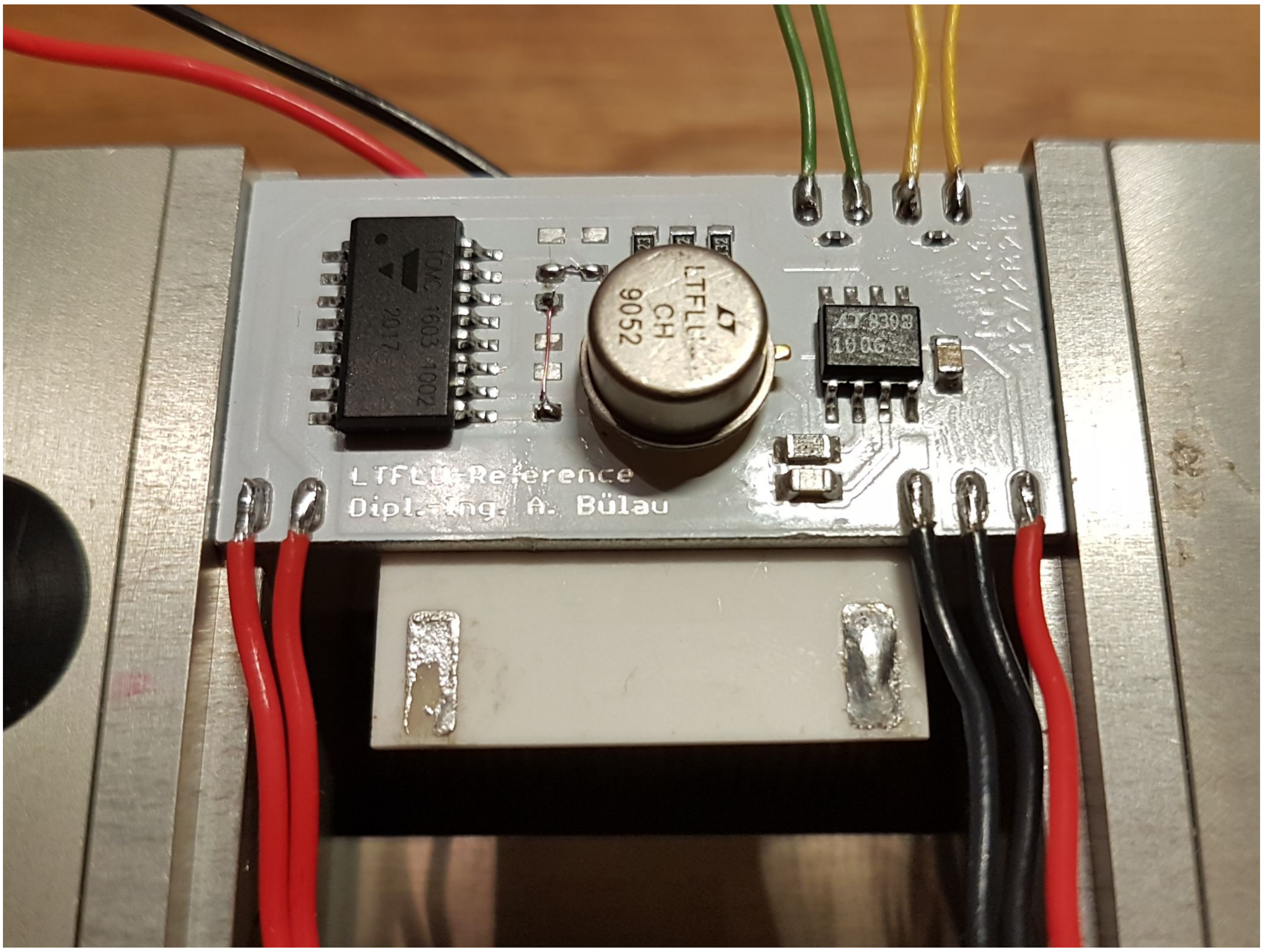

Figure 19: Assembly of new board

The board was then put back into its styrofoam box and connected to the TEC controller. Starting with the former found PID parameters a new autotune was performed using the first onboard NTC. It turned out that with the new board the parameters slightly changed from:

P=0.4760, I=0.0012, D=4.1801 to P=0.4716103, I=0.0012545, D=3.2423208

With this parameter another temperature sweep from 25 to 60°C and back was performed to test how zero t.c. temperature point changed. The second onboard NTC was monitored with a meter in parallel. The z.t.c. temperature was found at ~54.5°C, due to the higher output voltage of 10.35 V.

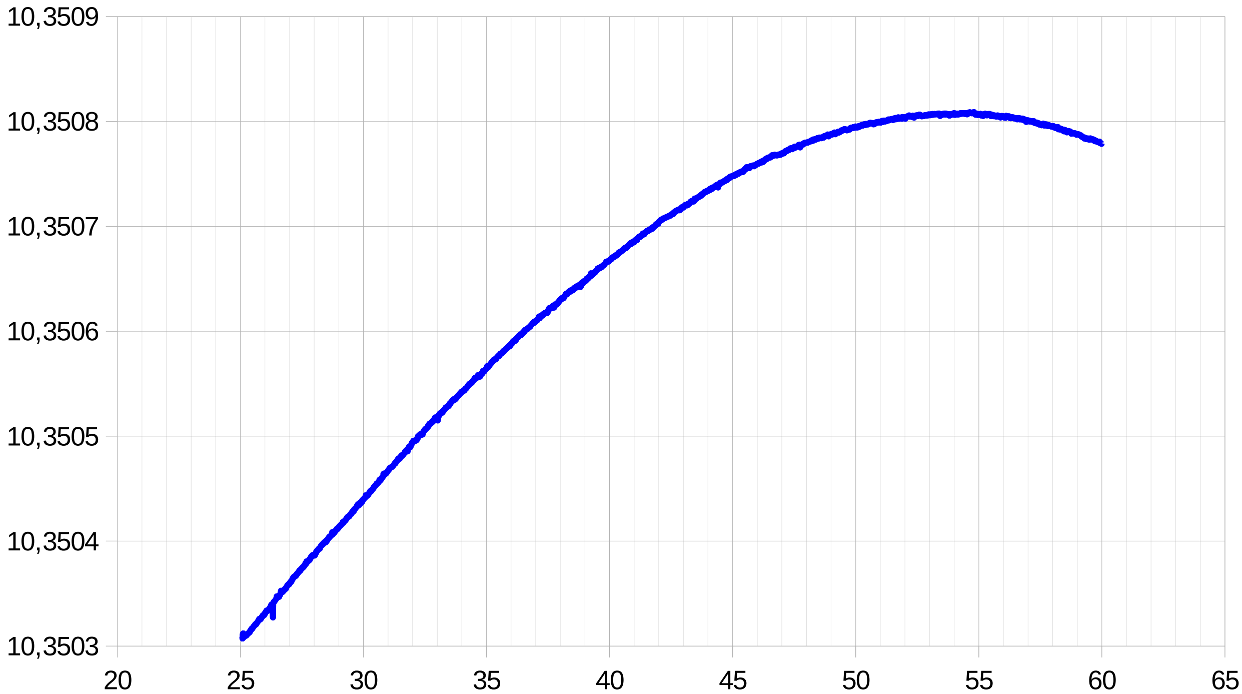

Figure 20: Temperature sweep

Next, stability at z.t.c. temperature was tested. The figure below shows the 1h stability. Compared to former stability measurement with NOMCA network, noise has somewhat improved, but still wasn't satisfying.

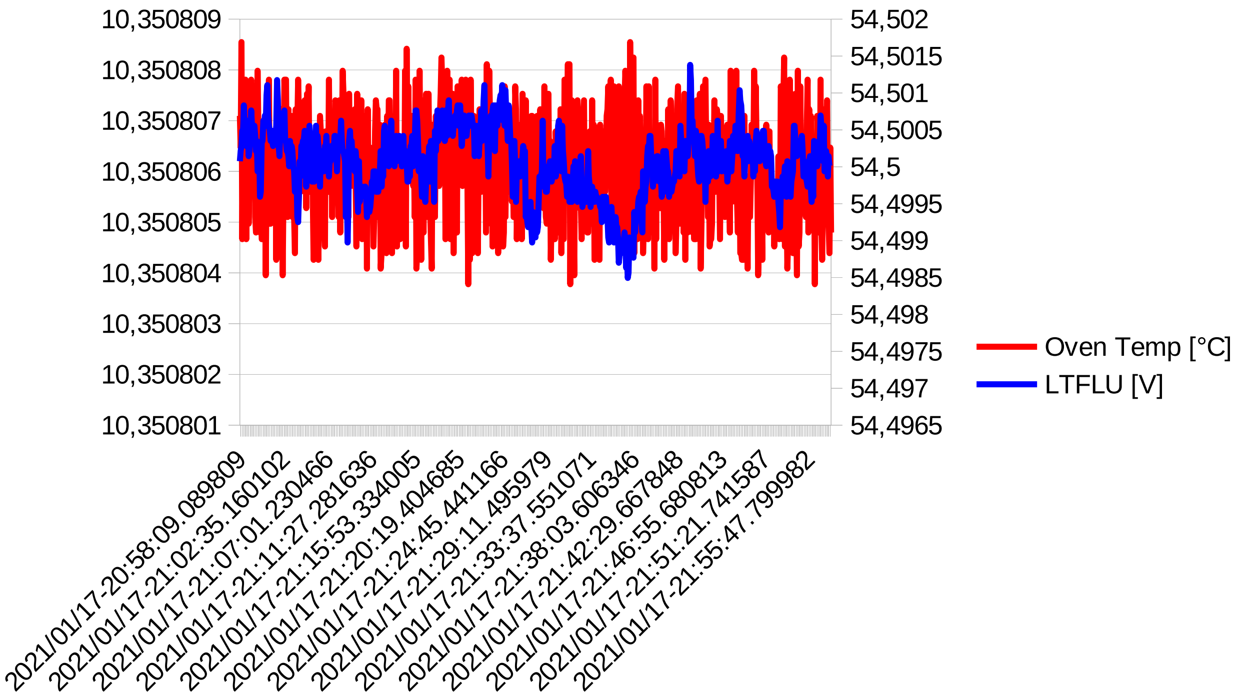

Figure 21: Stability measurement

The ouput voltage was then trimmed using a General Radio 1434-G decade resistors. Since this trimming changes the output voltage also the current I_C will change so does the z.t.c. temperature. Thus, another temperature sweep was performed and z.t.c. was found at about 45.5°C with the output voltage being about 20 ppm above 10V. Both, trimming and finding the new z.t.c.

temperature go hand in hand with each other, but the closer one gets to the final value for the output voltage and the smaller it changes, the smaller the effects on the z.t.c. temperature.

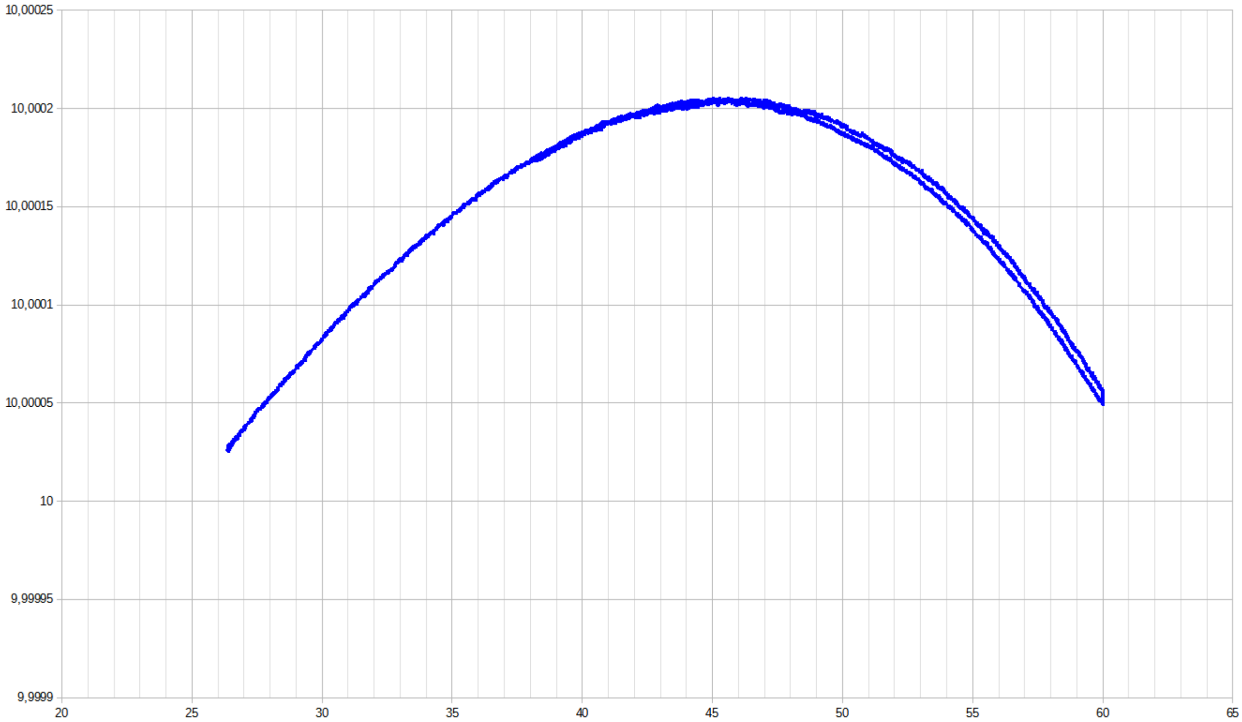

Figure 22: Temperature sweep

During the experiments it was observed, that leaving the aluminum board floating resulted in all sorts of disturbance of the reference output voltage and spikes by interference due to an unknown external source, that fully vanished, once the aluminum was tied to ground.
A measurement of the stability over a few hours shows, that noise is now more in the order of a conventional low noise reference such as LTZ1000, but still slightly higher. Though, using TOMC network improved things significantly.

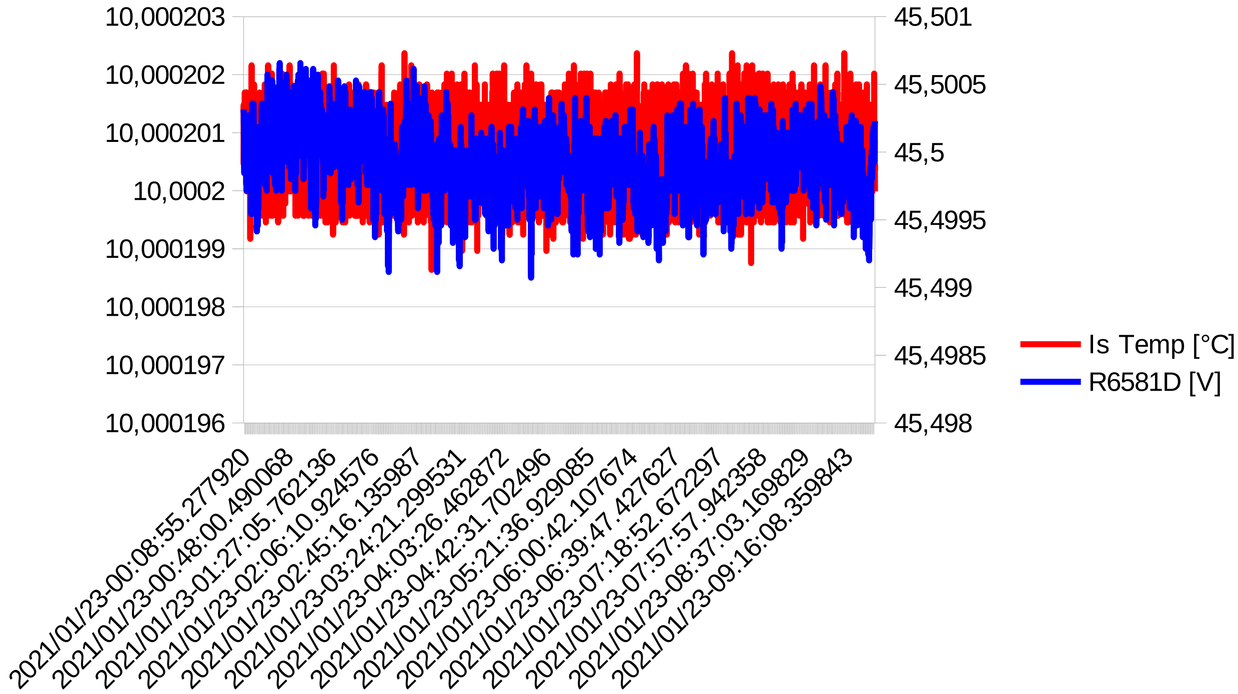

Figure 23: Stability measurement with aluminum board grounded

Next step is to adjust the discrete oven to the new temperature and repeat measurements (stability, noise etc.).

To be continued…

References

[EEV01] https://www.eevblog.com/forum/metrology/the-ltflu-(aka-sza263)-reference-zener-diode-circuit/msg911832/#msg911832
[EEV02] https://www.eevblog.com/forum/metrology/the-ltflu-(aka-sza263)-reference-zener-diode-circuit/msg1066470/#msg1066470