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Application Note

TDC-GP30-F01

Scaling calibration coefficients by 2-point calibration

Content Guide

1 General Description

The ams TDC-GP30-F01 comes with firmware that supports calibration methods for individual spool pieces. While a complete characterization for the design demands a wide set of measurement data, mass production should be more efficient. Therefore, the firmware supports a 2-point calibration in production, assuming that the set of non-linear coefficients (evaluated during development) is typical and valid for all devices.

Figure 1: Full characterization during development vs. 2-point calibration in production

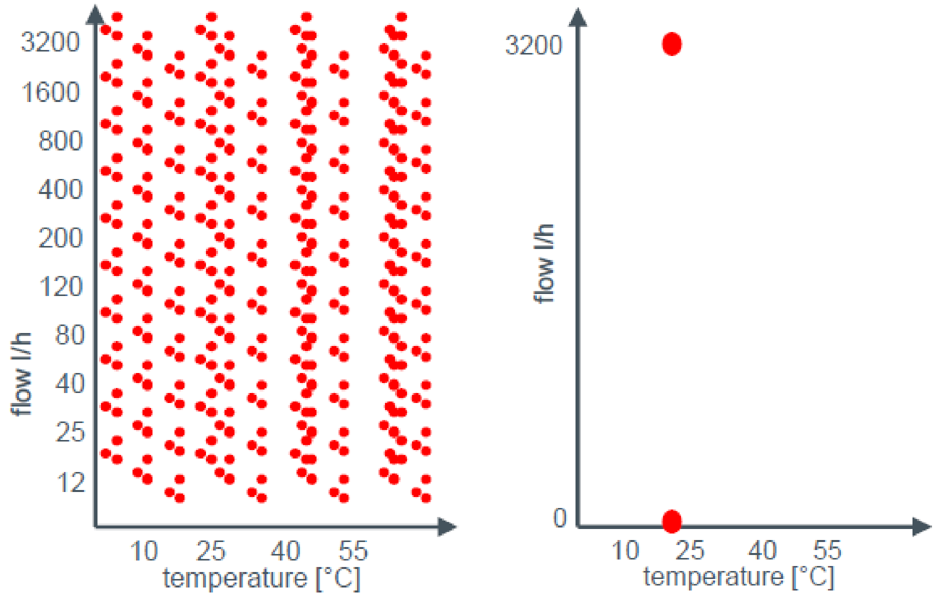
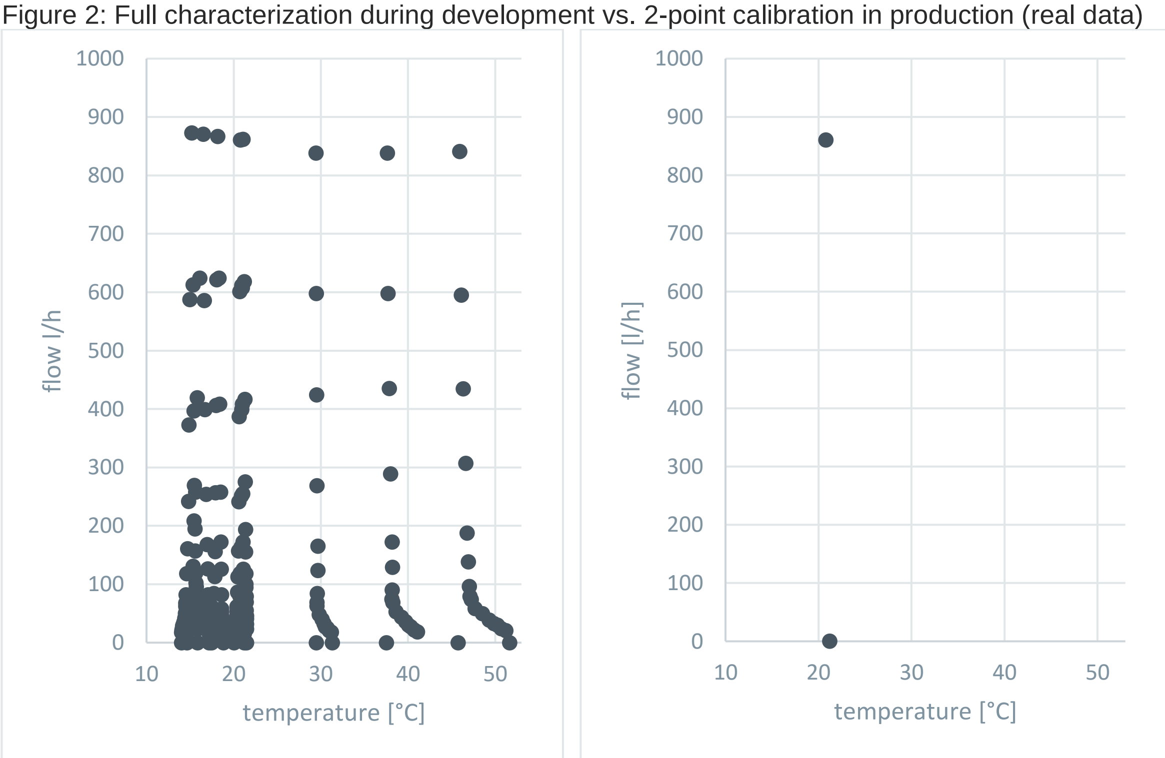


Figure 2: Full characterization during development vs. 2-point calibration in production (real data)



In this document we discuss the proposed method to adapt calibration coefficients, gained from a basic characterization of a particular spool piece design, into individual calibration coefficients for each device in production. For details on chip and firmware structure and function, please refer to the corresponding manuals in the GP30 documentation.

In principle, it would be possible to do a full characterization of each single spool piece, using a vast number of measurements and creating a completely autonomous set of calibration coefficients for each device. Of course, this is not at all desirable or even reasonable for mass production. Instead, a well-qualified and complete characterization is done during development phase, based on a representative sample lot of devices, and resulting in a general set of calibration coefficients. In production, these coefficients are adapted for each individual device using a minimum number of measurements. According to legal regulation, at least one flow measurement for each device is strictly required. The following proposal aims at using only this one flow measurement, and in addition one zero-flow measurement.

It should be pointed out that the methods and scaling rules discussed in this document have to be understood as a proposal. It is believed to be usable and reasonable, but it remains the customer's responsibility to check the validity and applicability. Of course, GP30 firmware and hardware permit the use of more advanced calibration methods, which may improve accuracy or which may be more advantageous in the particular case of the customer. Some approaches for more complex scaling rules are discussed at the end of the next two sections. It remains the customer's free decision which degree of effort is required or justified to suit his needs.

2 Assumptions and Conditions

The proposed method for production calibration using only one flow measurement and one zero-flow measurement rely on a number of assumptions which depend on production quality and aging behavior. It should be clear that with ideal tolerance-free and non-aging devices, no calibration in production would be needed and the same set of calibration coefficients would fit all devices. From measurement experience, this is unfortunately not the case for real spool pieces. The following properties will usually need an individual adjustment:

1. Linear proportionality factor F between measured DIFTOF (or flow speed) and actual flow. F defines the simple proportionality between DIFTOF and flow in sufficiently linear flow regions (typically high flow). Note that F is a function of temperature.
2. Zero flow offset O. This offset is the remaining measurement error at Zero flow. In general, O is a function of temperature, too.
3. SUMTOF offset O_S. This offset is used in temperature calculation and reflects the fact that the Up- and Down-TOF-measurements do not represent the actual physical travel time of the sound, but also include some additional time. O_S is a general constant of the calibration and not dependent on temperature.

These three parameters can be calculated from two DIFTOF-measurements since each measurements provides two TOF results. Adapting the calibration coefficients according to the calculation of the three parameters at only one calibration measurement temperature Tm results in a valid individual set of calibration coefficients for the current spool piece, as long as the following conditions are sufficiently well fulfilled:

- The behavior of F and O over temperature remains unchanged. This means that the shape of the correction curve over temperature is valid for all devices, and the adaption of these curves is done just by scaling to the individual value of $F(T_m)$ and setting the offset of $O(T_m)$ to obtain the right value at T_m, respectively.
- Physical lengths of ultrasonic sound travel paths are not essentially changing. Then the adaption of O_S is sufficient for a good temperature calculation from flow speed.

- The nonlinear corrections, calculated in the characterization phase in development, remain valid for the current device without changes and lead to sufficiently low measurement errors. This must be true both over DIFTOF as well as over temperature.

Of course, one additional condition must in any case be valid, no matter how the calibration coefficients are generated:

- Changes of device behavior over aging or due to environmental factors (like housing temperature or mechanical stress) must not result in measurement errors exceeding accuracy limits.

If any of these conditions is violated to an inacceptable extend, more complex measures have to be taken to obtain and preserve a sufficiently good individual device calibration. For example, if changes due to aging are too strong, the firmware would need to modify its own calibration coefficients during runtime. Of course this would require calculation rules for these changes. Up to now, no such rule was derived because no problems of that kind were observed. If, in another example, the housing temperature would influence the measurement too strongly, it would be necessary to measure this temperature and include its influence in flow calculation. Since such an extra effort is surely not desirable, it is recommended to exclude such influences by spool piece design.

The same is recommended if the behavior of any of the mentioned parameters deviates too much over temperature among devices in production. When temperature dependence changes too strongly, and no calculation rule is found to determine this change from a measurement at only one temperature, production measurements at different temperatures are inevitable and can't be avoided by measures taken in chip firmware or hardware. Again, this is not at all desirable in production, so it is strongly recommended to make sure that devices from production fulfill the above conditions sufficiently well. Of course, it solely depends on customer's needs what "sufficiently well" means in this context – mainly on the desired measurement accuracy.

3 Scaling of Actual Parameters

The following description refers to firmware data files for firmware version A1.A2.11.XX. In general, they apply to any set of calibration coefficients, when the location of parameters in the firmware data file is known.

Firmware data contains the complete configuration of the chip and the measurement setup as well as calibration data. Figure 2 shows an excerpt from the firmware data file GP30Y_A1.A2.11.03.dat with the data that need to be adopted by 2-point calibration. The structure of the complete file is explained in the firmware manual. You can also read the comments in the original template file.

Figure 3: Firmware data that need to be adopted

Field no.	Hex address	Description and variable name	Variable name, format, description
58	0x13A	SUMTOF offset O_S. This value determines the calculated temperature.	O_S, fd0, raw TDC values
62 - 64	0x13E – 0x140	Zero flow offsets *O* at temperatures *TC2* to *TC4*	*O*, fd16, raw TDC values
65 - 67	0x141 – 0x143	Zero flow offset slopes *S_O* between temperatures *TC1/TC2; TC2/TC3; TC3/TC4*	*S_O*, fd16, raw TDC values/K
68 - 70	0x144 – 0x146	Proportionality factor *F* slopes *S_F* between temperatures *TC1/TC2; TC2/TC3; TC3/TC4*; *F* here is the factor between flow speed and actual flow	*S_F*, fd16 in ((l/h)/(m/s)/K
71 - 73	0x147 – 0x149	Proportionality factors *F* at temperatures *TC2* to *TC4*; F here is the factor between flow speed and actual flow	*F*, fd16 in ((l/h)/(m/s)

* all variable names can be found in file GP30Y_A1.D2.11.03.h, contained in the evaluation package

Each entry of the firmware data is a 32 bit word. If this word represents a number, the following notation is used: The hexadecimal numbers x_{hex} are either int (integer) and can be directly converted decimal numbers, or fdN, for example fd16. The latter means N, for example 16, floating digits, and the corresponding decimal number x_d is calculated as

$$x_d = HEX\_TO\_DEC\ (x_{hex})/2^N \qquad [1]$$

It is important to understand how the coefficients are formatted and how calibration curves are modelled in the firmware data files. Of course, all values given in hexadecimal first have to be converted into integer.

The case of SUMTOF offset O_S is simplest – this is just a time value, given in raw TDC units. To convert into ns, multiply by the high-speed clock period (~250 ns) and divide by 2^{16}.

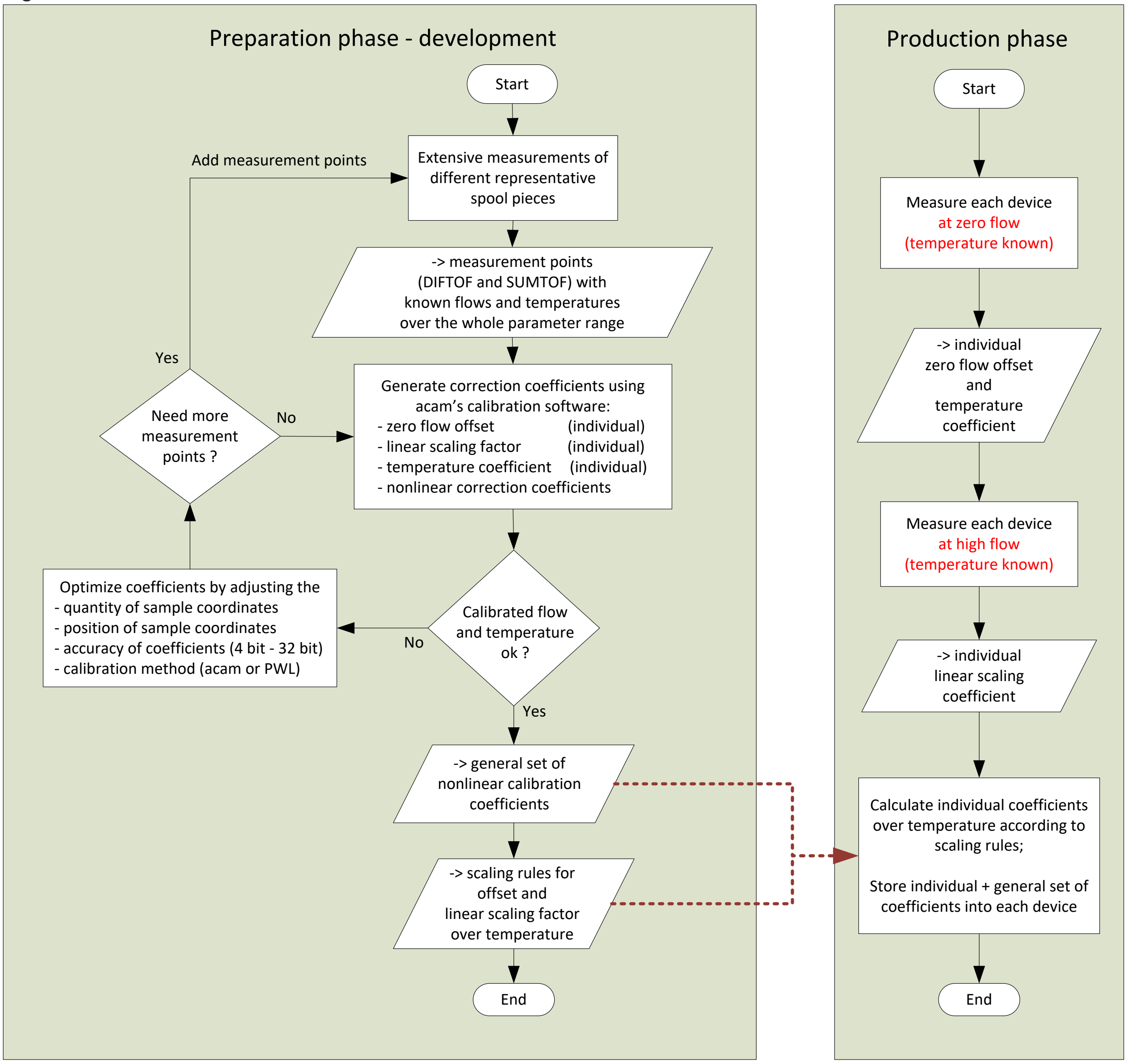
The parameters *F* and *O* depend on temperature and are – for simplified calculation routines – represented as given points (at three of the four calibration temperatures *TC1 to TC4*, see table field Nr 54 -57) and linear slopes between those points. The points for *F* are given in (l/h)/(m/s), since *F* is implemented as the factor between the calculated flow speed and the actual flow. Points for *O* are in also in raw TDC units, but fd16. With a zero flow offset point O_{ps} in picoseconds, calculate the data entry in hexadecimal O_{hex} as

$$O_{hex} = DEC\_TO\_HEX\left(\frac{2^{16}}{1000*250} O_{ps}\right) \qquad [2]$$

Of course, all corresponding slopes *S_O* and *S_F* have the same unit as the points, divided by Kelvin.

Just as a reminder, the following flow chart sketches the calibration procedure in development and production.

Figure 4: Flow chart calibration



Within this document, we assume that the characterization of the spool piece design in development was done, and a general set of calibration coefficients is available as firmware data file (reference calibration). Note that of course characterization in development and later measurements of production devices have to be done with identical configuration settings to avoid deviations in measurement results. Now the question is how to modify the parameters in table figure 2, based on a zero flow and one flow measurement at known temperature.

3.1 Adaption of the SUMTOF offset OS

The SUMTOF offset O_S determines, in combination with the sound path distances with and without flow S_f and S_0, the temperature calculated from speed of sound. During basic characterization, the sound path distance with flow Sf is an arbitrary constant which should be set to a reasonable geometrical value, for example the 0.06m distance between the two mirrors in a typical DN20 spool piece. Distance without flow S_0 and SUMTOF offset O_S are then results of the characterization – this requires exactly two measurements at two different temperatures during development (at any flow). Since the mechanical distances should remain more or less constant, it is sufficient in production to adapt only the SUMTOF offset O_S using one single measurement (either the zero flow or the flow measurement, it doesn't matter) at an arbitrary, but known calibration temperature Tm.

The simplest thing to do is to run the firmware and adjust the SUMTOF offset O_S – actually the value in field 58 – until the calculated temperature resembles the measurement temperature Tm. This method can also be used in production. It is also possible to calculate the new SUMTOF offset O_S directly, but this requires the knowledge of the ultrasound speed vc at the calibration measurement temperature T_m. This value can be found from functions given in various publications, for example Del Grosso, V. A., Mader, C. W. (1972); Speed of Sound in Pure Water,

J. Acoust. Soc. Am., Vol.52, S.1442-1446. Then, the adapted O_S can be calculated from the measured SUMTOF as

O_S = SUMTOF – $2*(S_0 + S_f)/v_c$

This calculation is actually less accurate as the simple method before, if the applied approximation for ultrasound speed differs from the implementation in the chip.

Example:

Measured SUMTOF is 142319 ns at a temperature of 26.2 °C, which corresponds to a speed of sound of 1500.67 m/s. Reference path lengths are S_0 = 0.018509m (0x000004BD, field 61),

S_f = 0.06m (0x00000F5C, field 60). This yields an adapted SUMTOF O_S = 37687 ns. To convert into raw TDC values, multiply by 2^{16} and divide by the high speed clock period (here for example 249.41ns; take the high speed clock calibration into account correctly, or use raw TDC values everywhere). This is in hexadecimal 0x00971AC6. This number is written to field 58 in the adapted firmware data file.

The method for calculating the temperature from the speed of sound in water completely relies on the accuracy of the known ultrasound speed relation and, on the other hand, on the stability of distances from device characterization. This is the reason why measurements over temperature are not necessary any more after characterization. The described method guarantees a correct temperature result at the calibration measurement temperature T_m. If deviating results are found at different temperatures, it must be checked if in fact the distances of the sound paths may have changed too much. Another reason could be that the medium may not be pure water. It is in principle possible to adapt the speed of sound curve for different media (through parameters 74 – 77 in the firmware data file). If this is desired, please contact ams.

3.2 Adaption of the zero flow offset *O*

The fully correct method is described further below. But in an optimized design with GP30Y, the zero flow offset is small and in addition has a small temperature dependence. This is the most simple case where all zero flow offset slopes *S_O* are zero and all sample points *O(TCX)* are equal – the correction curve is a constant. Then simply all three sample points *O(TCX)* must be set to the measured zero flow offset (of course using the right format as given above).

Example:

Measured zero flow offset O_C (at zero flow, averaged over e.g. 256 measurements) is -20ps. Multiplying by 2^{16}/250,000 and converting into two's complement hexadecimal (32 bit) yields 0xFFFAC1D3 (note the negative sign which is expressed in MSB=1). This number is written to fields 62 – 64 in the adapted firmware data file.

Else, when an actual temperature dependence should be preserved from the reference calibration curve, the method is to shift this curve to the right zero flow offset value at the actual calibration measurement temperature Tm. Mathematically, the fully correct method is:

- Calculate the zero flow offset from the reference calibration at the temperature Tm of the actual measurement. This means, search the interval of calibration temperatures *TCi*,*TCj* such that

$TCi < T_m \leq TCj$, and calculate the reference offset O_R by

$O_R = O(TCj) - (TCj - T_m) * S\_O(TCj, TCi)$

- Take the difference between actually measured value and reference value O_C - O_R and adapt all offset points

$O(TCn)$,adapted = $O(TCn)$,reference + $O_C - O_R$

- Format the three adapted values as described above and store under fields 62 – 64 in the adapted firmware data file.

More advanced methods for individual zero flow adaption need more knowledge on the desired parameter behavior: Are there changes over temperature or aging that can be predicted? Then, corresponding parameter adaption methods can be implemented. But current experience indicates that it is easier to design the flow meter system such that zero flow remains small and essentially independent of temperature.

3.3 Adaption of the proportionality factor F

The adaption of proportionality factor *F* is essentially the same process as the adaption of the zero flow offset *O* described above. The rule for selecting the right flow value is just that it should be in the linear correction range – typically this is high flow. The simplest way to determine the factor for scaling the reference F_R to the desired adapted *F* is: Let the firmware calculate a flow during the calibration flow measurement, while applying the reference calibration. The flow result $flow_R$ will differ from the real flow of the calibration measurement $flow_C$. Now calculate the adapted factor

$F = F_R * flow_C / flow_R$.

We can distinguish again two cases: If, as in the first zero flow case above, there is no temperature dependence, then all slopes *S_F* are zero and all points *F(TCn)* are identical. Then $F_R = F(TCn)$, and the adapted *F* has to be formatted and stored in fields 71 – 73 in the adapted firmware data file.

Example:

All reference points are $F_R = F(TCn)$= 0x0225000 = 549 (l/h)/(m/s).

Calibration flow is $flow_C$ = 2500 l/h, but the firmware with reference calibration calculates – when measuring with the spool piece under test – $flow_R$ = 2439 l/h.

Calculate the adapted

F = 549 (l/h)/(m/s)* 2500 l/h/2439 l/h = 562.7306 l/h

Multiplying by 2^{16} and converting into hexadecimal yields 0x0232BB0A. This number is written to fields 71 – 73 in the adapted firmware data file.

The other case, where an actual temperature dependence from the reference calibration should be preserved, is more common in case of the proportionality factor. In this case it is important to do the adaption of OS before, such that the chip's reference flow calculation takes place at the right temperature and thus results in the right value $flow_R$. Now all the flow points *F(TCj)* as well as all the slopes *S_F(TCj,TCi)* have to be adapted by multiplication with $flow_C / flow_R$. The six results have to be formatted as above and stored in fields 68 – 73 in the adapted firmware data file.

Again, more advanced methods to determine adapted proportionality factors require more knowledge on how the parameters change, in order to develop rules for advanced parameter adaption.

4 2-point calibration in Practice

With calibration three parameters will be corrected:

- SUMTOF offset O_S,

  This offset is used in temperature calculation and reflects the fact that the Up- and Down-TOF-measurements do not represent the actual physical travel time of the sound, but also include some additional time. O_S is a general constant of the calibration and doesn't depend on temperature.

- Zero flow offset *O*.

  This offset is the remaining measurement error at Zero flow. In general, *O* is a function of temperature.

- Linear proportionality factor *F*

  This factor corrects the proportionality between measured DIFTOF (or flow speed) and actual flow. *F* defines the simple proportionality between DIFTOF and flow in sufficiently linear flow regions (typically high flow). Note that *F* is a function of temperature, too.

Therefore, mount the device under test and measure the real temperature of the water by a reference on the test bench. Then measure time-of-flight at zero flow and at high flow. With firmware on the chip, you can read SUMTOF and DIFTOF directly from RAM address 8 and 7. As an alternative, without the need of firmware, you can read the original TOF_UP and TOF_DOWN from RAM addresses 0x80 and 0x84.

By means of the Excel sheet described below or your own production software you calculate the corrected firmware data and write them back into FWD2 of the chip.

4.1 Excel Support

We provide an Excel document that allows the user to enter his measurement data and to calculate the appropriate correction values. The file shows where to read data and where to write back data. In addition, it displays the formulas so that users can implement those calculations into their own production software.

The yellow fields show the fixed parameters as defined in the FWD2 after characterization.

The orange fields shows data that have to be collected from reference instruments at the test bench.

The green field are the time-of-flight data as measured by the GP30 in the device under test.

The blue field display the corrected parameters that the user shall write back into FWD2.

The light blue boxes on the right show the formulas embedded. User can take this to implement the calculation in their own software.

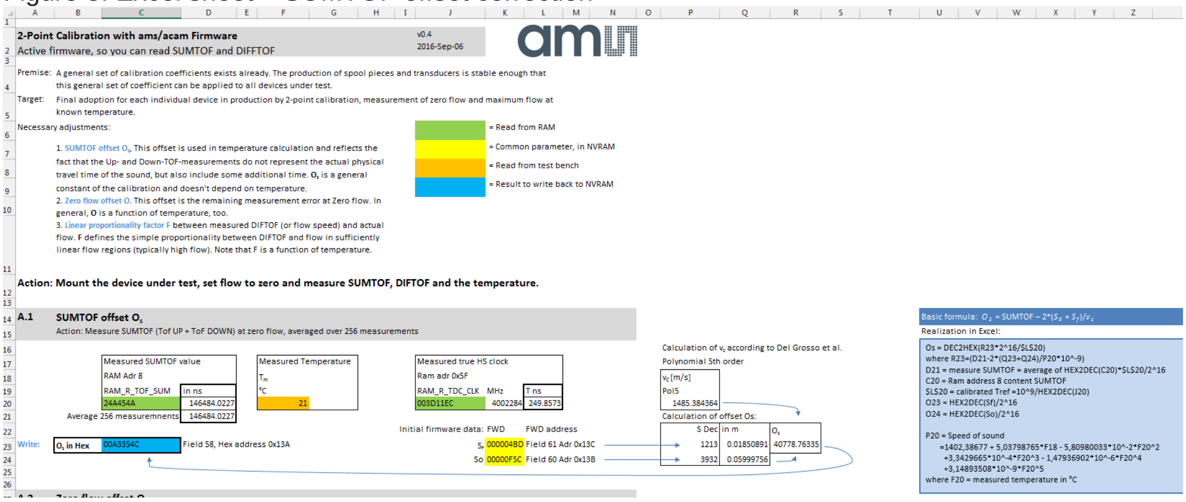
4.1.1 SUMTOF Offset

In the first step, A.1, the temperature calculation based on SUMTOF is calibrated.

The data needed are:

- The real temperature, read from the reference device.
- The real high-speed clock as given by clock calibration. Read from address 0x5F.
- The real SUMTOF as measured by GP30. Read from address 0x08.
- As default the values from FWD2 for the sound path with flow and without flow.

Figure 5: Excel sheet – SUMTOF offset correction



Write back the new value for O_S in to FWD2 cell 58 and download the data to the chip.

4.1.2 Zero Flow Offset

In a second step, the zero flow offset is corrected. Read the DIFFTOF value from address 0x07. Double-check the FWD2 data for the temperature points *TC1* to *TC4* as well as the initial firmware data for *O(TC2)* to *O(TC4)* and *S_O(TC2)* to *S_O(TC4)*.

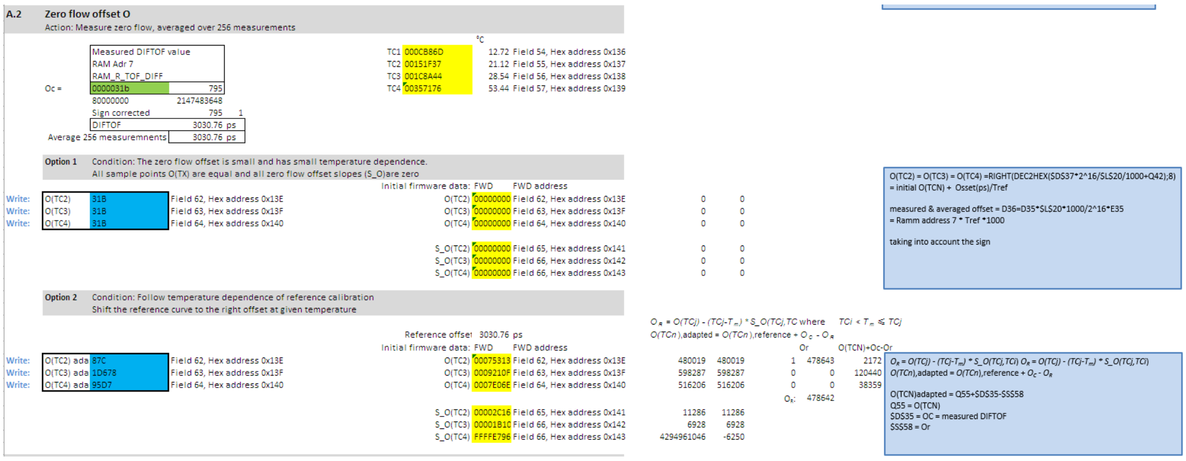
Option 1 describes a situation where the zero flow offset is small and does not depend much on temperature. In this case, one and the same value can be used.

Option 2 describes the more common case that the offset is corrected individually between four reference points of temperature.

Data needed are:

- The real temperature, read from the reference device.
- The real high-speed clock as given by clock calibration. Read from address 0x5F.
- The real DIFTOF as measured by GP30. Read from address 0x07.
- Default the values from FWD2 for *TC*, *O(TC)* and *S_O(TC)*.

Figure 6: Excel sheet – Zero flow offset correction



Write back the new values for *O(TC)* in to FWD2 cells 62 to 64 and download the data to the chip.

4.1.3 Proportionality Factor F

As a last step, apply flow. Read the calculated flow value from address 0x02. Double-check the FWD2 data for the temperature points *TC1* to *TC4* as well as the initial firmware data for *F(TC2)* to *F(TC4)* and *S_F(TC2)* to *S_F(TC4)*.

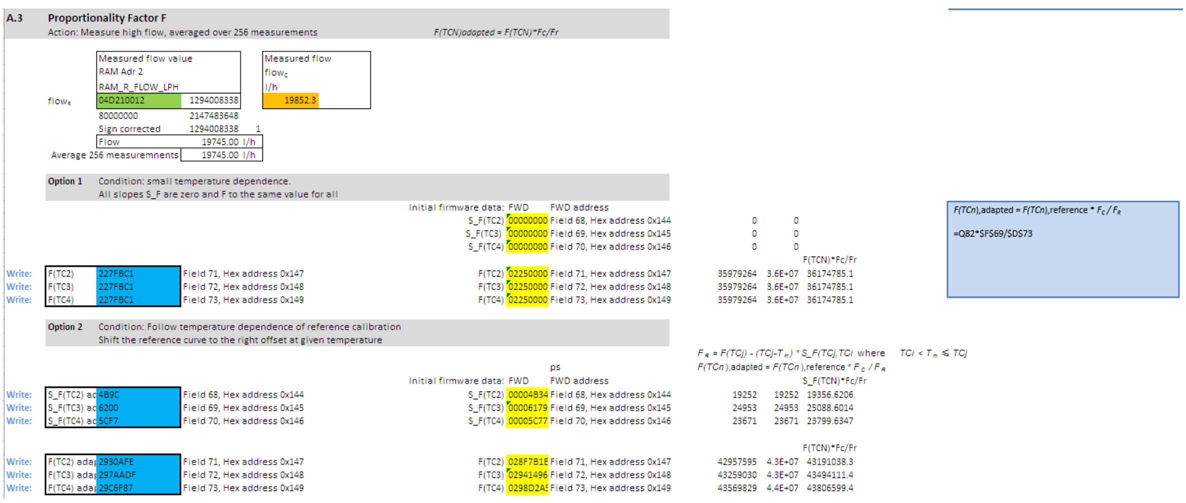
Option 1 describes a simplified situation where the factor offset is small and does not depend much on temperature. In this case, one and the same value can be used.

Option 2 describes the more common case that the factor offset and slope is corrected individually between four reference points of temperature.

The data needed are:

- The real temperature, read from the reference device.
- The real high-speed clock as given by clock calibration. Read from address 0x5F.
- The real SUMTOF as measured by GP30. Read from address 0x08.
- As default the values from FWD2 for *F(TC)* and *S_F(TC)*.

Figure 7: Excel sheet – Flow correction / Proportionality factor



Write back the new values for *F(TC)* in to FWD2 cells 62 to 64 and download the data to the chip.

Having that done the device under test is calibrated.

Please watch our video tutorial for the first step, SUMTOF correction. It can be downloaded from: http://www.acam.de/fileadmin/Download/_software/UFC/GP30_SUMTOF_Cal.zip

The principal method is the same for steps 2 and 3, zero flow and flow calibration.

5 Contact Information

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7 Revision Information

Changes from previous version 1-02 to current revision 1-03 (2017-Nov-30)	Page
Add Figure 2: Full characterization during development vs. 2-point calibration in production (real data)	3

Note: Page numbers for the previous version may differ from page numbers in the current revision.
Correction of typographical errors is not explicitly mentioned.