Calibrating the Thermal Assist Unit in the IBM25PPC750L Processors

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Abstract *– This Note describes methods of calibrating the Thermal Assist Unit in the IBM25PPC750L family of processors..*

The IBM™ PowerPC 750™ family of microprocessors contains a Thermal Assist Unit (TAU) which is designed to operate as a thermal limit switch. The purpose of the TAU is to provide an auxiliary mechanism for limiting the maximum junction temperature of the device. A user-defined setpoint is programmed into the TAU, and when the TAU reading crosses the setpoint, an interrupt is signalled.

Definitions

Reading - The temperature that is read from the TAU during a successive approximation operation.

LSB - The Least Significant Bit of the TAU. A change of +/-1 LSB is the smallest increment of change in the TAU reading.

Resolution - The resolution of the TAU is the smallest amount of change in the reading. This corresponds to 1 LSB. In the TAU, 1 LSB corresponds to 4C.

Actual - The actual junction temperature of the device.

Threshold - The value programmed into TAU register THRM1 or THRM2. During operation, the TAU will signal a thermal management interrupt when the TAU reading crosses the Threshold value.

Offset error - Offset errors are those that are present at a constant value over the entire range of the device. Offset errors are due to unit-to-unit differences in the devices, differences in Vdd from the design Vdd, and other factors. Offset errors can be compensated for by using a single-point calibration.

Slope error - Slope errors are those that cause a change in actual temperature to produce a different change in the temperature reading. Slope errors can be compensated for using dual-point calibration.

Drift error - Drift errors manifest as changes in the reading that are not due to a change in the actual temperature of the device.

Uncertainty - Analog sensors in general are subject to a +/- 1 LSB uncertainty error.

Point of Interest - The Point of Interest (POI) is the actual temperature at which the TAU will be set to signal an interrupt. The accuracy of the TAU is of concern only at the POI. There can be two POIs, one each for THRM1 and THRM2, possibly corresponding to the temperature at which to initiate thermal throttling, and the other corresponding to the temperature at which to initiate a checkstop.

TAU Error Sources

The error sources in the TAU can be categorized as offset errors, slope errors, drift errors, and uncertainty. For simplicity, an accuracy specification for the IBM25PPC750L TAU is assumed in this note, but the official accuracy specification is given in the current Datasheet for the device. In case of conflict, use the specification found in the device Datasheet.

Offset Errors

The offset errors present in the IBM25PPC750L family can be modeled as an offset in the reading that exists over the entire range of the sensor. These errors are due to process variations, nonideality of the circuit design, differences in actual Vdd from nominal, and other factors.

Offset errors are generally calibrated out by finding the offset between reading and actual temperature, and applying that offset to each reading.

At 22C, the TAU offset error ranges from +10C to -20C. In other words, for an actual temperature of 22C, the TAU reading might range from 32C to 2C due to offset errors.

Slope Errors

The linearity of the TAU is sufficiently good that the TAU response over temperature can be considered to be a straight line. The slope error of the TAU is the extent to which the line deviates from a slope of 1.

Slope error can be calibrated out by two different methods. If a single-point calibration can be done at the point of interest, then slope error does not affect the system. Alternately, a simple two-point calibration can also eliminate the slope error.

In the region from 22C to 128C, the TAU slope error ranges from .81 to 1.05. In other words, the slope could range from 81% of nominal to 105% of nominal. This error is in addition to the offset specification.

Drift

There are two drift sources in the TAU: errors due to an external source, such as a change in Vdd, and errors due to an internal source. Errors due to internal drift are less than +/-1 LSB.

External drift errors can be eliminated by keeping Vdd constant. The drift error due to Vdd is less than –2C/100mv. In other words, as Vdd increases 100mv, the reading would decrease 2C. This ½ LSB error can safely be ignored in most applications.

Uncertainty

The uncertainty error of the TAU refers to the basic +/- 1 LSB error that is common to analog sensors as a class. This error describes the limitations of the resolution of the sensor. The resolution of the TAU is 4C, and actual TAU readings are 0, 4, 8, …, 124, 128. Since the resolution is 4C, a reading of 8C indicates a temperature of anywhere between 6C and 10C.

With a constant Vdd, the combination of drift errors and uncertainty is typically less than +/-1 LSB, or +/-4C.

Uncalibrated TAU Accuracy

The uncalibrated error budget for the TAU consists of offset, slope, drift, and uncertainty errors. In general, the drift and uncertainty errors are not included in a non-calibrated error budget because they are swamped by the offset and slope errors.

To determine the range of TAU readings that correspond to a given actual temperature, first apply the offset error, and then the slope error.

In Table 1, the Max High Offset is 10C in all cases. The slope error in the specification is referenced to 22C, and is calculated as a percentage of the difference between the actual temperature and 22C. Combining the two error factors:

Eq. 1 Highest Reading = Actual + 10C + (Actual – 22C) * .05.

Likewise, the Max Low Offset is 20C in all cases. The slope error in the specification is referenced to 22C, and is calculated as a percentage of the difference between the actual temperature and 22C. Combining the two error factors:

Eq. 2 Lowest Reading = Actual - 20C - (Actual – 22C) * .19.

Table 1 shows the tabulated results of the formulas.

Table 1. Uncalibrated Worst Case TAU Readings for Selected Actual Temperatures

Actual	Max High Offset	Max High Slope Error	Highest Reading		Max Low Offset	Max Low Slope Error	Lowest Reading
22	10	0	32		20	0	2
35	10	1	46		20	2	13
45	10	1	56		20	4	21
55	10	2	67		20	6	29
65	10	2	77		20	8	37
75	10	3	88		20	10	45
85	10	3	98		20	12	53
95	10	4	109		20	14	61
105	10	4	119		20	16	69

Viewed another way, for selected TAU readings, Table 2 shows the range of possible actual junction temperatures. By derivation from the preceding formulas, the Lowest Actual possible temperature corresponding to a given TAU Reading is:

Eq. 3 Lowest Actual = (Reading – 8.9) / 1.05

And the Highest Actual possible temperature corresponding to a given TAU Reading is:

Eq. 4 Highest Actual = (Reading + 15.82) / .81

Table 2. Uncalibrated Worst Case Actual Temperatures for Selected TAU Readings

TAU Reading	Lowest Actual	Highest Actual		TAU Reading	Lowest Actual	Highest Actual
22	12	47		76	64	113
24	14	49		80	68	118
28	18	54		84	72	123
32	22	59		88	75	128
36	26	64		92	79	133
40	30	69		96	83	138
44	33	74		100	87	143
48	37	79		104	91	148
52	41	84		108	94	153
56	45	89		112	98	158
60	49	94		116	102	163
64	52	99		120	106	168
68	56	103		124	110	173
72	60	108		128	113	178

Most applications can not tolerate this amount of inaccuracy, so a calibration of some sort is required.

TAU Calibration

The left side of Figure 1 shows a geometric representation of the range of readings possible from an uncalibrated TAU. The dashed lines above and below the ideal line represent the maximum high and low errors. For an actual temperature of **b**, the TAU reading could be anywhere from **a** to **c**.

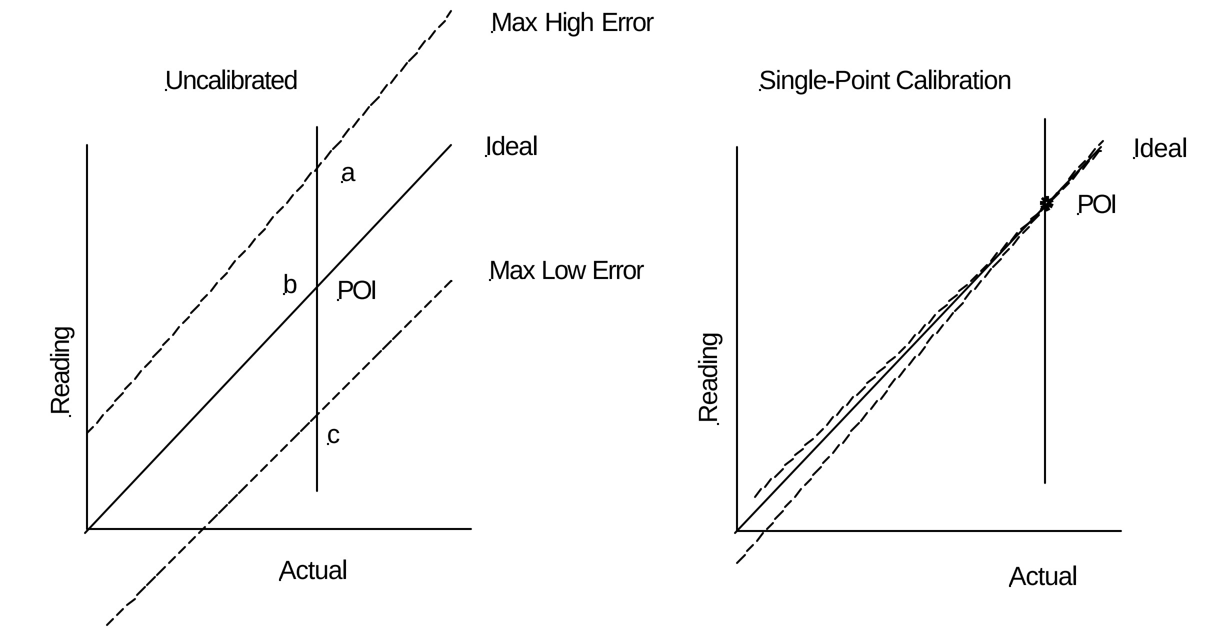

Figure 1. Calibration at the Point of Interest

In general, three calibration methods are feasible; single-point calibration at the point of interest (POI), single-point calibration at another point, and dual-point calibration. Single-point calibration at the POI and dual-point calibration are the most accurate.

Calibration at the Point of Interest

The right side of Figure 1 shows the effect of a single-point calibration on the accuracy of the TAU reading. The dot represents the POI. The calibration reduces the offset error to zero at all temperatures, and reduces the slope error to zero at the POI.

Setting and Measuring the Junction Temperature

The first step in setting the Threshold with a single-point calibration is to bring the junction temperature to the point of interest. This can be done using a temperature-controlled heater plate, a high-temperature soak, a hot air jet, or code that heats up the processor to the POI.

In the case of a heater plate, soak or hot air jet, the junction temperature will be set by the external device. In the case of using code to heat the device, the junction temperature must be measured externally.

Depending on the application, several different temperature measurement technologies may be feasible. Non-contacting infrared (IR) temperature measurement may be possible. This is potentially a faster solution than contacting technologies, which have to allow settling time for the thermal probe. Contact vendors for details.

Another group of technologies relies on placing a thermal probe in contact with the die. Low-mass thermistors, thermocouples, and solid state sensors are available. These can be incorporated into a cap assembly that covers the chip die and allows the temperature to stabilize.

Attaining a stable junction temperature is important to the accuracy of the calibration. If the junction temperature is changing during the temperature measurement process, the calibration may not be accurate.

Using code to heat up the processor may not be the best option, because the kind of code that is running affects the junction temperature. Some experimentation may have to be done to achieve code that maintains a constant junction temperature. A heat sink or other thermal mass can smooth out the effects of changing power dissipation due to changing code.

A third measurement possibility is to measure the temperature at another point on the thermal path than the junction. This relies on accurate characterization of the thermal path, and can be difficult, because all of the heat flow paths (eg. through the device balls) must be taken into account. For example, if a sensor is inserted into a heat pipe that connects the junction surface to a heatsink, and the complete heat path is known, then the temperature of the die can be calculated.

Calculating the Calibration

Once the die is at the POI temperature, read the TAU using a successive approximation algorithm, and record the TAU reading and the actual temperature. The difference is now the offset correction factor. For example, if the actual temperature at the POI is 104C, and the reading is 90C, then 104 – 90 = 14C must be added to each TAU reading to obtain the actual temperature.

That corrects for the offset error. Since the calibration was done at the POI, the effects of slope error are negligible. Note that as the actual temperature varies from the calibration point, the slope error becomes nonzero.

Finally, the uncertainty and drift errors contribute a +/- 4C irreducible error.

Setting the Threshold

Since the reading is 90C at an actual junction temperature of 104C, the nominal Threshold value is 90C. But since there is a remaining error of +/- 4C, the Threshold is set to 90C – 4C = 86C, which corresponds to an actual temperature of 100C. This ensures that the TAU interrupts at an actual temperature of 104C or below even if the TAU is reading 4C high.

In addition, the TAU may actually be reading 4C low, in which case it will interrupt at a reading of 86C – 4C = 82C, which corresponds to an actual temperature of 96C.

To summarize, with a single-point calibration at the point of interest, the Threshold is set to the reading corresponding to 4C less than the POI. It is recognized that the TAU may interrupt 4C lower than the threshold value.

Calibration at Less Than the POI

If the TAU cannot be calibrated at the point of interest, then the slope error also has to be taken into account.

Setting and Measuring the Junction Temperature

The same measurement challenges exist as must be accounted for with a POI calibration.

Calculating the Calibration

Once the die is at the calibration temperature, read the TAU using a successive approximation algorithm, and record the TAU reading and the actual temperature. The difference is now the offset correction factor. For example, if the actual temperature is 60C, and the reading is 44C, then 60C – 44C = 16C will be added to each TAU reading to obtain the actual temperature.

In addition, if the POI is not 60C, then the slope error must be taken into account. The slope of the IBM25PPC750L TAU ranges from .81 to 1.05.

Eq. 5 High Slope Error at POI = (POI - cal temp) * .05

Eq. 6 Low Slope Error at POI = -(POI – cal temp)* .19

In this case:

Eq. 7 High Slope Error at 104 = (104 - 60) * .05 = 2 C

Eq. 8 Low Slope Error at 104 = -(104 – 60)* .19 = - 8C

In the example, the predicted reading (before slope error) at 104C will be:

Eq. 9 104C – 16C = 88C

With the slope errors, the predicted reading now ranges:

Eq. 10a From 88C + 2C = 90C,
Eq. 10b To 88C – 8C = 80C.

Note that there is a problem with using 90C as a reading, because the TAU will never read 90C, because all readings are 0 mod 4. Usually when correction factors exceeding 1 LSB are encountered, the uncertainty error term is absorbed into the other error terms. We will do so in this case, with the single effect of increasing the predicted reading from 90C to 92C. So then, the predicted range of the reading is:

Eq. 11 80C to 92C at 104C

Setting the Threshold

Since the predicted reading ranges from 80C to 92C, the TAU Threshold must be set to 80 to ensure that the junction temperature never exceeds 104C.

And since the reading could be as much as 92 – 80 = 12C higher than that, it is possible that the TAU will signal an interrupt when the actual temperature is 104 – 12C = 92C.

In summary, in this case, the Threshold is set to 80C to keep the junction temperature less than 104C, and it is possible for the TAU to signal an interrupt as low as 92C.

Dual-Point Calibration

A dual-point calibration may be most appropriate for some applications where the TAU can not be accurately set to the POI. It consists of reading the TAU at two different known temperatures, and deriving the equation for the line that defines the reading as a function of the actual temperature.

Setting and Measuring the Junction Temperature

Since the TAU is essentially linear, two temperatures are needed for this calibration scheme. The accuracy of the calibration depends on the distance between the readings, because each of the calibration readings is subject to a +/-4C uncertainty. The calibration readings must of course be accurately done.

If the calibration method uses a temperature chamber or soak to set the temperature of the device, a dual-point calibration may not be feasible. In this case, of course, since a single-point calibration at the POI can be accomplished, a dual-point calibration is not required.

If the calibration method uses a hot air jet or a heated plate to set the junction temperature above ambient, then a dual-point calibration is no more difficult than a single-point calibration. A low-temperature reading can be taken before the device is heated, and a second reading can be taken when the device is heated.

Calculating the Calibration

At a low temperature, read the TAU using a successive approximation algorithm, and record the TAU reading and the actual temperature. To avoid heating the device with the code that reads the TAU, avoid spin loops for timing. Then heat the device to a high temperature and record the TAU reading.
Let:

Tl = Actual low temperature	Rl = Reading at low temperature
Th = Actual high temperature	Rh = Reading at high temperature
m = the slope of the Reading line	b = the y-intercept of the Reading line

Then:

Eq. 12 $(Rh - Rl) / (Th - Tl) = m$ and $R = mT + b$

Assume two readings:

Tl = 32C	Rl = 20C
Th = 90C	Rh = 72C

Eq. 13 $m = (72 - 20) / (90 - 32) = 0.897$ and
Eq. 14 $b = 72 - (0.897 * 90) = - 8.73$

So:

Eq. 15 $R = 0.897 * T - 8.73$

If the POI is 104, then the predicted reading is:

Eq. 16 $R = 0.897 * 104 - 8.73 = 84.6C$

Calibration Errors

The sources of error in the dual-point calibration derive from uncertainty, as shown in the preceding examples, and from errors in the calibration measurements.

With each reading, there is an uncertainty error of +/-4C. So the combined error between two measurements ranges from 0 to 8C. A typical case is 4C. This error is applied over the distance between the calibration measurements. Thus the error effect on a calibration done at 30C and 50C is much greater than the effect of the error on a calibration done at 30C and 90C.

For example, if in our last example, the readings had been

Tl = 32C	Rl = 20C
Th = 90C	Rh = 76C (instead of 72C)

Eq. 17 m = (76 – 20) / (90 – 32) = 0.966 and
Eq. 18 b = 76 – (0.966 * 90) = - 10.94

So:

Eq. 19 R = 0.966 * T – 10.94

If the POI is 104, then the predicted reading is:

Eq. 20 R = 0.966 * 104 – 10.94 = 89.52C

And the error is

Eq. 21 89.52 – 84.6 = 4.9C

In contrast, if the calibration had been done at

Tl = 32C	Rl = 20C
Th = 61C	Rh = 50C (instead of the correct 46C)

Eq. 22 m = (50 – 20) / (61 – 32) = 1.034 and
Eq. 23 b = 50 – (1.034 * 61) = - 13.07

So:

Eq. 24 R = 1.034 * T – 13.07

If the POI is 104, then the predicted reading is:

Eq. 25 R = 1.034 * 104 – 13.07 = 94.47C

And the error is

Eq. 26 94.47 – 84.6 = 9.87C

which is roughly twice the error of the previous case.

So the larger the difference between the two calibration measurements, the more accurate will be the calibration.

Setting the Threshold
Assuming the above data for a dual-point calibration at 32C and 90C (Eq. 12 – 16), and a calibration error of 4.9C (Eq. 21):

The predicted reading is 84.6C.
The Threshold is 84.6 – 4.9 = 79.7 => 80C (which corresponds to a Tj of 99.1C)
And the TAU could interrupt as low as 99.1 – 4.9 = 94.2 => 92C.

The accuracy of this method is equivalent to the accuracy of the single-point calibration at the POI, given a sufficiently large difference between the two calibration points.