AN2971
Application note

Using the typical temperature characteristics of 32 KHz crystal to compensate the M41T83 and the M41T93 serial real-time clocks

Introduction

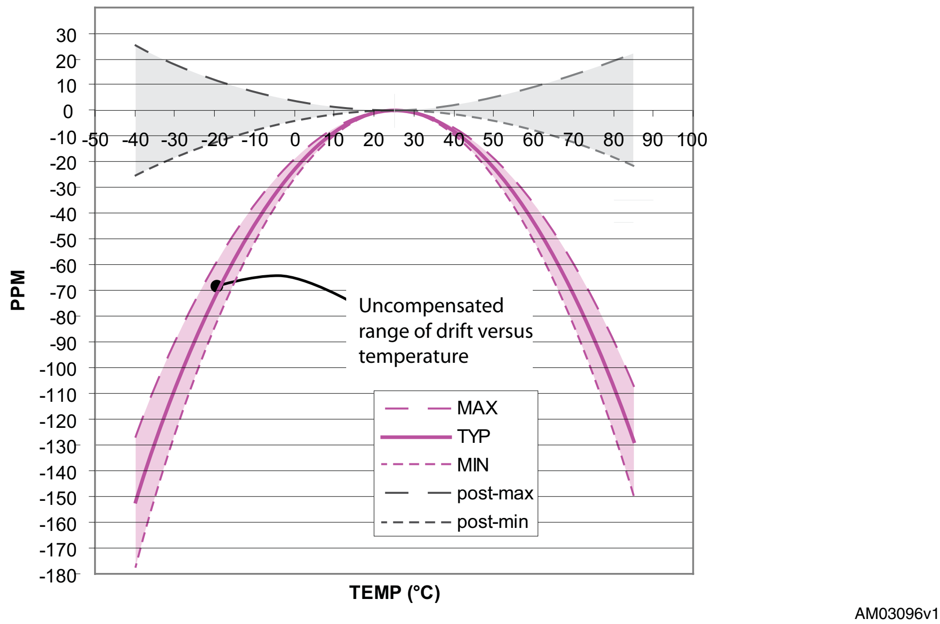
Typical real-time clocks employ 32 KHz tuning fork crystals. While being well suited to the low-power needs of battery-backed applications, they can drift significantly over the industrial temperature range –40 to +85°C. At the extreme temperatures, drifts are somewhere between –108 and –177 parts per million (ppm), a loss of about 5 to 8 minutes per month. Full temperature compensation is possible, but costly. However, a simplified technique can be employed which can greatly improve the drift, and hence improve the timekeeping accuracy of the RTC without adding significant cost.

Knowing the general shape of the tuning fork crystal's temperature curve, such a compensation scheme is possible in applications where a temperature sensor is in use.

As shown in *Figure 1* below, in the shaded portion nearer the bottom, the accuracy of the 32 KHz crystal falls off appreciably as the temperature approaches the limits of operation. The pink line in the middle of that region is considered the typical behavior. If the oscillator is adjusted for the expected or typical curve, the accuracy approaches the shaded region depicted at the top of the figure, to something nearer the range ±25 ppm, about 1 minute per month, a much more tolerable range of accuracy. Essentially, this technique takes the bottom shaded region and straightens it out along the temperature axis.

In many applications that level of accuracy is all that is required. This document describes how to implement such a compensation scheme.

Figure 1. 32 KHz crystal drift versus temperature



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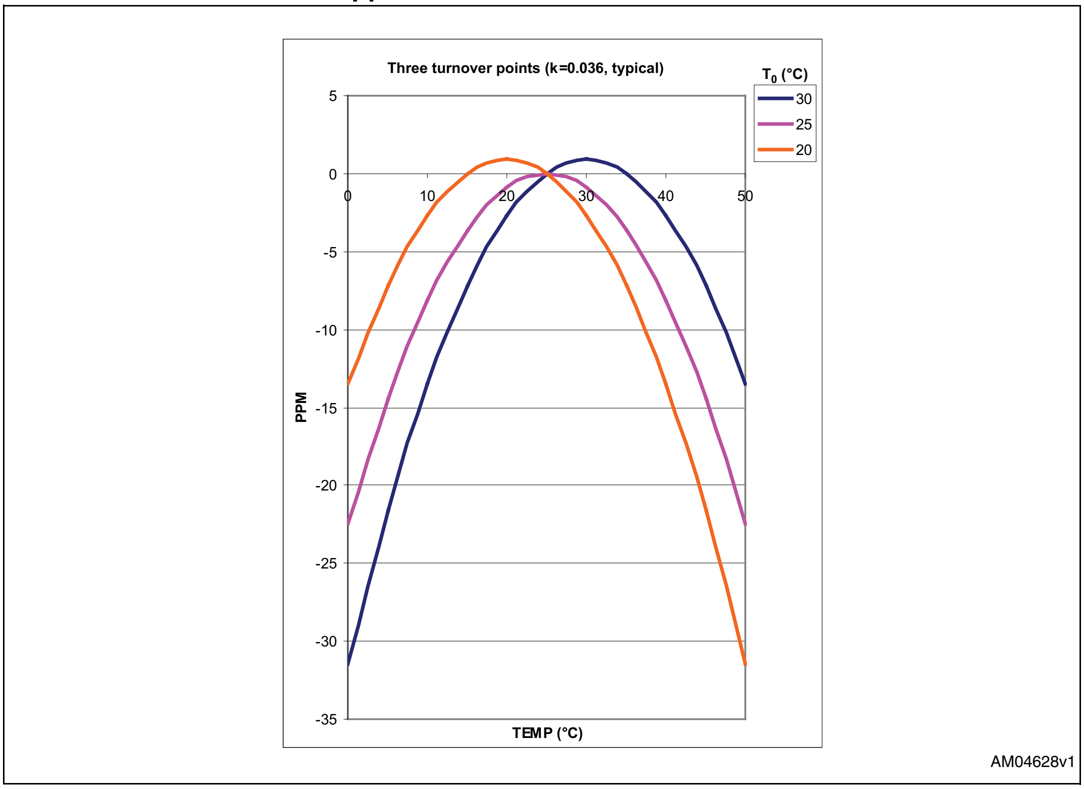
1 Additional considerations

The turnover point is the temperature at which the crystal is at its highest frequency. This is the maximum or highest point on the temperature parabola and is referred to as T_0. In *Figure 1*, it was assumed the turnover point was 25°C. It will in fact range between 20 and 30°C for most 32 KHz crystals.

Figure 2. Typical temperature curves for three different turnover points after calibration to 0 ppm at 25°C



During factory calibration of the M41T83 and M41T93, the oscillator frequency is adjusted until the device is very close to 0 PPM at 25°C. This has the effect of moving the temperature curve up and down.

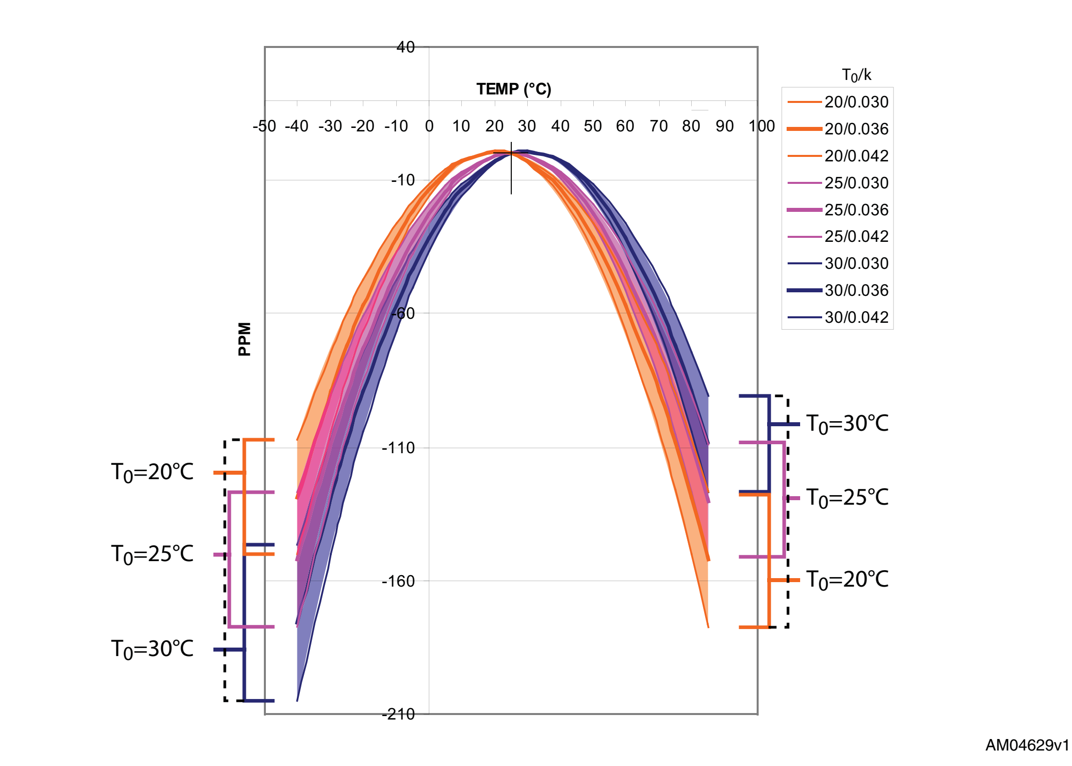
If the turnover point is at 20°C, after factory calibration, the device will be at 0 PPM at 25°C, but will run at its fastest at 20°C. This is depicted by the orange curve.

Similarly, if the turnover point is at 30°C, after factory calibration, the device will be at 0 PPM at 25°C, but will run at its fastest at 30°C. This is depicted by the blue curve.

Thus, the temperature turnover point moves up and down with calibration, but remains at the same temperature.

When the minimum and maximum values are included for all three turnover points, the curves of *Figure 3* are derived. The pink region is the same as before in *Figure 1* and represents the minimum and maximum cases for a turnover of 25°C. The pink brackets on either side of *Figure 3* help make this clear.

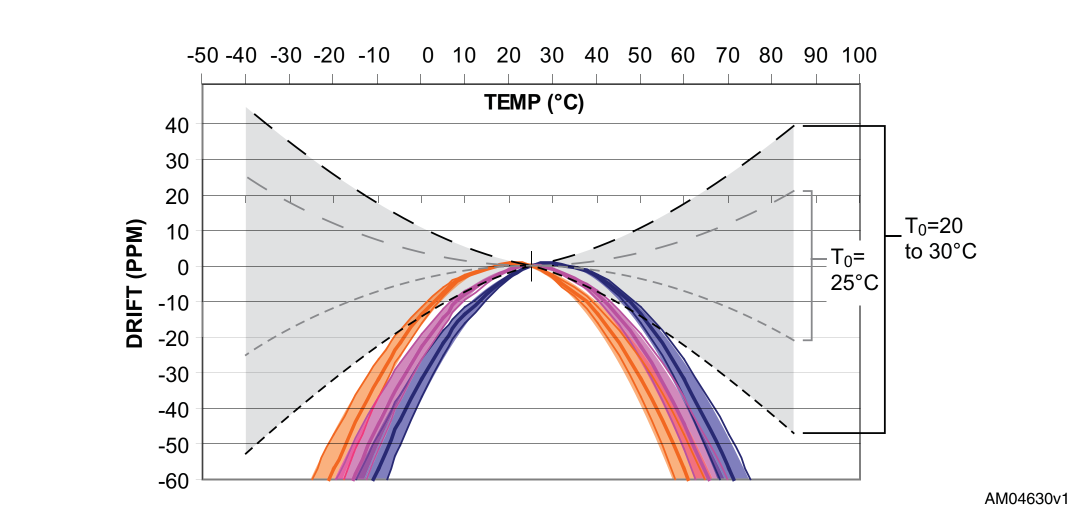
Figure 3. Range of drift for three turnover points



The blue shaded region covers the minimum and maximum cases for a turnover of 30°C, and the orange shaded region covers the minimum and maximum cases for a turnover of 20°C. The entire range of drift is indicated by the dashed black lines, and is the sum of the three cases.

For the purposes of this application note, the net result of considering the turnover point is an increase in the amount of uncertainty in the drift at the temperature extremes. With this added, the straightened uncertainty region shown at the top of *Figure 1* becomes that of *Figure 4* below.

Figure 4. Range of drift after compensation



In *Figure 4*, the black dashed lines show the entire range of the drift after compensation. As before, in *Figure 1*, the gray region represents the parabolas after they have been straightened along the temperature axis.

After compensation, the drift should be no worse than ±20 ppm in the range –10 to +50°C, and typically less than ±10 ppm in that range as shown by the gray dashed lines for $T_0 = 25°C$

Crystal equation

The drift of a tuning fork crystal is described by the equation below.

$$\frac{\Delta f}{f_0} = -k \cdot (T - T_0)^2$$

Here, the drift is expressed as a fraction of the nominal frequency, f_0. The factory calibration adjusts for the deviation of f_0 from 32768 Hz. T_0 is the turnover point, and T is the temperature, in Celsius. k is a constant in the range 0.030 to 0.042, with a typical value of 0.036. When plotted, the equation gives the curves shown in *Figure 1* through *4*. The typical case in *Figure 1* is for k = 0.036. The other values of k give the minimum and maximum (dashed line) curves.

2 Application theory

As shown in *Figure 5*, the typical temperature characteristics of the 32 KHz crystal are described by a parabola. Away from the center point, at temperatures above and below 25°C, the crystal tends to run at lower frequencies. A table can be derived from the curve from which the user can look up the approximate drift (in parts per million or PPM) of the clock for a given temperature. Thus, if the application can measure the temperature, it can predict the drift of the real-time clock and compensate accordingly by adjusting the RTC's calibration circuit.

The M41T83 and M41T93 employ analog calibration circuits which adjust the frequency of the oscillator by adding or removing capacitance. The non-linear relationship between the load capacitance and frequency is depicted in the curve of *Figure 7*.

Note that, since the curve is non-linear, the incremental change in PPM of the oscillator varies with the position on the curve. That is, a small change in capacitance does not have the same effect on PPM at one point on the curve as at another. Therefore, in order to determine how much incremental capacitance to add or remove to achieve a desired PPM shift, the user must first determine where on the curve the device is operating.

In the cases of the M41T83 and M41T93, in the embedded crystal package, a factory-calibration value is programmed into a permanent (one-time programmable) register which can be read by the application. This provides the starting point for the calibration procedure. It indicates where on the curve the device is operating at room temperature.

In summary, *Figure 5* (tabularized in *Figure 6*) tells the user the necessary PPM of calibration required for a given temperature. In turn, *Figure 7* and *Figure 8* allow the user to determine the load capacitance setting necessary to achieve the desired PPM shift.

3 Example

The first step is to determine the temperature. That in turn is used to look up the expected amount of drift, as shown in step 2. The easiest way to do this is to use a table as illustrated in *Figure 6*, which shows an expected drift of –43 ppm at 58°C. Thus, the oscillator should be adjusted for a 43 ppm shift in the opposite direction.

In step 3, the factory calibration value is used as a starting point on the capacitance-ppm curve in *Figure 7*. The factory calibration value of 0x14 corresponds to a capacitance of +5 pF (above the nominal 12.5 pF). That corresponds to –7.78 ppm as shown in *Figure 8*. Adding 43 ppm to that gives +35.22 ppm. Thus, capacitance must be removed to speed up the oscillator.

In step 4, the user finds the ppm value nearest 35.22 in the list in *Figure 8*. In this case, that is 34.97 ppm, which calls for an analog calibration value of 0xA9 (which corresponds to –10.25 pF). This value is then placed into the user analog calibration register at address 0x12, and the OTP bit is cleared (address 0x13) forcing the device to employ the user analog calibration value in lieu of the factory calibration value.

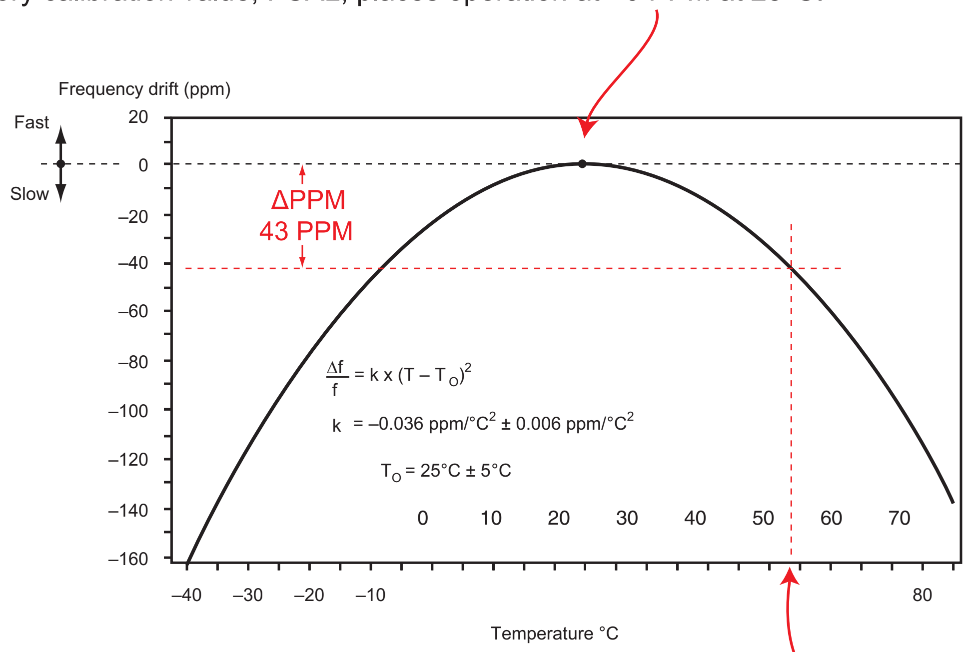
This results in the oscillator running at a slightly different speed which in turn helps it keep time more accurately at the ambient temperature.

By performing this procedure periodically, the application can keep the timekeeping accuracy at an acceptable level.

Using these few simple steps, users can greatly improve the timekeeping performance of their M41T83 and M41T93 real-time clock devices.

Figure 5. 32 KHz crystal curve, PPM versus temperature

Factory calibration value, FCAL, places operation at ~0 PPM at 25°C.



Analog calibration sequence:

Steps	Example:
Step 1: Read temperature Step 2: Look up ΔPPM from PPM vs. temperature graph/table (figure 5 and figure 6)	Temperature read is 58°C. Curve/table shows that clock will be ~43 PPM slow. Thus, ΔPPM should be +43 PPM (Here, + means faster).

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Figure 6. Drift versus temperature

Temperature (°C)	drift (PPM)
-30	-116.5
-29	-112.3
-28	-108.2
-27	-104.1
-26	-100.2
-25	-96.3
-24	-92.4
-23	-88.7
-22	-85.0
-21	-81.4
-20	-77.9
-19	-74.5
-18	-71.1
-17	-67.8
-16	-64.6
-15	-61.5
-14	-58.5
-13	-55.5
-12	-52.6
-11	-49.8
-10	-47.0
-9	-44.4
-8	-41.8
-7	-39.3
-6	-36.9
-5	-34.5
-4	-32.2
-3	-30.0
-2	-27.9
-1	-25.9
0	-23.9
1	-22.0
2	-20.2
3	-18.5
4	-16.8
5	-15.3
6	-13.8
7	-12.3
8	-11.0
9	-9.7
10	-8.5
11	-7.4
12	-6.4
13	-5.4
14	-4.6
15	-3.8
16	-3.0
17	-2.4
18	-1.8
19	-1.3
20	-0.9
21	-0.6
22	-0.3
23	-0.1
24	0.0
25	0.0

Temperature (°C)	drift (PPM)
25	0.0
26	-0.1
27	-0.2
28	-0.4
29	-0.7
30	-1.0
31	-1.5
32	-2.0
33	-2.6
34	-3.3
35	-4.0
36	-4.8
37	-5.7
38	-6.7
39	-7.8
40	-8.9
41	-10.1
42	-11.4
43	-12.8
44	-14.2
45	-15.8
46	-17.4
47	-19.0
48	-20.8
49	-22.6
50	-24.5
51	-26.5
52	-28.6
53	-30.7
54	-33.0
55	-35.3
56	-37.6
57	-40.1
58	-42.6
59	-45.2
60	-47.9
61	-50.7
62	-53.5
63	-56.4
64	-59.4
65	-62.5
66	-65.7
67	-68.9
68	-72.2
69	-75.6
70	-79.0
71	-82.6
72	-86.2
73	-89.9
74	-93.7
75	-97.5

measured temp

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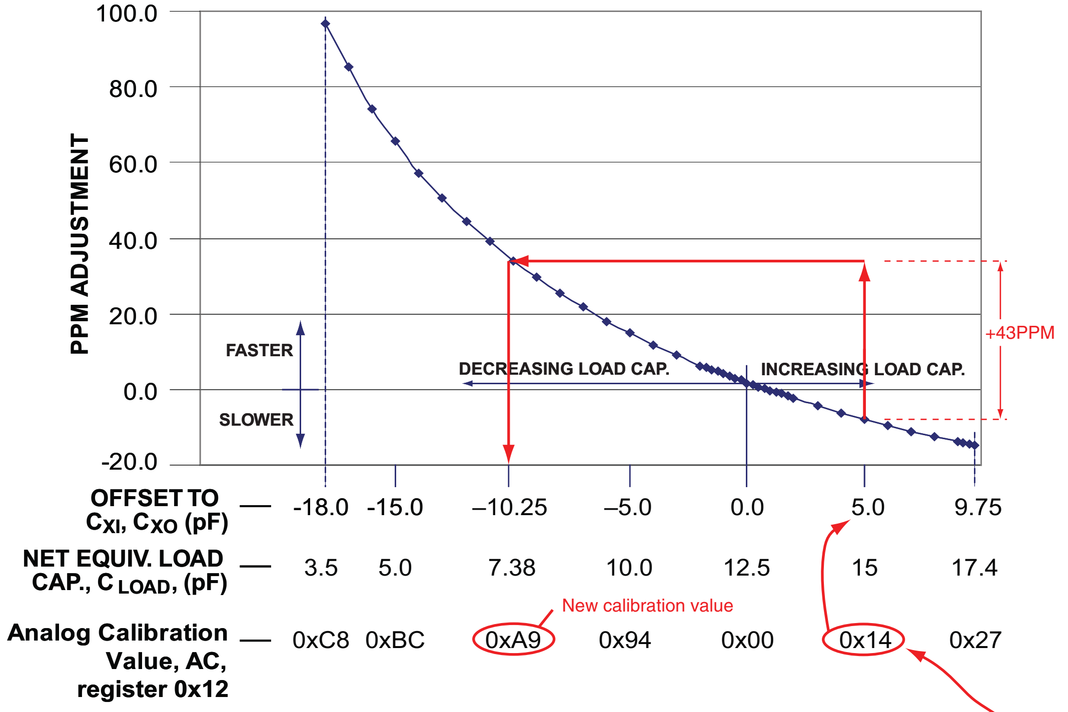
Figure 7. Typical oscillator accuracy versus load capacitance



Steps (continued)	Example (continued):
Step 3: **Read factory calibration value:** Set OTP bit to 1, wait 4ms, then read analog calibration register (address 0x12). This will return factory calibration value (for 0 PPM @ 25°C).	Analog calibration value read was 0x14 (+5 pF).
Step 4: Find factory calibration value on the curve, then move ΔPPM (from step 2) up/down from there and read new calibration value from PPM vs.load capacitance table/graph (figure 7 and figure 8)	Move +43 PPM from 5 pF (0x14). Value read is –10.25 pF (0xA9).
Step 5: Clear OTP bit, then write new value to analog calibration register.	Clear OTP bit at address 0x13. Write 0xA9 to address 0x12.

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Figure 8. Load capacitance versus PPM

Anlog cal value versus PPM			
Δcap	Analog Cal	PPM	CLOAD
9.75	0x27	-14.83	17.37
9.50	0x26	-14.56	17.25
9.25	0x25	-14.25	17.12
9.00	0x24	-13.95	17.00
8.75	0x23	-12.17	16.88
8.50	0x22	-11.92	16.75
8.25	0x21	-11.67	16.63
8.00	0x20	-12.63	16.50
7.75	0x1F	-11.11	16.38
7.50	0x1E	-10.81	16.25
7.25	0x1D	-10.50	16.13
7.00	0x1C	-11.08	16.00
6.75	0x1B	-9.84	15.88
6.50	0x1A	-9.49	15.75
6.25	0x19	-9.13	15.63
6.00	0x18	-9.64	15.50
5.75	0x17	-8.38	15.38
5.50	0x16	-8.00	15.25
5.25	0x15	-7.60	15.13
5.00	0x14	-7.78	15.00
4.75	0x13	-6.78	14.88
4.50	0x12	-6.36	14.75
4.25	0x11	-5.93	14.63
4.00	0x10	-6.20	14.50
3.75	0x0F	-5.04	14.38
3.50	0x0E	-4.59	14.25
3.25	0x0D	-4.13	14.13
3.00	0x0C	-4.27	14.00
2.75	0x0B	-3.20	13.88
2.50	0x0A	-2.72	13.75
2.25	0x09	-2.23	13.63
2.00	0x08	-2.50	13.50
1.75	0x07	-1.56	13.37
1.50	0x06	-1.19	13.25
1.25	0x05	-0.70	13.12
1.00	0x04	-0.27	13.00
0.75	0x03	0.31	12.87
0.50	0x02	0.70	12.75
0.25	0x01	1.25	12.62
0.00	0x00	1.71	12.50
-0.25	0x81	2.66	12.37
-0.50	0x82	3.05	12.25
-0.75	0x83	3.60	12.12
-1.00	0x84	4.09	12.00
-1.25	0x85	4.76	11.87
-1.50	0x86	5.22	11.75
-1.75	0x87	5.80	11.62
-2.00	0x88	6.32	11.50
-2.25	0x89	7.59	11.38
-2.50	0x8A	8.20	11.25
-2.75	0x8B	8.83	11.13
-3.00	0x8C	9.22	11.00
-3.25	0x8D	10.11	10.88
-3.50	0x8E	10.77	10.75
-3.75	0x8F	11.44	10.63
-4.00	0x90	11.78	10.50

FCAL

add 43 PPM

look up new value

Anlog cal value versus PPM			
Δcap	Analog Cal	PPM	CLOAD
-4.25	0x91	12.81	10.38
-4.50	0x92	13.52	10.25
-4.75	0x93	14.24	10.13
-5.00	0x94	14.89	10.00
-5.25	0x95	15.72	9.88
-5.50	0x96	16.48	9.75
-5.75	0x97	17.26	9.63
-6.00	0x98	17.85	9.50
-6.25	0x99	18.87	9.38
-6.50	0x9A	19.70	9.25
-6.75	0x9B	20.55	9.13
-7.00	0x9C	21.85	9.00
-7.25	0x9D	22.32	8.88
-7.50	0x9E	23.23	8.75
-7.75	0x9F	24.17	8.63
-8.00	0xA0	25.36	8.50
-8.25	0xA1	26.11	8.38
-8.50	0xA2	27.12	8.25
-8.75	0xA3	28.15	8.13
-9.00	0xA4	29.69	8.00
-9.25	0xA5	30.31	7.88
-9.50	0xA6	31.43	7.75
-9.75	0xA7	32.58	7.63
-10.00	0xA8	33.87	7.50
-10.25	0xA9	34.97	7.38
-10.50	0xAA	36.22	7.25
-10.75	0xAB	37.51	7.13
-11.00	0xAC	39.22	7.00
-11.25	0xAD	40.18	6.88
-11.50	0xAE	41.58	6.75
-11.75	0xAF	43.01	6.63
-12.00	0xB0	44.34	6.50
-12.25	0xB1	46.01	6.38
-12.50	0xB2	47.58	6.25
-12.75	0xB3	49.18	6.13
-13.00	0xB4	50.72	6.00
-13.25	0xB5	52.54	5.88
-13.50	0xB6	54.30	5.75
-13.75	0xB7	56.10	5.63
-14.00	0xB8	57.13	5.50
-14.25	0xB9	59.87	5.38
-14.50	0xBA	61.84	5.25
-14.75	0xBB	63.86	5.13
-15.00	0xBC	65.80	5.00
-15.25	0xBD	68.09	4.88
-15.50	0xBE	70.30	4.75
-15.75	0xBF	72.57	4.63
-16.00	0xC0	74.19	4.50
-16.25	0xC1	77.31	4.38
-16.50	0xC2	79.78	4.25
-16.75	0xC3	82.32	4.13
-17.00	0xC4	85.17	4.00
-17.25	0xC5	87.62	3.88
-17.50	0xC6	90.39	3.75
-17.75	0xC7	93.23	3.63
-18.00	0xC8	96.68	3.50

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4 Revision history

Table 1. Document revision history

Date	Revision	Changes
23-Jul-2009	1	Initial release.