Implementing a Temperature Compensated RTC

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Agenda

- **Building a simple RTC with the MSP430**
- **What limits the accuracy of the simple RTC?**
- **What can we do to improve accuracy?**
- **An example of using correction techniques**

A simple real time clock

- **Simple MSP430 software RTCs are popular**
- **The 32kHz crystal osc is a suitable source of timing**
- **Several timers can generate 1 interrupt/second from the 32kHz oscillator**
  - Timer A, Timer B, Basic Timer, Watchdog timer
- **Each second, the CPU can wake very quickly (<6us) from LPM3, run at full speed to update time and date variables in RAM, and go back to sleep**
- **Typically an application would also do some housekeeping in the per second interrupt routine**
  - Total system consumption can be <1.2uA
  - A 3022 coin cell battery can run many products for >10 years
- **This is a classic MSP430 application**

A simple real time clock - tradeoffs

- **MSP430x4xx users usually use the basic timer**
  - Part of LCD controller support
  - A very simple timer for just this type of application
- **Users of other devices use Timer A/B or WDT**
  - The watchdog timer can be used, if watchdog functionality is not required
- **Care is needed, if WDT is performing its watchdog function**
  - The longest watchdog timeout is 1s, but the interrupt period is also 1s
  - Kicking the WDT at both the start and the end of the interrupt service can avoid false expiry of the WDT

Real time clocks – the problem

- **Many appliances, such as water and electricity meters, operate over a wide temperature range**
- **Watch crystal frequencies vary significantly over this range**
  - You don't cook or freeze your wrist, so the good timekeeping of a watch is no indicator of performance
- **Utilities are demanding precision real time clocks**
  - This demands temperature compensation
- **Precision real time clocks usually need to be ultra low power**
  - They need to run for years from a small battery, for cost or size reasons

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Factors affecting clock accuracy

- **Manufacturing tolerance of the crystal**
  - Crystals better than 10ppm at room temp. can be expensive
  - 100ppm crystals are cheaper, if we can tolerate them
- **Incorrect loading of the crystal**
  - Crystals can be pulled off frequency by the loading applied to them (think VCXO)
  - A very poorly loaded crystal might be unstable, especially in the presence of high EMI
- **Handling can change the crystal**
  - Thermal shock during soldering can alter a crystal's frequency
- **Temperature changes the crystal**
  - Over a wide temperature range, this is the biggest factor affecting clock accuracy
- **Crystals change with age**
  - Several ppm per year for typical 32kHz crystals

Real time clocks – the solution

- **Every ADC used in the MSP430 family has an internal temperature sensor we can use for RTC compensation purposes**
  - Requires calibration as the product is tested
  - Quick, simple calibration is adequate for most uses
  - Devices without a true ADC might use Comp_A to form a slope ADC, and sense temperature with an external device
- **Low precision crystals are cheaper than high precision, and may have just as good an aging characteristic**
  - Manufacturing tolerance error can be calibrated away as the product is tested
  - Calibration can be fast, cheap and simple
  - Calibration is best delayed as long as possible, so stresses relax

A typical crystal (Microtune)

Package Size		DS26	DS15	DS10	
Nominal frequency	F_L	32.768	32.768	32.768	kHz
Load capacitance [1)]	C_L	8.2	8.2	8.2	pF
Frequency tolerance [2)]	$\Delta F/F$	+/-20	+/-20	+/-20	ppm
	$\Delta F/F$	+/-30	+/-30	+/-30	ppm
	$\Delta F/F$	+/-100	+/-100	+/-100	ppm
Series resistance typ./max.	R_S	30 / 42	35 / 50	45 / 60	kΩ
Motional capacitance typ.	C_1	2.1	2.1	2.1	fF
Static capacitance typ.	C_0	0.9	0.9	0.9	pF
Drive level max.	P	1.0	1.0	1.0	μW
Quality factor min.	Q	55'000	45'000	38'000	
Insulation resistance min.	R_i	500	500	500	MΩ
Aging first year max.	$\Delta F/F$	+/-3	+/-3	+/-3	ppm
Turnover temperature	T_0	25 +/-5	25 +/-5	25 +/-5	°C
Frequency vs. temperature	$\Delta F/F_0$	$-0.035\ ^{ppm}/_{°C^2}\,(T - T_0)^2$ +/-10%			ppm

Data sheet for a typical 32kHz crystal. Note:

- The crystal frequency peaks close to 25C
- Frequency falls in a parabolic manner above and below 25C
- The parabolic curve varies little between samples of crystal
- Aging is the same for low and high precision versions

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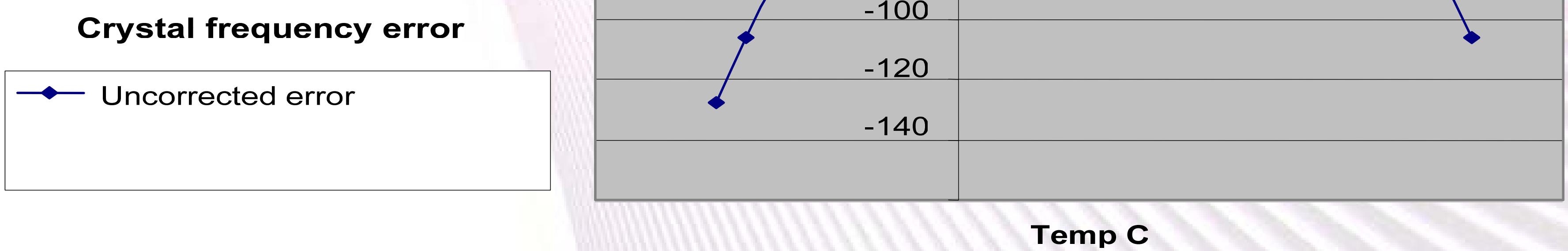
Crystal frequency with no correction

- **Without correction, the crystal frequency changes parabolically with temperature**
- **At high and low temperatures, realistic for severe climates and self-heating, the error is quite large**

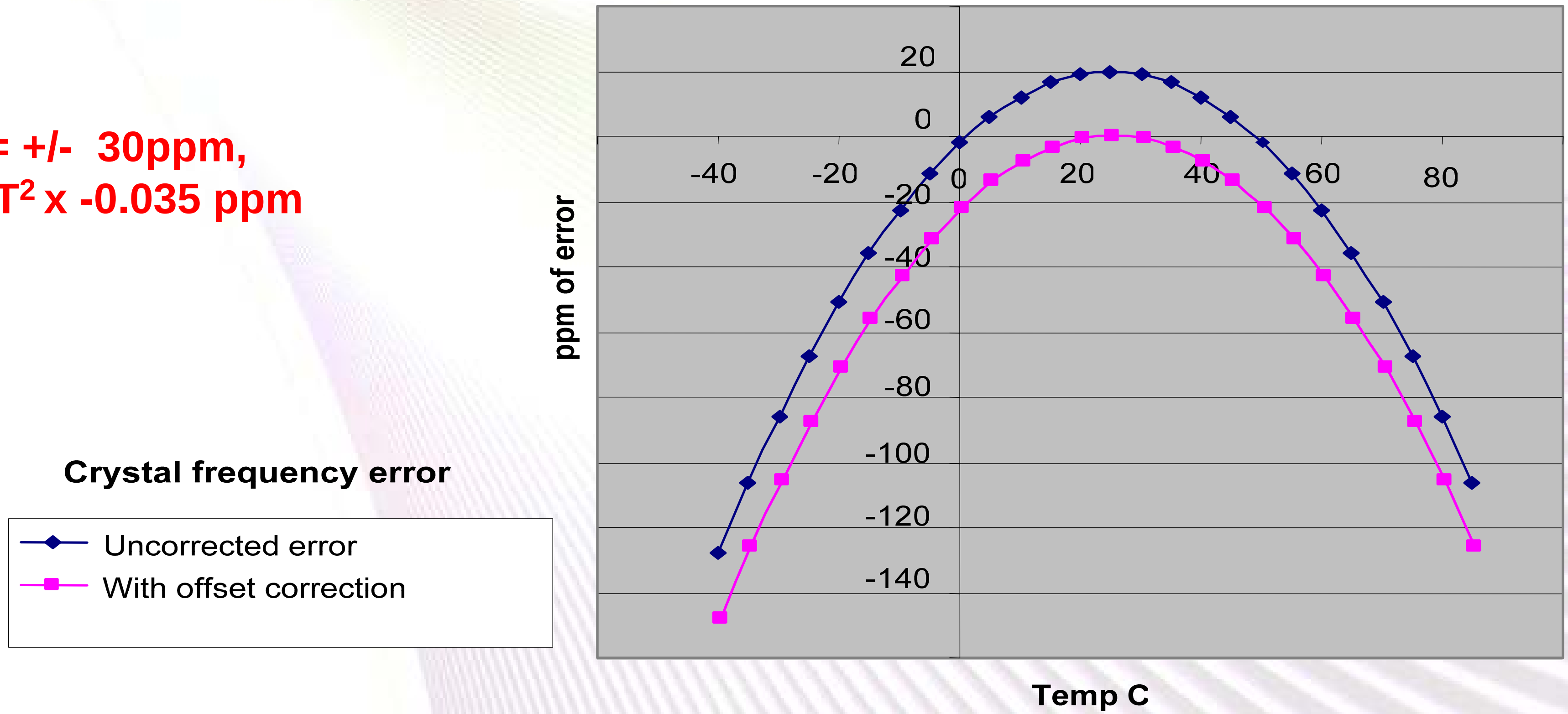
Crystal spec:
Offset at 25 C = +/- 30ppm,
Coefficient = ΔT^2 x -0.035 ppm



Correcting for manufacturing tolerance

- With compensation for crystal manufacturing tolerance results are better at room temperature
- There is no improvement elsewhere

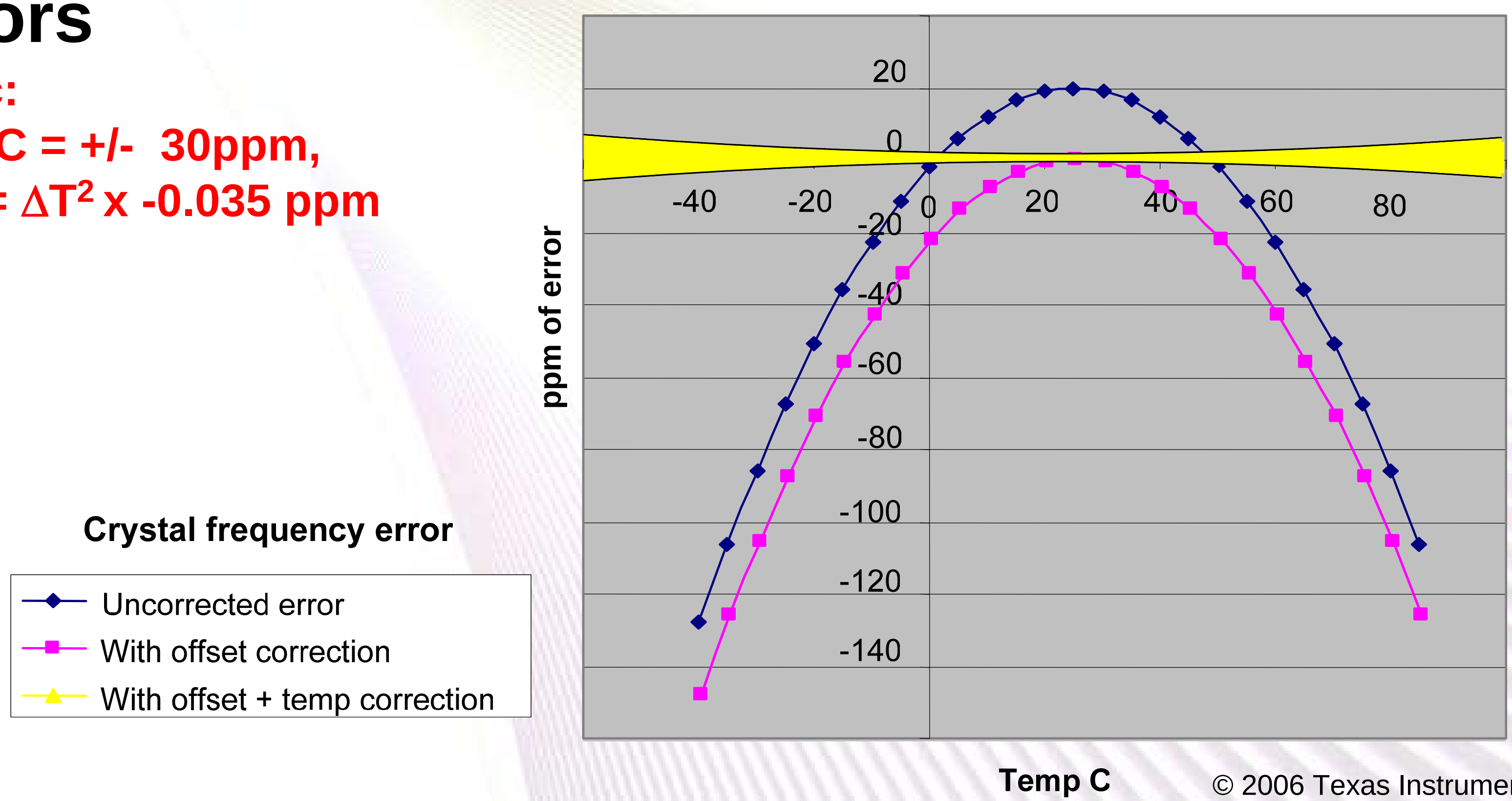
Crystal spec:
Offset at 25 C = +/- 30ppm,
Coefficient = ΔT^2 x -0.035 ppm



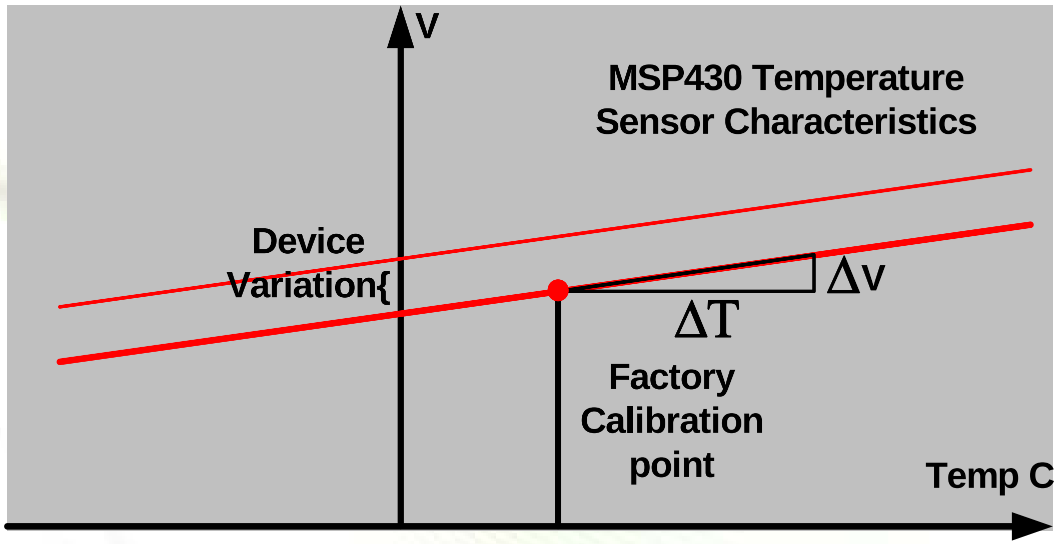
Fully correcting the crystal frequency

- With compensation for manufacturing tolerance and temperature a spread of errors something like the yellow band is achievable
- Actual results will depend on layout and other factors

Crystal spec:
Offset at 25 C = +/- 30ppm,
Coefficient = ΔT^2 x -0.035 ppm



Internal temperature sensors



- Each ADC in the MSP430 range – ADC10, ADC12, SD16 and SD16A has a temperature sensor with a near to straight line characteristic
- The slope and the y-axis intercept point varies from sample to sample
- Precise calibration requires measurement at two temperatures
- Using a compromise value for the slope, and finding the y-axis intercept through a measurement at room temperature is good enough for most purposes

External temperature sensors

- **Some small MSP430 device have no true ADC, but they do have comparator A**
  - Can be used to make a low power slope ADC
- **Used with an external temperature sensor, this could be the basis for a temperature compensated RTC design**

A ULP temp corrected RTC

- **We can compensate the clock with very little power increase over the simple RTC, if we:**
  - Run the ADC for a very short time, at well spaced intervals, and measure the temperature
  - Calculate the current error in the crystal frequency, and integrate this over time, until we are one second fast or slow
  - Make the time hop by one second, when the integration reaches its threshold
- **Current consumption still extremely low**
  - A 3022 coin cell typically still runs products for 10 years
- **Time hops can be mitigated if necessary**
  - Clock updates can be increased around the hop time, to allow them to be smoothed out

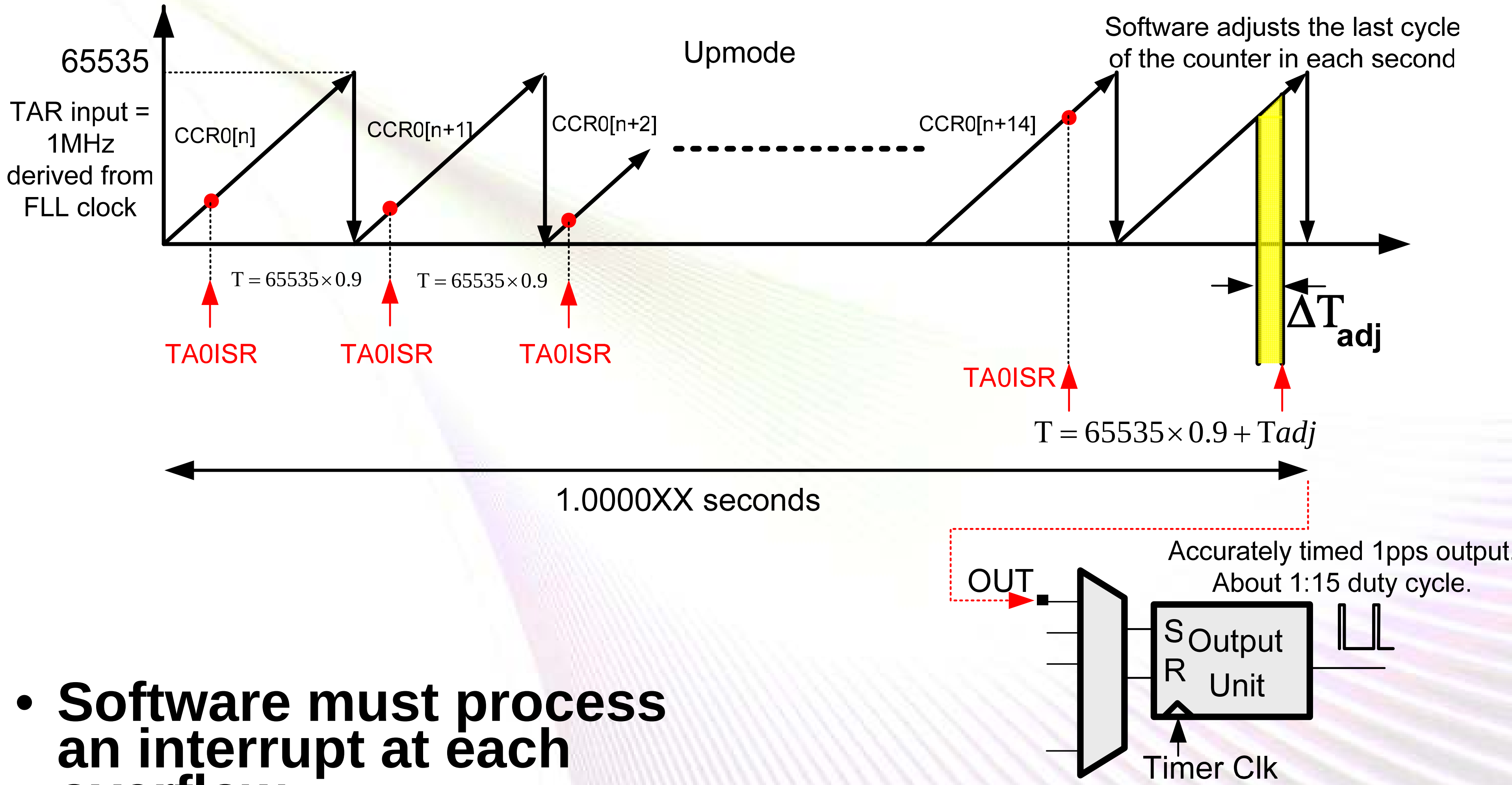
A low power temp corrected 1pps out

- **Often, approvals, or other tests, require a 1pps output**
- **We can generate this very well on devices with the FLL clock module**
- **We use the fast CPU clock locked to the 32kHz clock**
  - A special feature of Timer A lets us time the output of the 1pps output to within one CPU clock cycle
  - Most of the time the device can be in the LPM0 state
- **Power consumption can still be quite low (~30uA)**
  - The additional consumption is usually not too important. The 1pps output does not need to be enabled at all times

What about devices without an FLL?

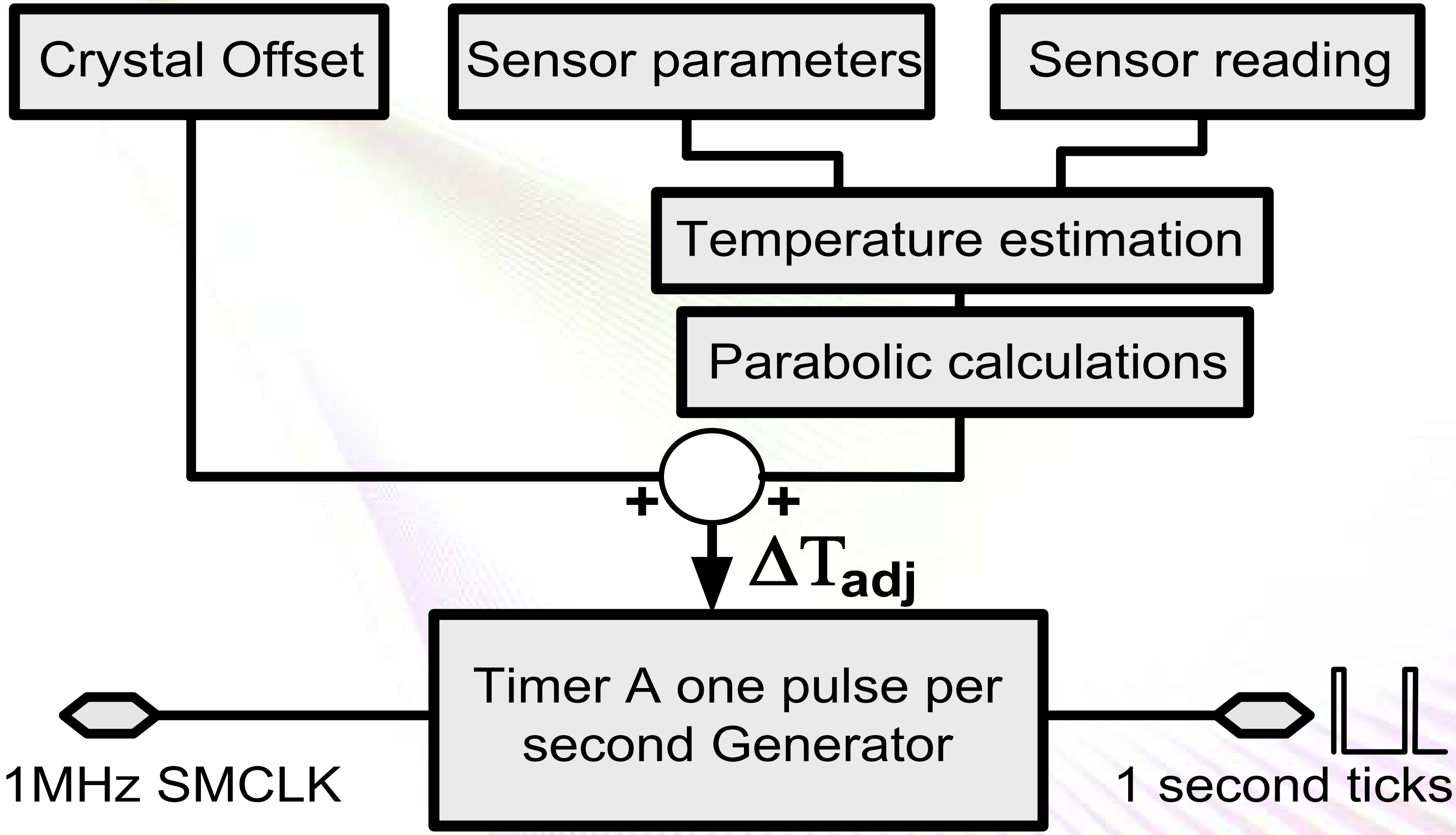
- **We have used the hardware module so far**
  - The simple factory calibration used it
  - The 1pps output used it
  - The corrected RTC only used the 32kHz crystal
- **We can calibrate the basic error by using an accurate external timer**
- **We can build a corrected RTC without the FLL**

Timer A generating an accurate 1pps



- **Software must process an interrupt at each overflow**
- **Interrupt rate is low**

Crystal frequency error estimation



Factory calibration

- **The basic error at the centre of the parabola can be measured quite simply at production time**
  - A precision 32kHz clock is connected to a Timer A input pin on the MSP430
  - Timer A, a CPU clock frequency locked to the MCU's 32kHz crystal, and a little software do the work
  - We tell the meter the calibration room temperature, so the software can allow for the current position on the crystal's parabola
  - About 30 seconds of self calibration is all that is needed
- **The MSP430's internal temperature sensor can be calibrated at the same time**
- **Calibration parameters can be stored in the 430's information memory**

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Example: putting it all together in an energy meter application

- The real time clock is updated only once a second
- Correction by adding or subtracting a whole second is generally acceptable in a meter
- We could measure the temperature once a second in normal operation, without affecting energy measurement
- When the meter is in power off/RTC only mode we can measure the temperature once every few minutes, without high overall battery consumption
- We integrate error each second, at the current rate, until we are either:
  - a whole second ahead – we increment an extra second, or…
  - a whole second behind – we skip an increment of one second

Some Code & Demonstration

- **We will look through key elements of some demonstration code, in C, to see in detail how it works**
  - This code implements both the ultra low power, and 1pps forms of compensated clock
  - This code has been provided, and runs on the ATC board
- **We will show it working in the 1pps mode**
  - Updates occur too infrequently in the ultra low power mode to provide a workable demonstration
- **We will hand calibrate for the sample of MCU and crystal we have, and show the results we can achieve**

Set things up, Interrupts do the rest

```
void main(void)
{
    WDTCTL = WDTPW | WDTHOLD;   /* Stop watchdog timer */
    init_fll();                 /* Lock the FLL at 4MHz */
    init_lcd();                 /* LCD to show the time */
    init_basic_timer();         /* Provides 1s kicks */
    set_rtc_sumcheck();         /* Init. the RTC */
    if (one_pps_active)
        init_pulse_stuffer();   /* Init. 1pps generation */
    init_adc();                 /* Init. temp. sensing */
    _EINT();
    /* Sleep, and let interrupts do the work */
    if (one_pps_active)
        LPM0;
    else
        LPM3;
}
```

Estimating the crystal clock speed...

```
void estimate_current_cycles_per_second(int16_t temperature)
{
    int32_t temp;

    /* A simple IIR filter smoothes noisy sensor readings */
    raw_temperature_from_adc +=
        temperature – (raw_temperature_from_adc >> 3);
    /* Find the temp., in Celsius, based on the sensor
       characteristics found at calibration time. */
    temp = raw_temperature_from_adc
         - temperature_sensor_intercept;
    temp *= temperature_sensor_slope;
    temp >>= 16;
    temperature_in_celsius = temp
```

…Estimating crystal clock speed…

```
/* Now we need to calculate the ppm of clock error due to
   the current temperature. */
/* Subtract the centre point of the crystal curve. */
temp -= CRYSTAL_QUADRATIC_CENTRE_TEMPERATURE;
/* Do the parabolic curve calculation, to find the
   current ppm of error due to temperature. */
temp = temp*temp;
temp = (temp*CRYSTAL_QUADRATIC_COEFF) >> 16;
```

…Estimating crystal clock speed…

```
switch (correction_components)
{
case RTC_CORRECTION_NONE:
    current_rtc_correction = 0;
    break;
case RTC_CORRECTION_CRYSTAL_ERROR:
    current_rtc_correction = crystal_base_error;
    break;
case RTC_CORRECTION_TEMPERATURE:
    current_rtc_correction = -temp;
    break;
case RTC_CORRECTION_CRYSTAL_ERROR_AND_TEMPERATURE:
    current_rtc_correction = crystal_base_error - temp;
    break;
}
current_estimated_cycles_per_second =
      CRYSTAL_BASE_CYCLES_PER_SECOND
    + current_rtc_correction;
```

Prepare to generate the 1pps output

```
void init_pulse_stuffer(void)
{
    TAR = 0;
    TACCR0 = 0;
    TACTL = TASSEL_2 | MC_2 | ID_2;
    P1SEL |= BIT0;
    P1DIR |= BIT0;
    TACCTL0 = OUTMOD0 | CCIE;
    /* Initialize the cycles per second with an
       approximation */
    current_estimated_cycles_per_second =
        CRYSTAL_BASE_CPS + crystal_base_error;
    cycles_left_this_second =
        current_estimated_cycles_per_second;
}
```

Generate a precise 1pps output

```
void update_pulse_stuffer(void)
{
    uint16_t step;
    step = 65536U - 655U;
    cycles_left_this_second -= step;
    if (cycles_left_this_second <= 655)
    {
        step += cycles_left_this_second;
        TACCTL0 &= ~OUTMOD2;
        cycles_left_this_second =
             current_estimated_cycles_per_second;
    }
    else
    {
        TACCTL0 |= OUTMOD2;
    }
    TACCR0 += step;
}
```

Update the RTC

```
int update_rtc(void)
{
    integrated_rtc_correction += current_rtc_correction;
    if (integrated_rtc_correction >= CRYSTAL_BASE_CPS)
    {
        integrated_rtc_correction -= CRYSTAL_BASE_CPS;
        /* We need to add an extra second to the RTC */
        bump_rtc();
    }
    else if (integrated_rtc_correction <= -CRYSTAL_BASE_CPS)
    {
        integrated_rtc_correction += CRYSTAL_BASE_CPS;
        /* We need to drop a second from the RTC */
        return;
    }
    bump_rtc();
}
```

A Real-Time Demonstration

- We will see the software's 1pps mode in operation
- We will hand calibrate for the sample of MCU and crystal we have, using an accurate timer-counter
- We will show the results we can achieve with an accurate timer-counter, and…… a hairdryer!
- We cannot run this as a hands on lab session, as each person would need an accurate timer-counter…
- All the materials are provided, so you can try this for yourselves later