Low-Power High-Accuracy Timing Systems for Efficient Duty Cycling

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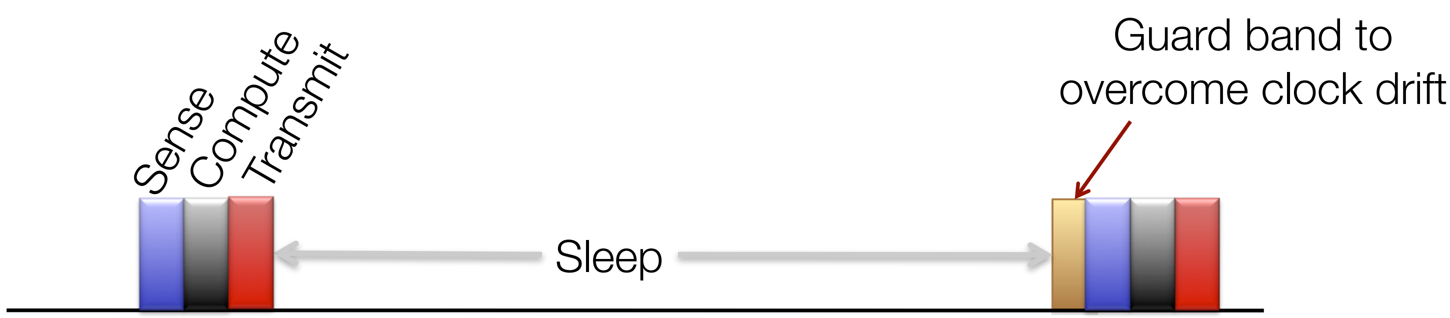
Duty Cycling with Accurate Clocks

- Most WSN applications have a need for synchrony
- MAC protocols that utilize Scheduling and LPL
- Synchronous sensing (for beam forming applications)

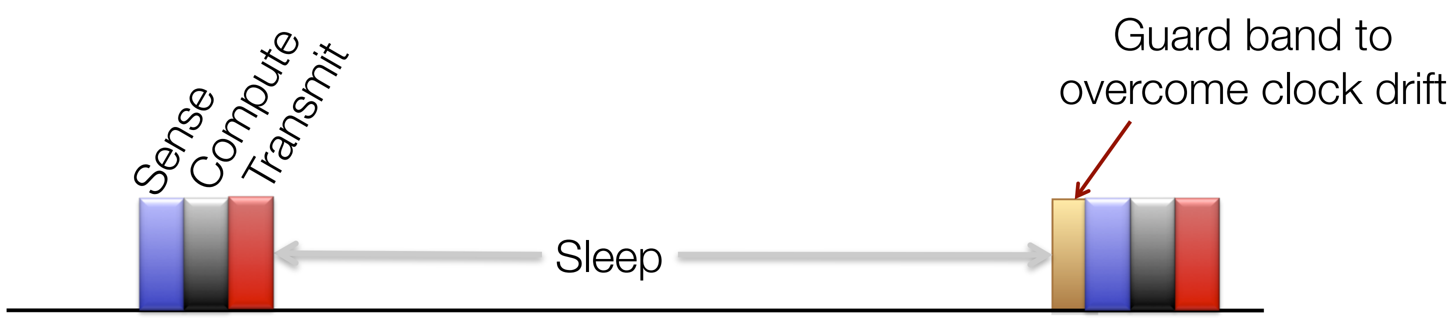


- Minimizing guard bands to reduce wasted active-time and increase channel capacity

Duty Cycling with Accurate Clocks

- Duty cycling is a key mechanism for conserving energy
- A timer remains active while the node is asleep

$$DC = \frac{t_{active}}{t_{active} + t_{sleep}} \qquad P_{avg} = DC \cdot P_{active} + (1 - DC) \cdot P_{sleep}$$



- As duty cycle decreases, sleep power starts to dominate average power consumption

Observations

Accurate clocks can save energy by reducing guard times

↓

For equal guard times, a node with a more accurate clock can sleep longer

↓

But, we must ensure that this accuracy does not come at increased cost

Balancing Stability, Granularity and Power

Device	Granularity	Stability	Power
Tuning Fork XO	Coarse	25ppm	<50uW
AT-cut Quartz XO	Fine	25ppm	200uW
8 MHz XCXT	Fine	1ppm	1.4mW
Smart Timer Unit			
DS4026 10MHz TCXO	Fine	1ppm	6mW

Granularity + Stability = Power

Outline

- Introduction
- Differential Frequency Error
- XCXT Prototype Implementation
- Evaluation and Power Numbers
- The Smart Timer Unit
- Conclusion

Some Nomenclature

- Temperature dependent

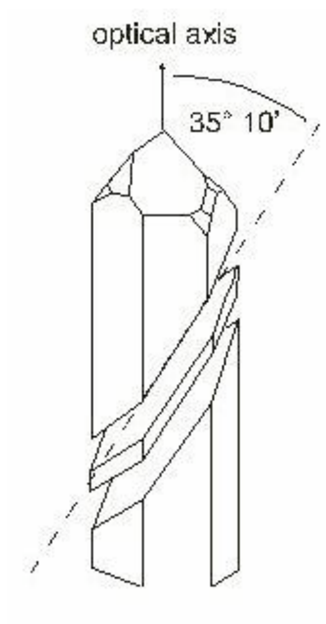
  Frequency: $f(T)$

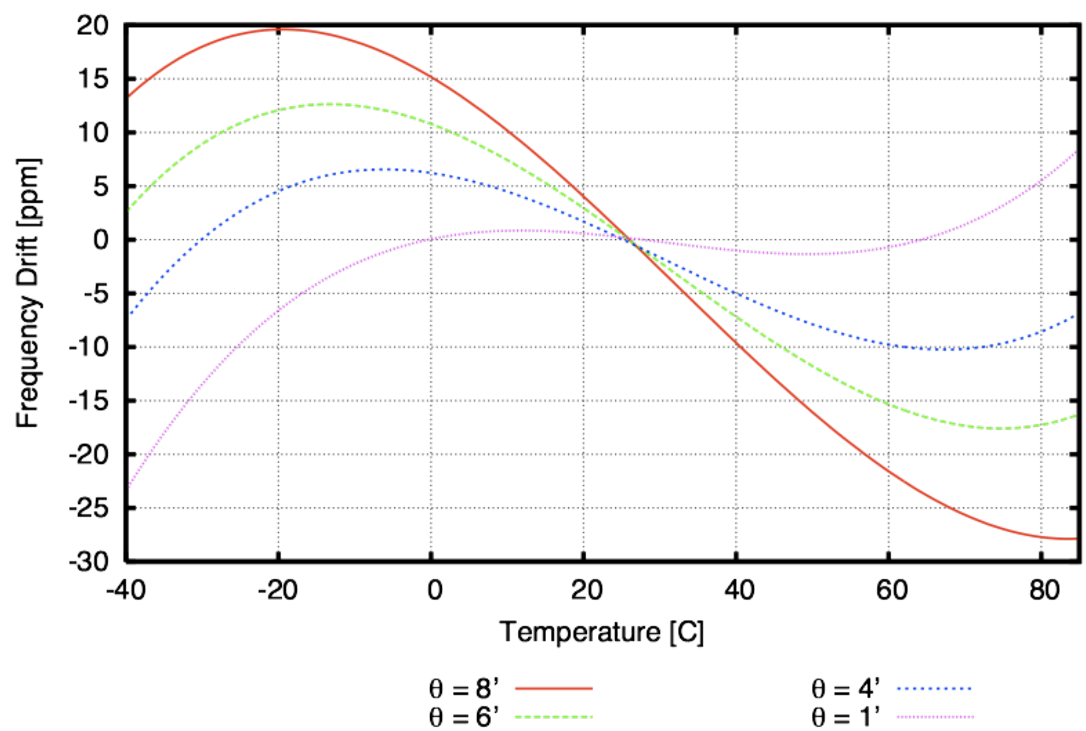
- Nominal Frequency: F_0
- Frequency Error: $\Delta f(T) = f(T) - F_0$
- Normalized Error: $\delta f(T) = \dfrac{\Delta f(T)}{F_0} = \dfrac{f(T) - F_0}{F_0}$
- Differential Frequency Error:

$$\delta f_{12}(T) = \delta f_1(T) - \delta f_2(T)$$

Frequency - Temperature Dependence of AT-cut

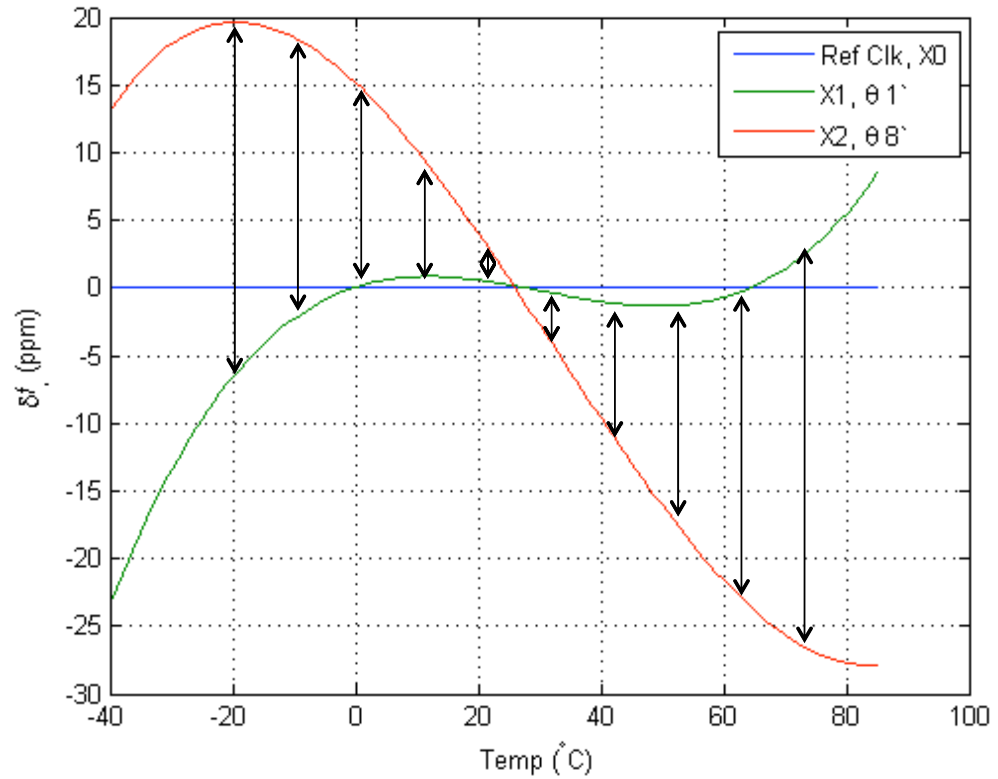
- AT-cut Quartz crystals inside most XOs today
- Characteristic cubic temperature curve with slope dependent on slight variations in cut angle





Differential Frequency Error

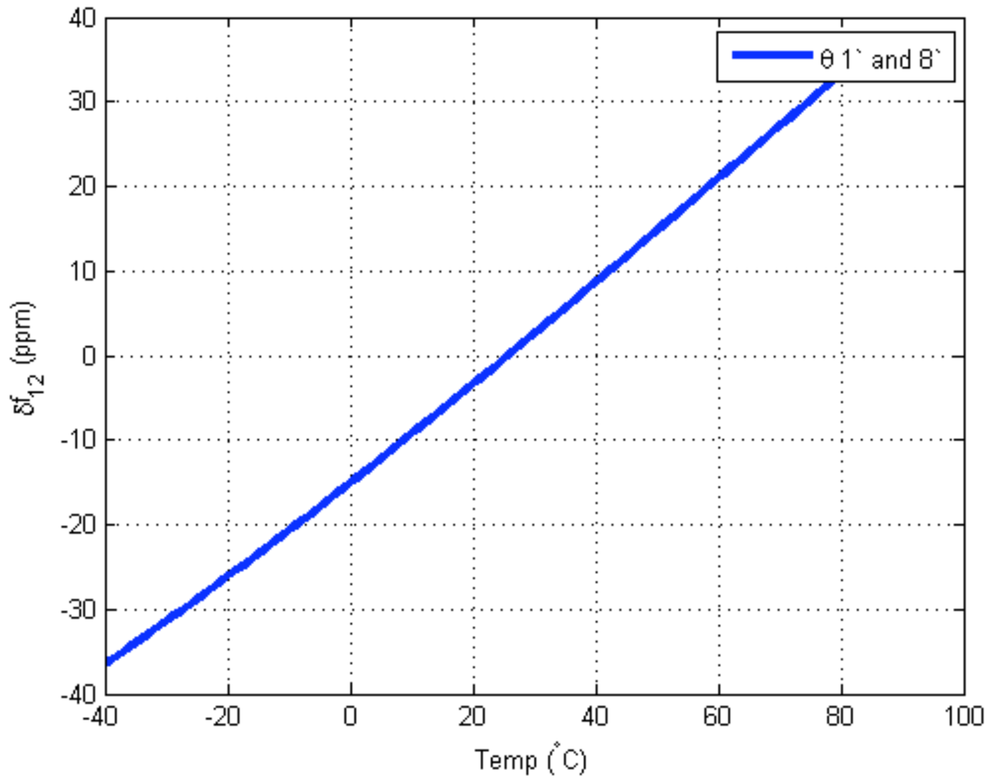
Normalized Frequency Error vs. Temperature



AT-cut Quartz Crystals

$$\delta f_{12} - T$$

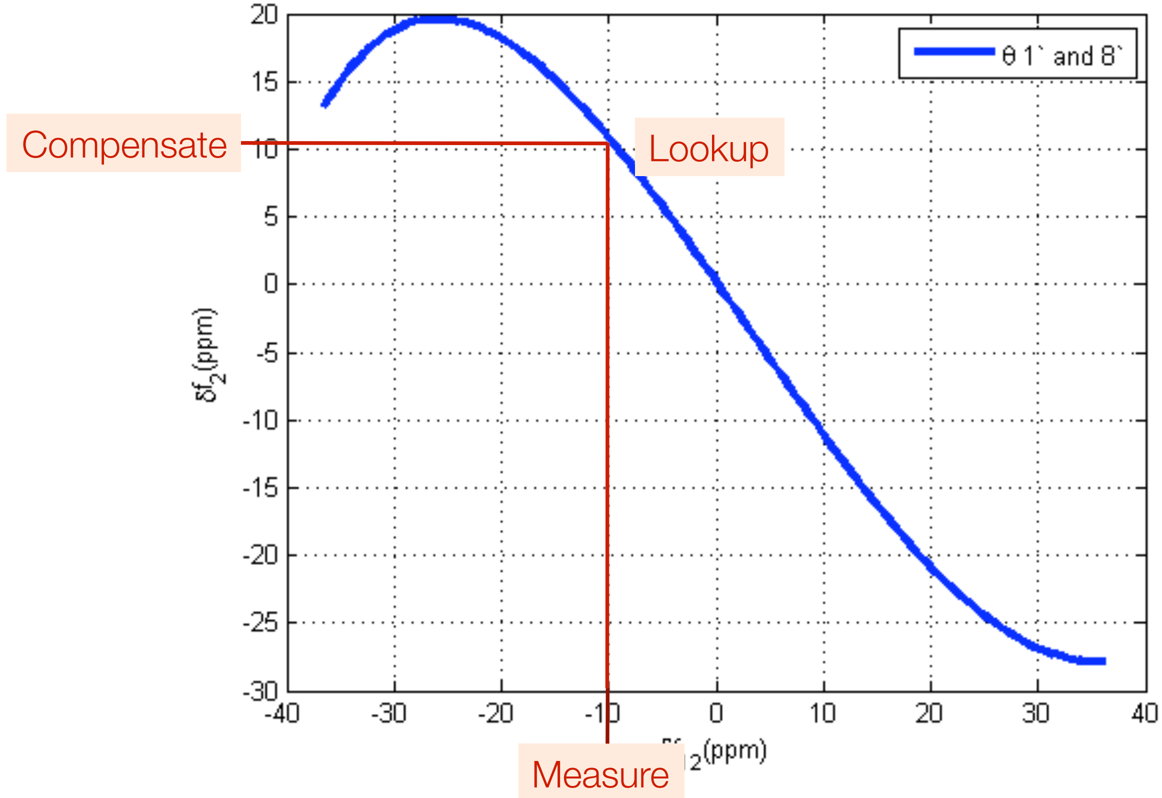
Differential Frequency Error vs. Temperature



AT-cut Quartz Crystals

$$\delta f_2 - \delta f_{12}$$

Normalized Frequency Error vs. Differential Frequency Error



Exploiting Differential Frequency Error

- If $T - \delta f_{12}$ is a bijection, we know there exists a unique mapping from differential frequency error to the temperature
- Then, we construct the $\delta f_1 - \delta f_{12}$ curve using a stable clock reference (factory calibration)
- At run time, we measure δf_{12} and then estimate δf_1 using the calibration curve
- Compensating by this amount, we can achieve the same stability as the factory reference

Why not use a Temperature Sensor?

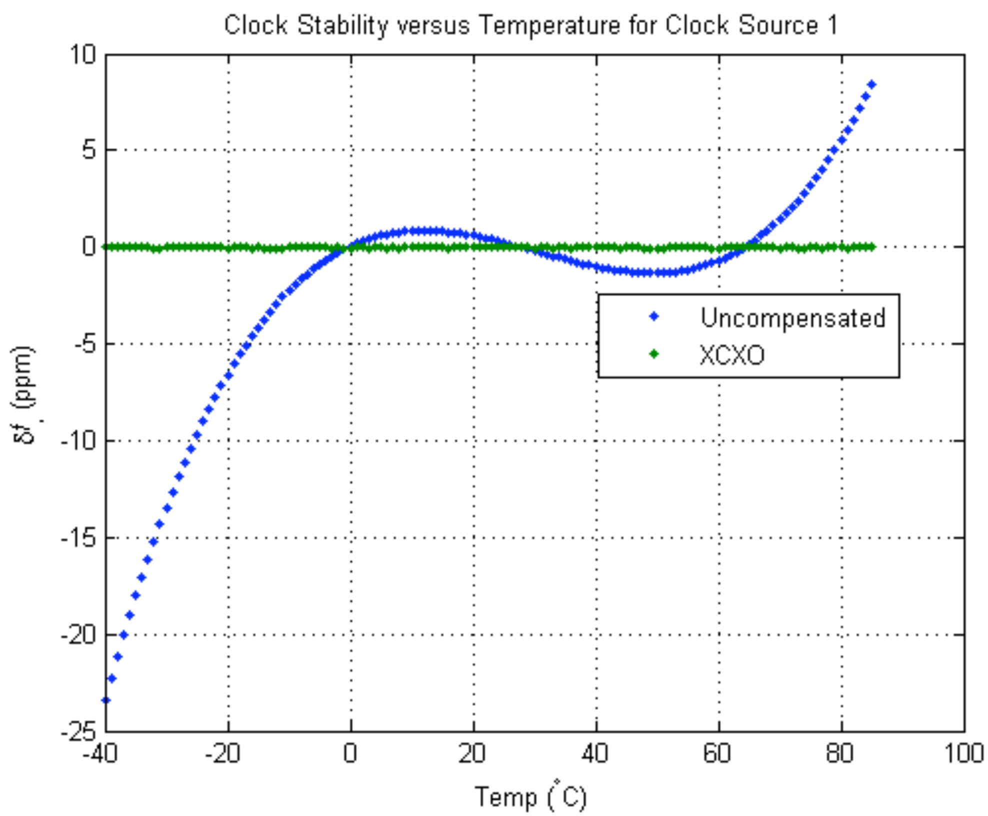
Cons:

- Temperature sensor itself requires calibration
- Hysteresis due to unequal heating of sensor and crystal
- Temperature sensor needs an ADC

Pros:

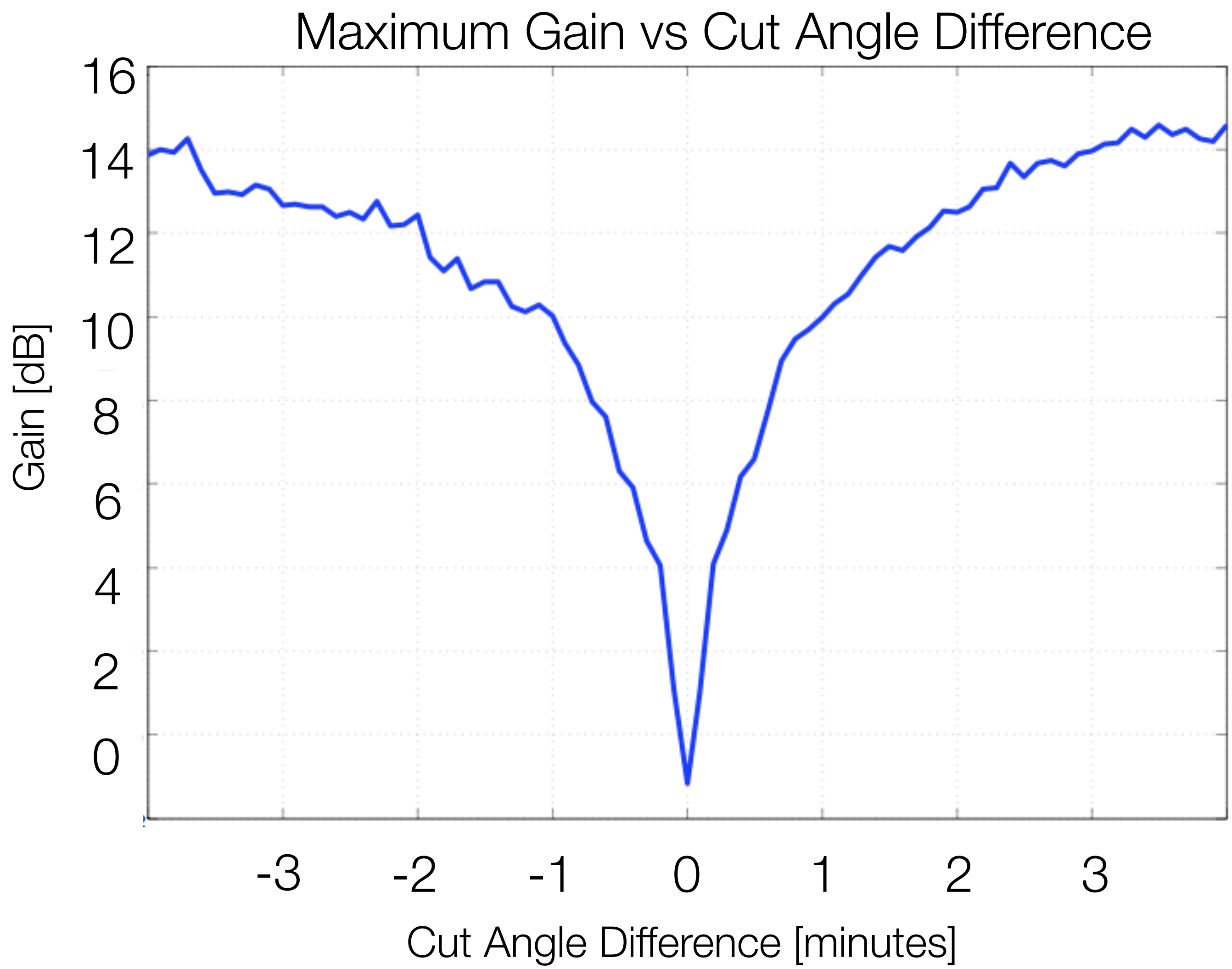
- DFE measures the phenomena of interest directly – frequency error
- DFE can be all digital and lower power

Compensation Results (Simulation)



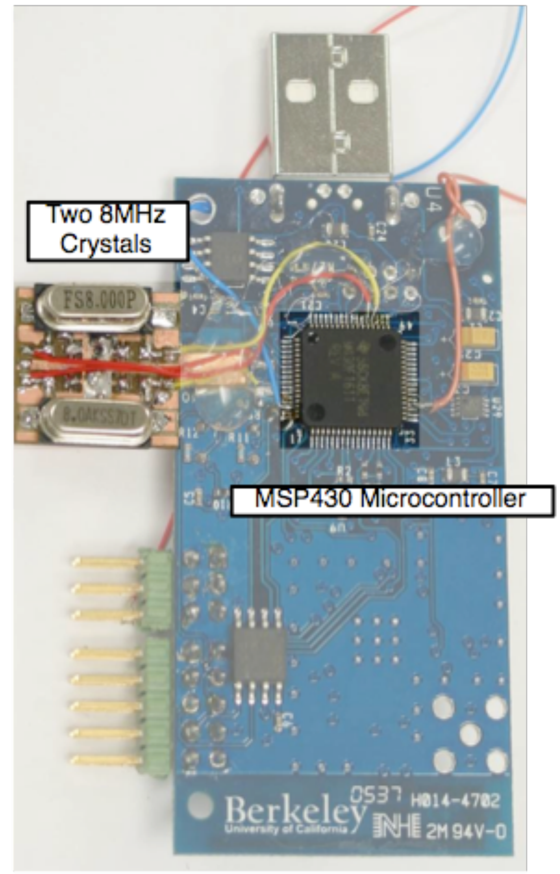
- Using 1’ and 8’ AT-cut Quartz crystals
- Compensation ‘gain’ of about 40x (16dB)

Change in Angle

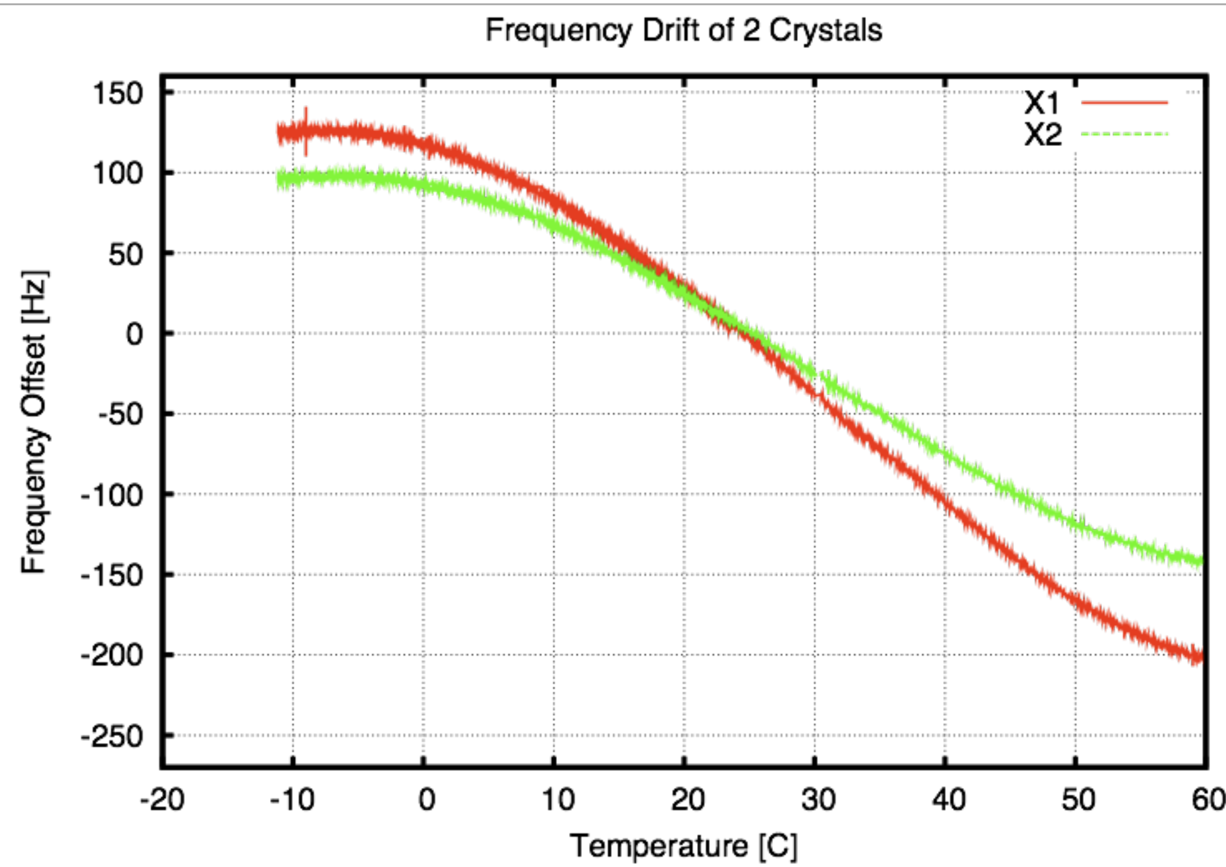


XCXT Prototype Implementation

- Telos mote with MSP430 µC
- MSP430 has 2 crystal inputs
- Added a small extension board that holds the two crystals
- Replaced standard 32kHz clock with a 8MHz crystal
- Software using SOS operating system for calibration and compensation
- Temperature chamber to cool and heat the device: -10°C to 60°C

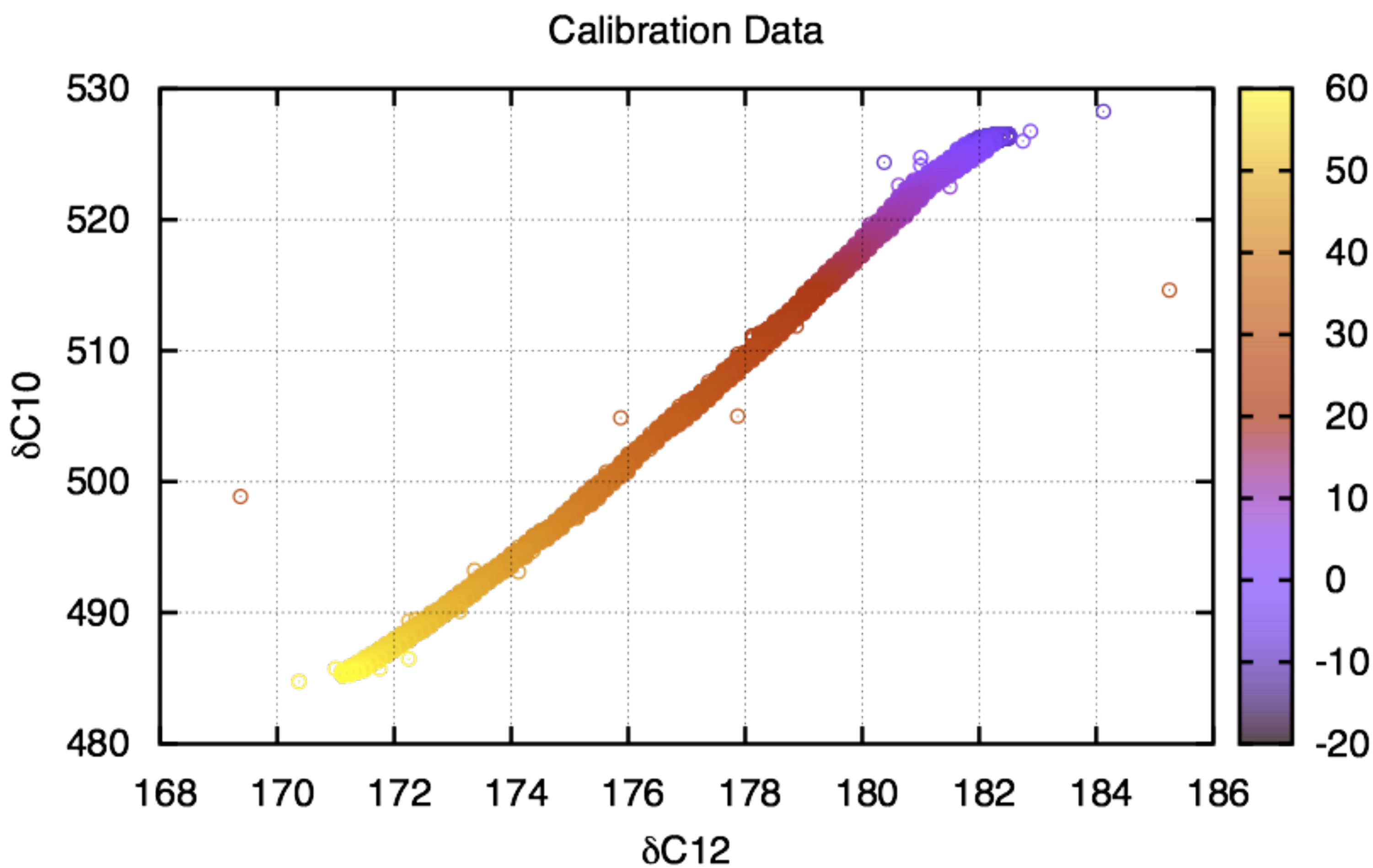


8MHz Crystal Measurements

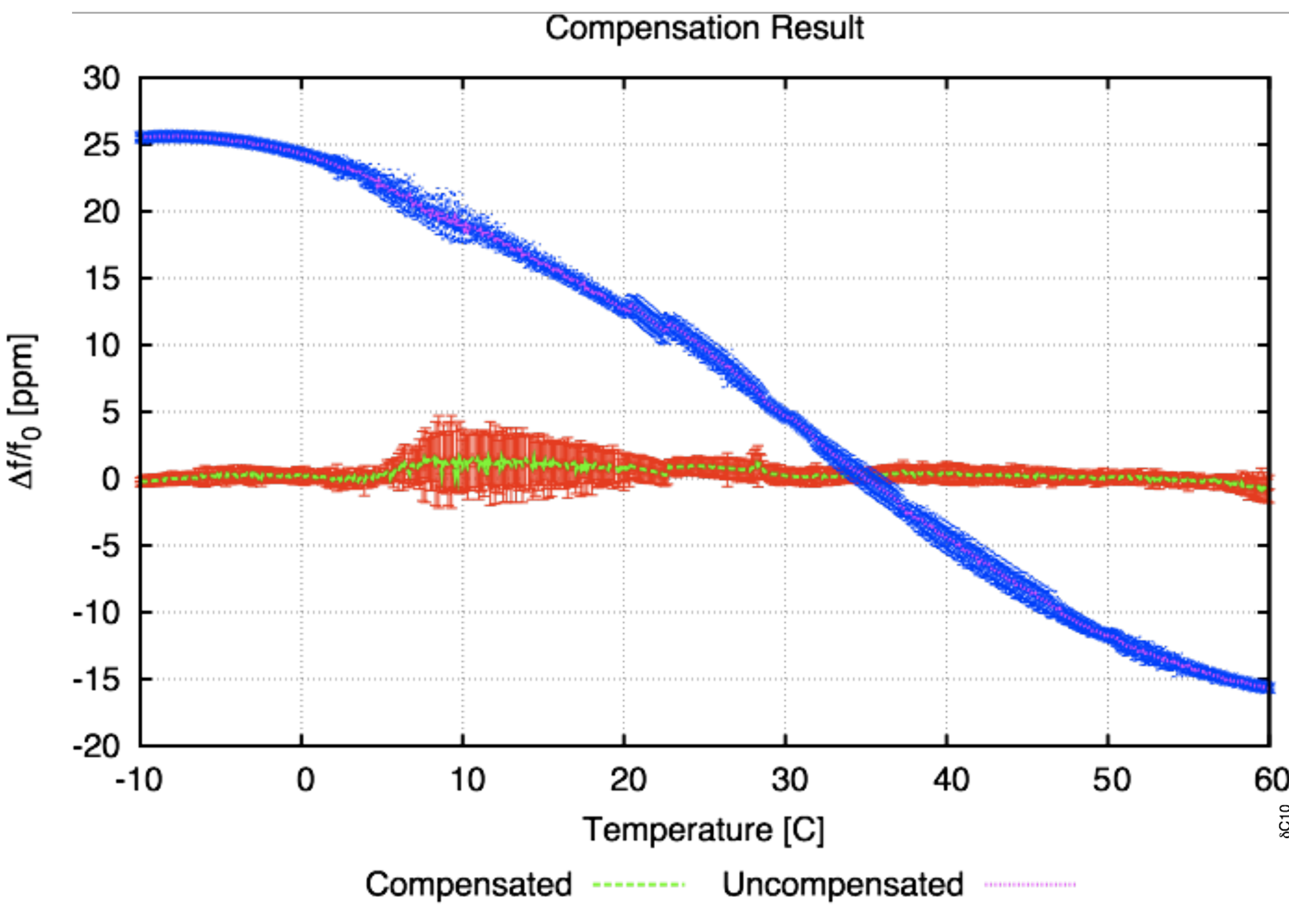


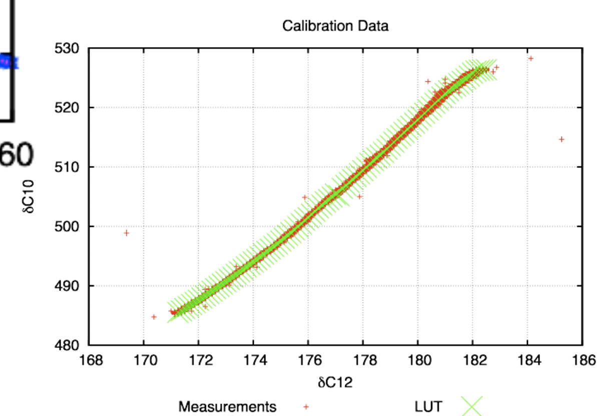
- Kyocera HC49SFWB and FOX HC49SDLF
- 8.000 MHz fundamental frequency with 50ppm stability

XCXT Calibration



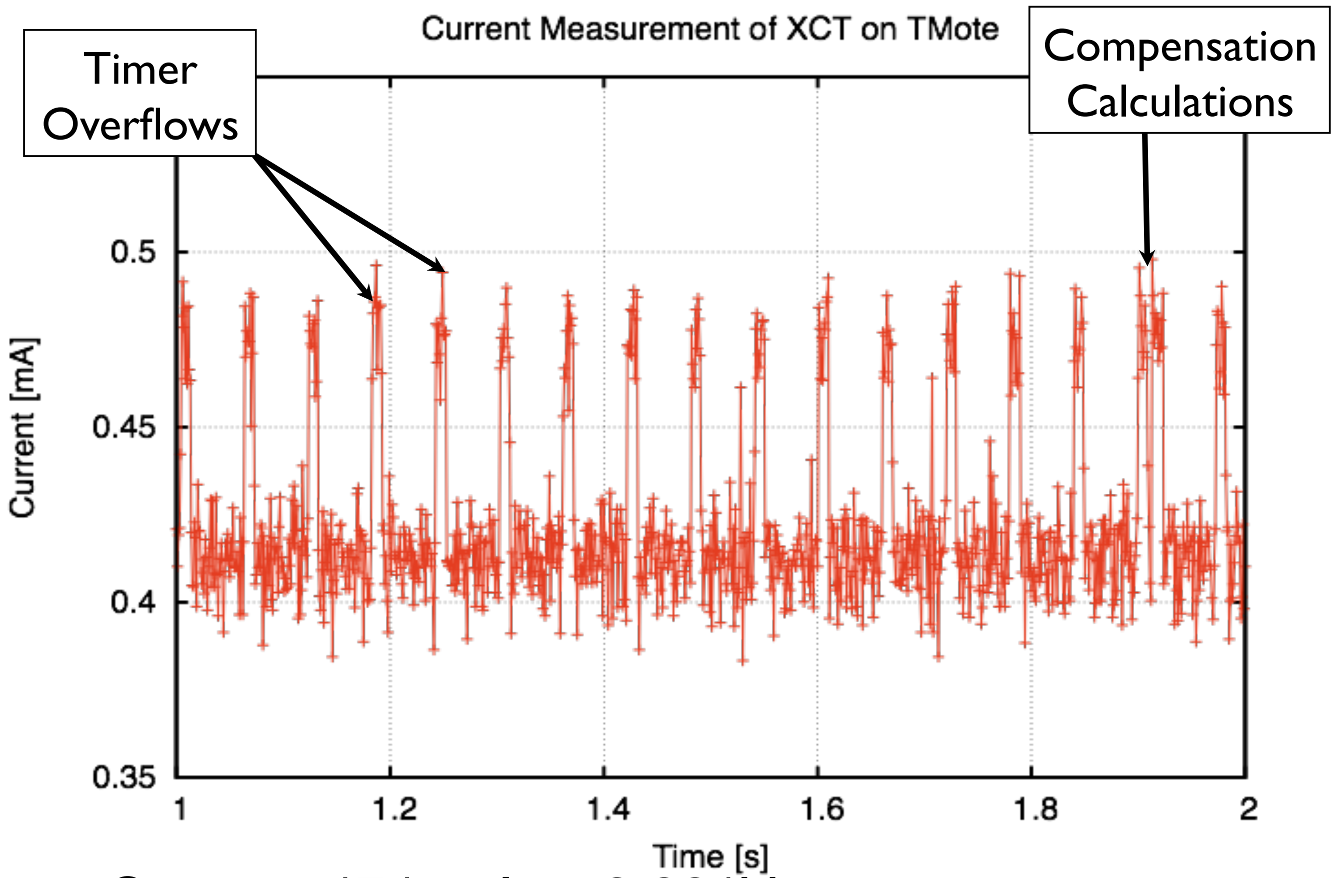
XCXT Compensation





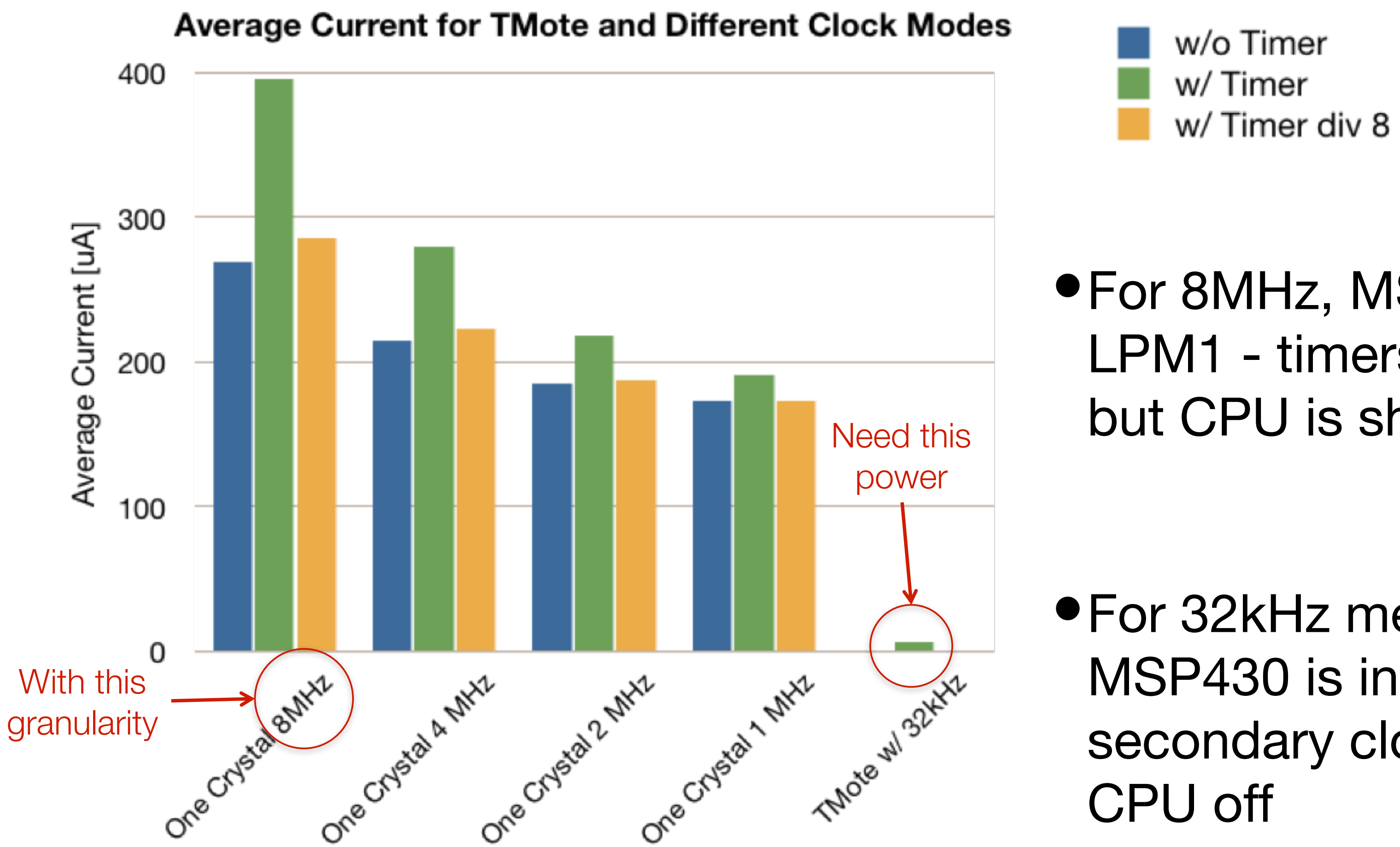
We achieve a mean stability of 0.47ppm with a sample standard deviation of 0.31ppm

8MHz XCXT Power Measurements



- Average Current: 474 μA at 3.001V
- Average Power: 1.4 mW compared to 6 mW of a DS4026 TCXO

How does Granularity affect Timer Power?



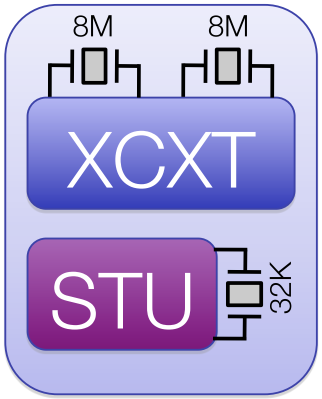
- For 8MHz, MSP430 is in LPM1 - timers are active, but CPU is shut down
- For 32kHz measurement, MSP430 is in LPM2 - secondary clocks are off, CPU off

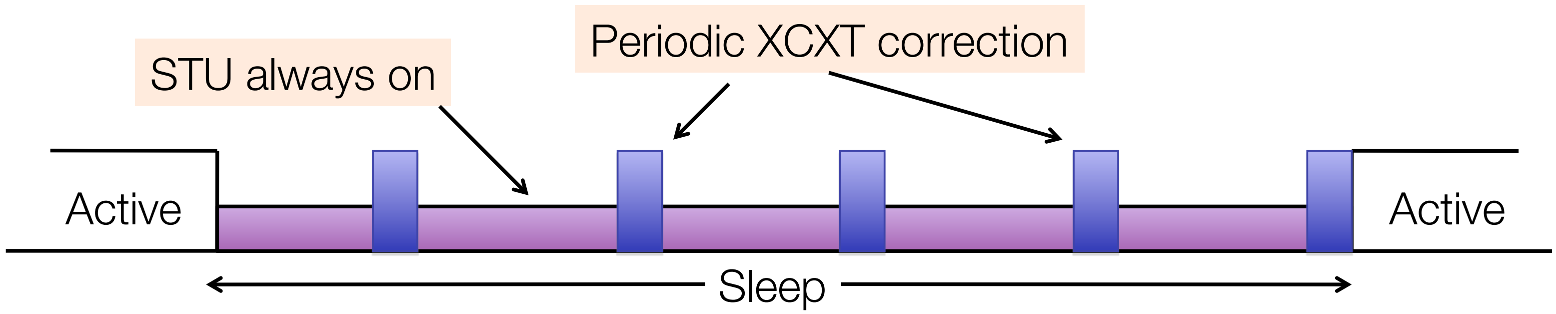
Exploiting Temperature Dynamics

- Temperature changes slowly (max. 1°C per minute) even in outdoor environments
- Clock correction/compensation needed only once a minute
- Can adapt to actual rate of change through DFE based temperature sensing
- But, increasing interval between compensations would save some power but not much

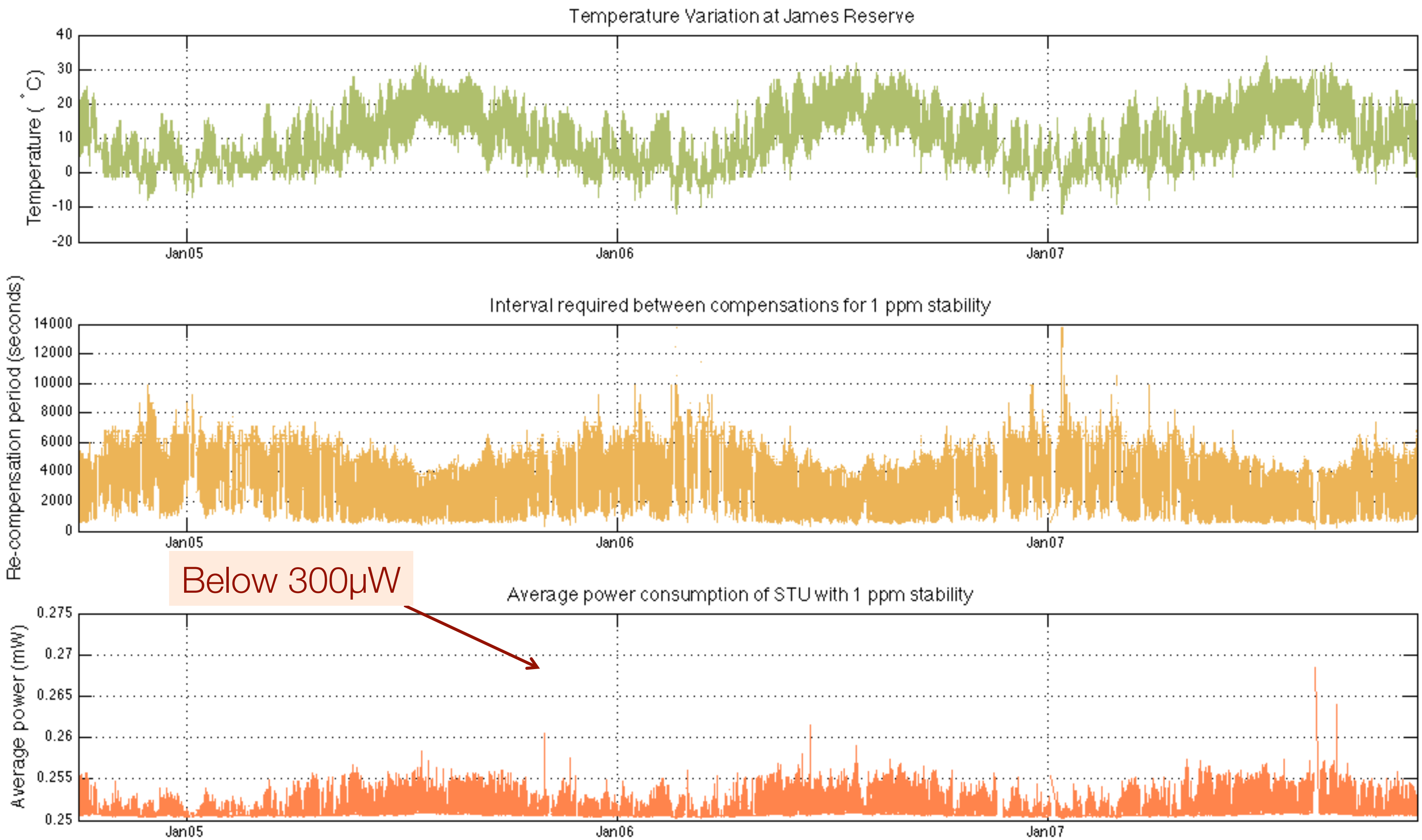
Smart Timer Unit

- Use 32KHz clock as primary during sleep, 8MHz XCXT as duty cycled secondary
- Use 8MHz XCXT in the last 32KHz pulse to increase granularity
- Exploit higher stability of the XCXT to compensate the 32KHz once every minute





Preliminary Simulation Results



Conclusion

- Compensating a pair of AT-cut crystals using Differential Frequency Error can provide sub-ppm accuracy
- A prototype implementation verifies lower power ability of XCXT
- Even lower power can be achieved using a coarse granularity timer corrected by a duty cycled XCXT

Thank you!

For more information, please visit
http://nesl.ee.ucla.edu/research/xcxt/

Related Work

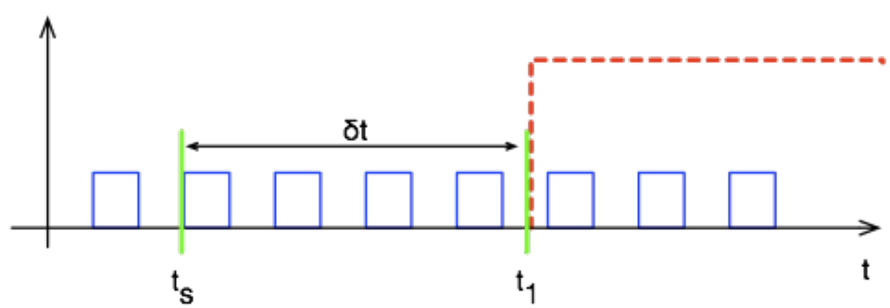
- Use two different cut crystals (AT-cut & Y-cut) [Onoe 1975]
- Use of one SC-cut crystal and two harmonics [Schodowski 1983]

  This became the MCXO (~70mW, instead of ~1.5W for an OCXO with the same precision)
- Use two AT-cut crystals for temperature measurement, [Satou 1991]

Interpolating Slow Clocks

- Timer A: slow; Timer B: fast
- Start both timers at the exact same time
- after t_s, get both counter values
- at the rise of the next timer A tick, get reading of timer B

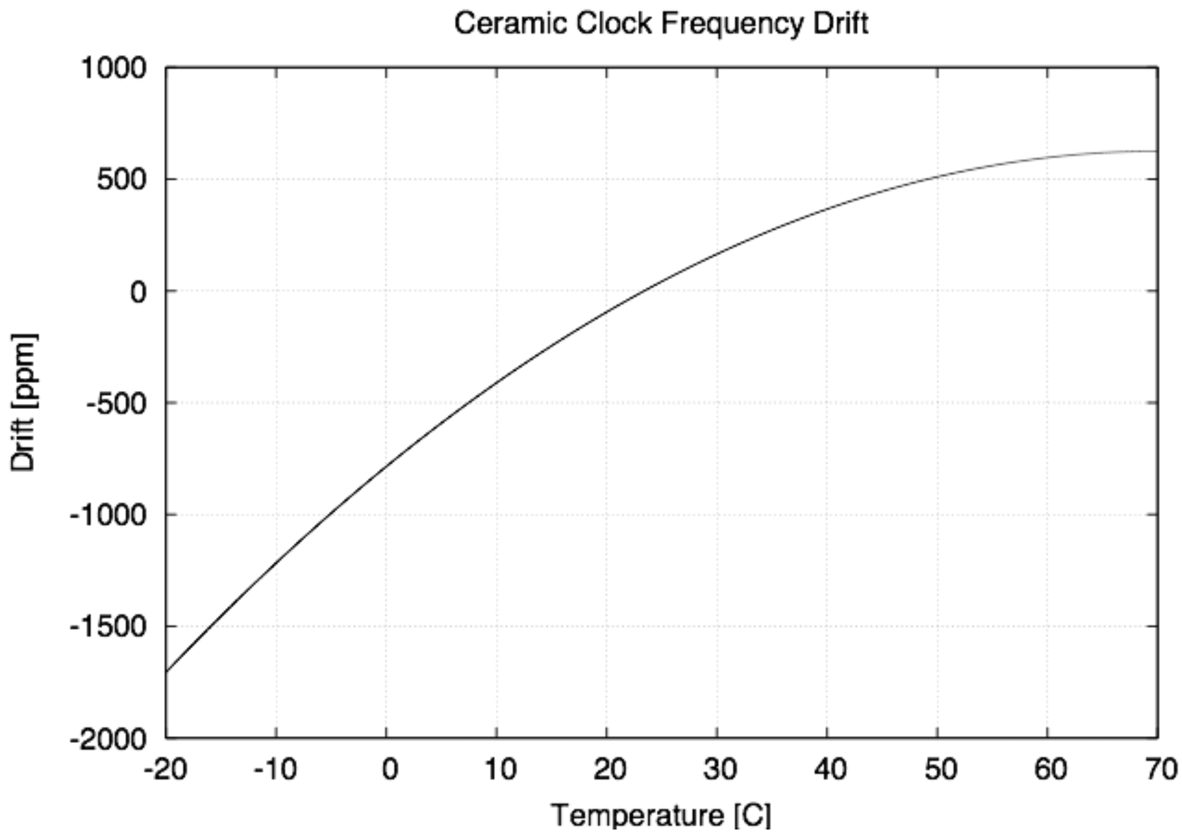
$$\phi_A(C_B) = \frac{f_B/f_A - (C_B(t_1) - C_B(t_s))}{f_B/f_A} = 1 - \frac{\lfloor \delta t \cdot f_B \rfloor}{f_B/f_A}$$



Technical Problems

- Technical problems: Differential Frequency Error using tuning fork and AT-cut crystal doesn’t work!
- Possible solution: Ceramic resonator!

Ceramic Resonator stability



- Very unstable to voltage changes
- Hysteresis problems

Sources of Error in Timing

- Local clock source
  - Environmentally induced drift - Temperature
  - Aging
- Time Synchronization
  - Time of flight / transmission
  - Computational jitter (interrupts, algorithm calculations)
  - Time stamping accuracy (platform dependent)

AT-cut Quartz Crystal

$$\delta f - T$$