Compensation of Environmental Effects on Crystal Oscillators Using an Artificial Neural Network

John Esterline
Greenray Industries

The Long Island Chapter of the IEEE
Microwave Theory & Techniques Society

Topics

- Introduction and background
- Artificial Neural Network (ANN) overview
- ANN oscillator compensation
  - Hardware configuration
  - Testing methodology
- Various Compensations
  - Temperature, Trim, Hysteresis, Aging, Warm-up
- Conclusion
- Questions

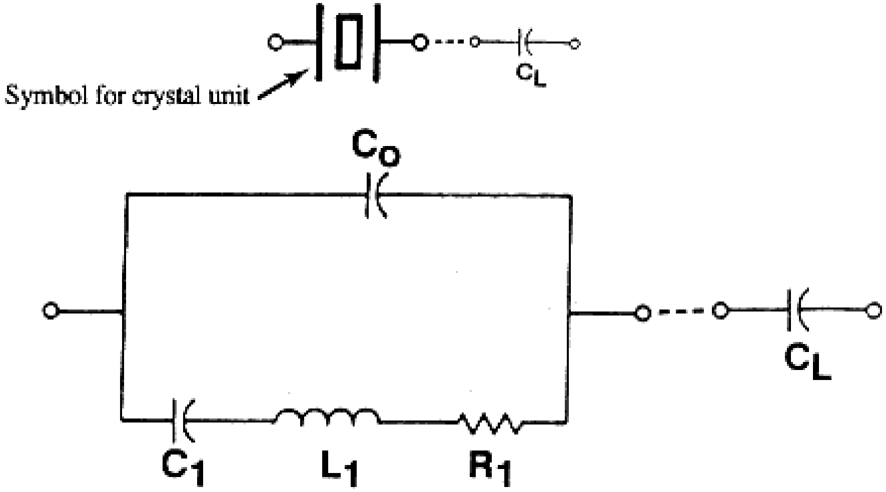
Introduction

- Quartz crystals provide superior performance to most other resonator types and half been used widely since 1939
  - Small
  - Extremely high Q (>20,000 for AT, >1,000,000 for SC)
  - Superb temperature performance

- Oscillator Types
  - XO
  - VCXO
  - TCXO
  - MCXO
  - OCXO
  - DCOCXO

Introduction

- Quartz Crystal equivalent circuit



- Crystal equivalent circuit
  - C_1, R_1, and L_1 are the “Motional Parameters”
  - C_0 holder capacitance

$$Q = \frac{1}{2\pi f_s R_1 C_1}$$

Introduction

- Fractional Frequency Stability
- Relative measure of frequency variation

$$S=\Delta F/F$$

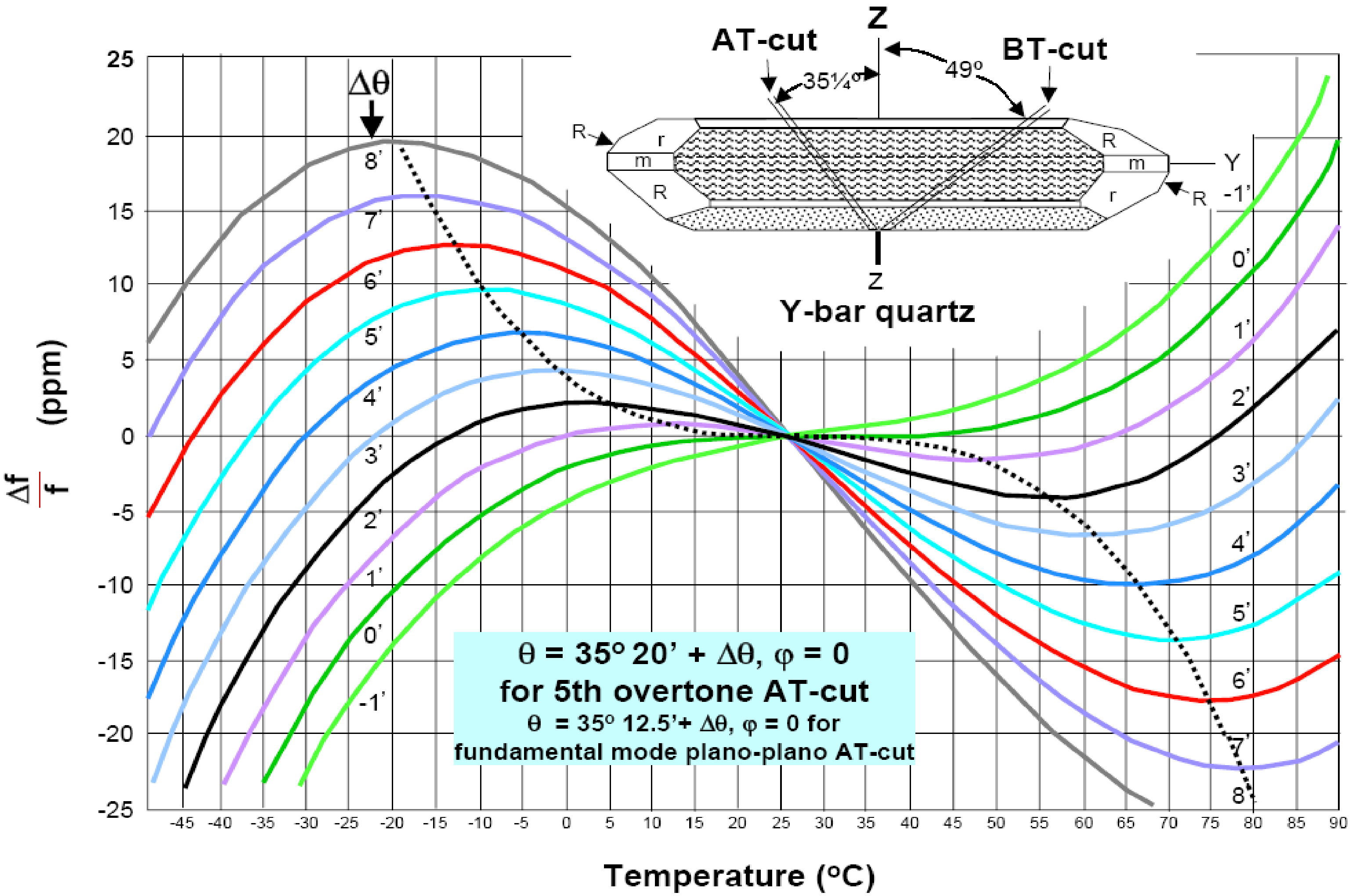
- i.e. (change in Freq. / Nominal Freq.)

- Ex: 1Hz/100Hz = .01 = 1%
- 1Hz/1MHz = $1x10^{-6}$ = 1ppm
- 0.01Hz/10MHz = $1x10^{-9}$ = 1ppb

Introduction

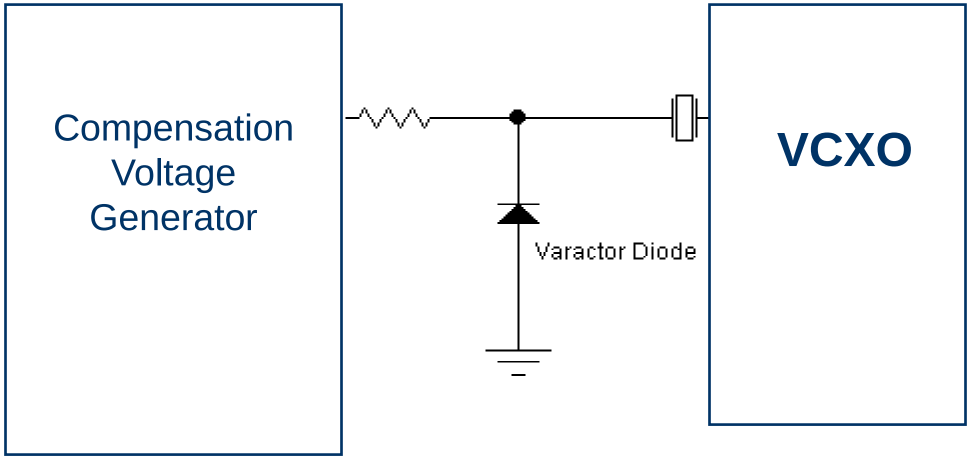
- TCXO (Temperature Compensated Crystal Oscillator)
- Quartz has natural frequency versus temperature response
- Compensation circuit creates a temperature dependent voltage that changes the load capacitance the crystal sees
- Classically done with thermistor resistor networks
- Modern TCXO use a 5th order polynomial generator

Introduction



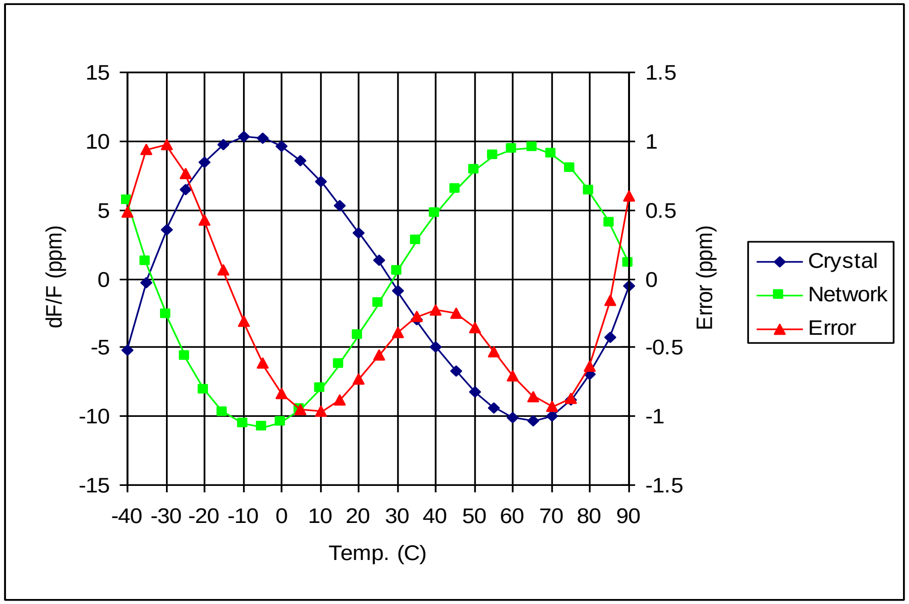
θ = 35° 20' + Δθ, φ = 0
for 5th overtone AT-cut
θ = 35° 12.5'+ Δθ, φ = 0 for
fundamental mode plano-plano AT-cut

Generic TCXO Block Diagram



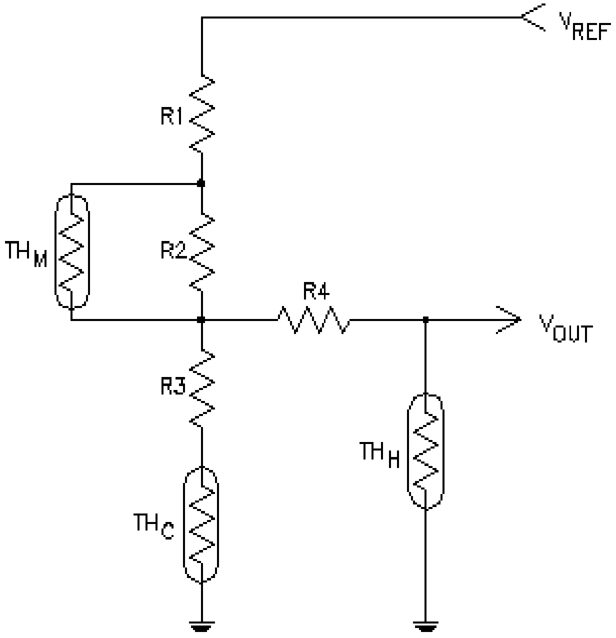
Compensation Voltage Generator

VCXO



TCXO Introduction

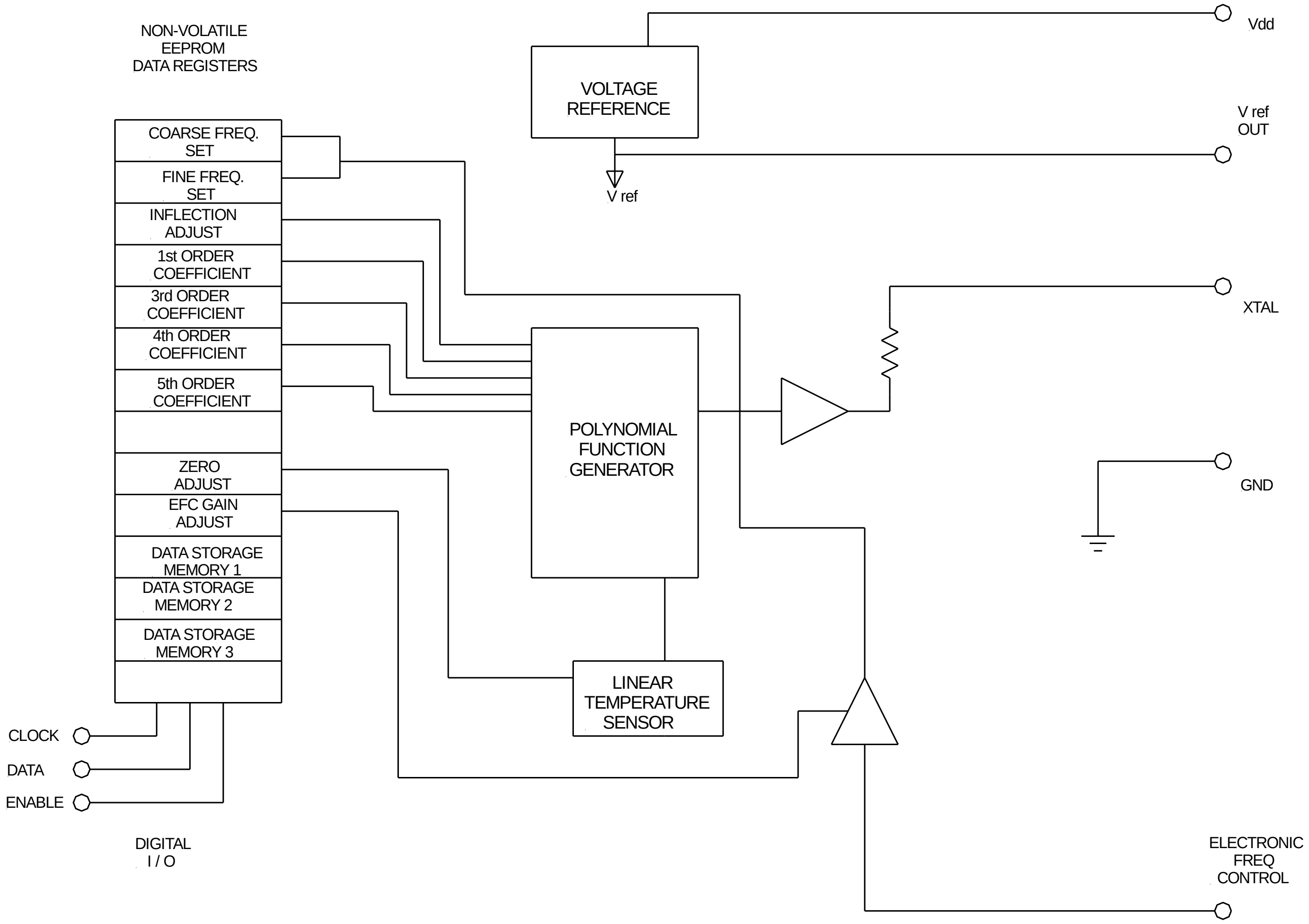
- Thermistor resistor network



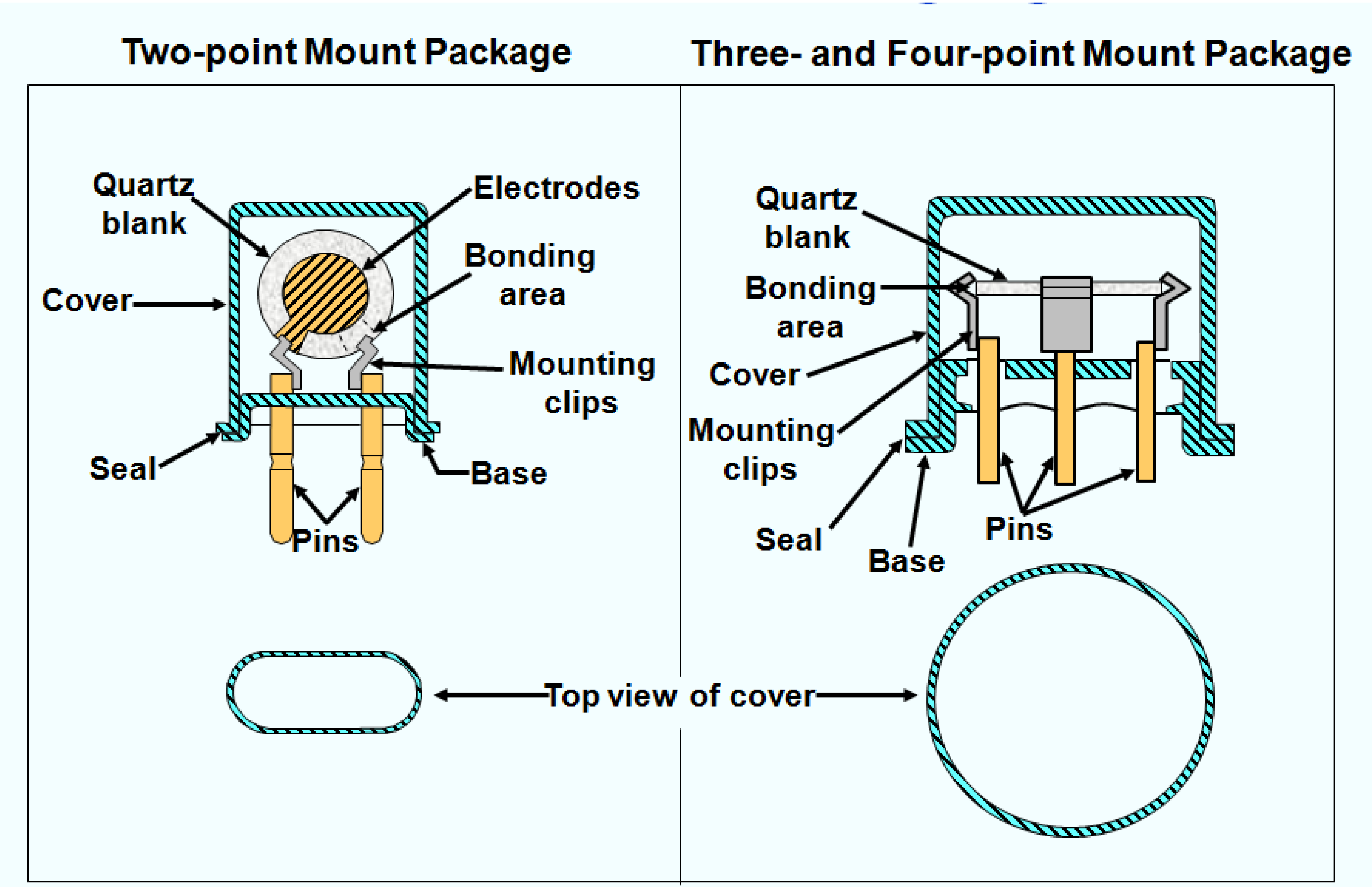
- Limitation on curve fitting
- Manual selection of resistors
- Difficult to miniaturize

TCXO Introduction

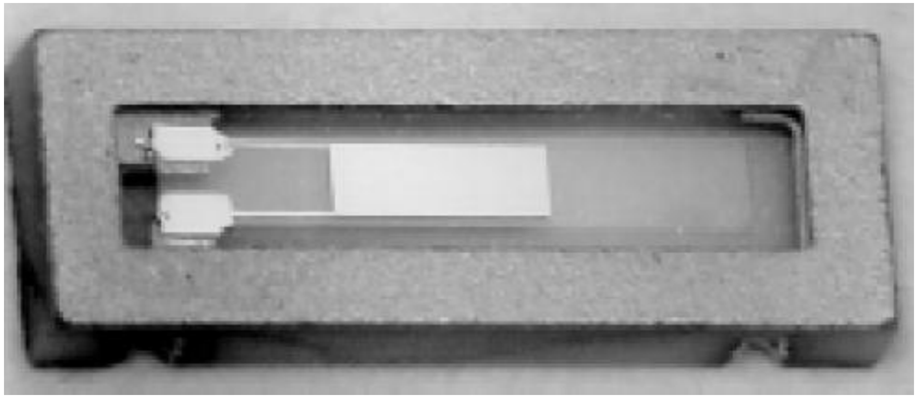
- Polynomial Function generator

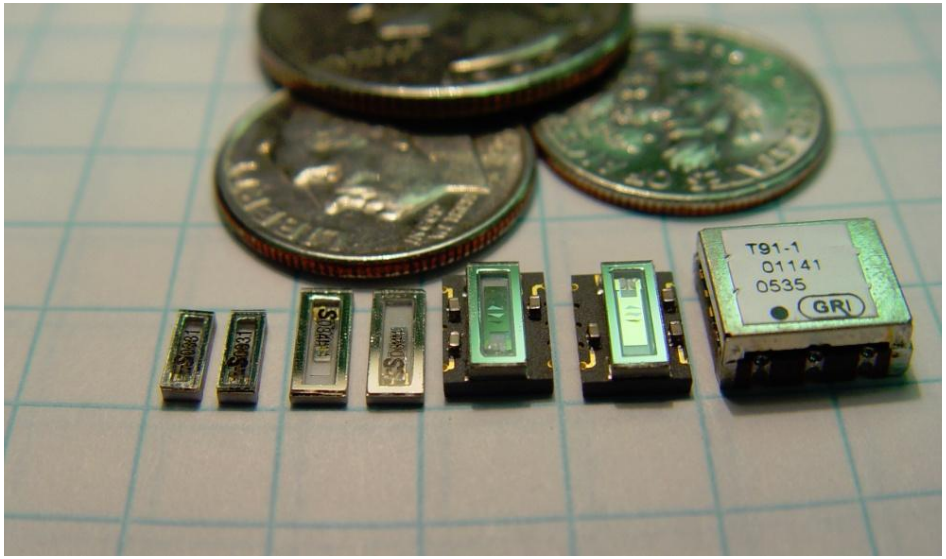


Conventional Crystal Packages



Modern Strip Crystal Packages





Artificial Neural Network Compensation

- TCXO’s are limited in temperature stability performance because of the following factors:
  - Polynomial generator is limited in shape it can generate
  - Crystals are not perfect polynomials

- Artificial Neural Network (ANN) is not inherently limited in shape
  - Can adapt to any shape
  - Just add neurons

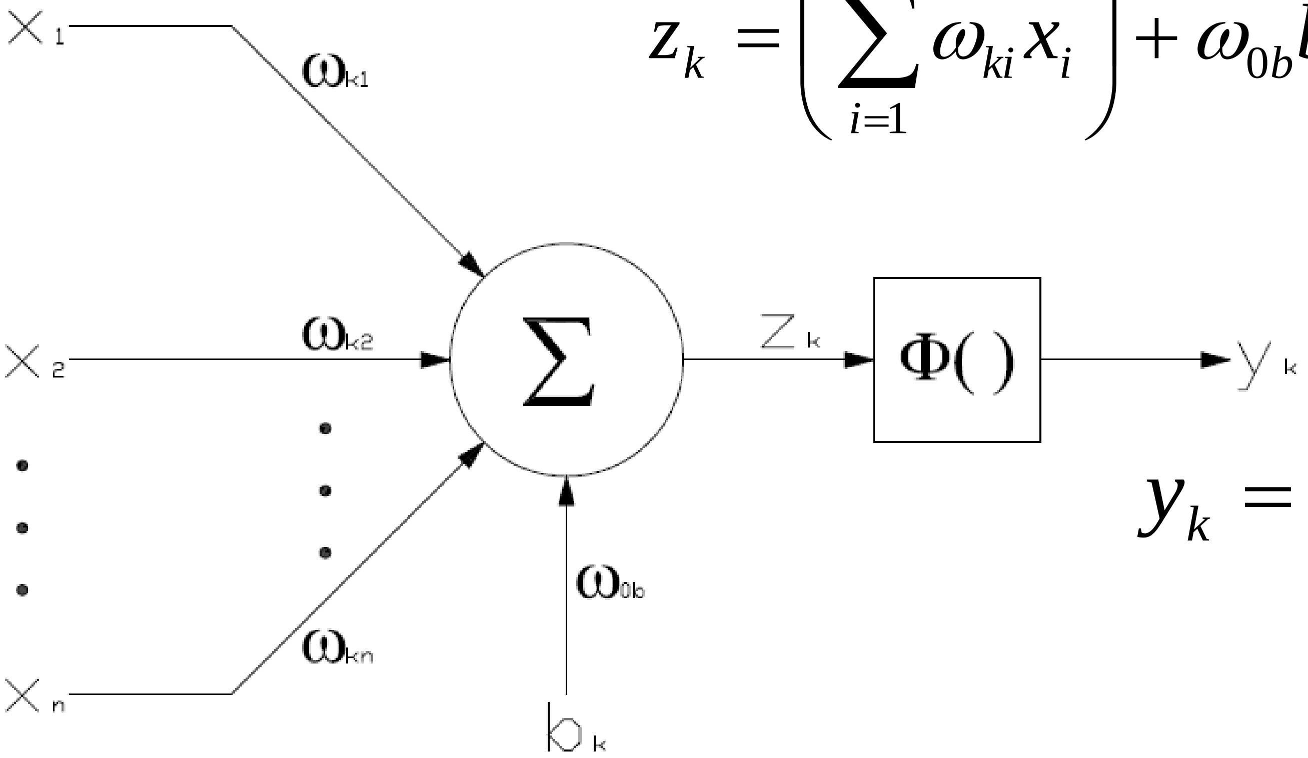
Artificial Neural Network Overview

- ANN Definition
  - A machine that is designed to model the way in which the brain performs a particular function or task of interest [4]
  - It achieves this function through the use of simple processing units called neurons
  - The ability to "learn" or modify its response to given stimuli

Artificial Neural Network Overview

- Neuron Model

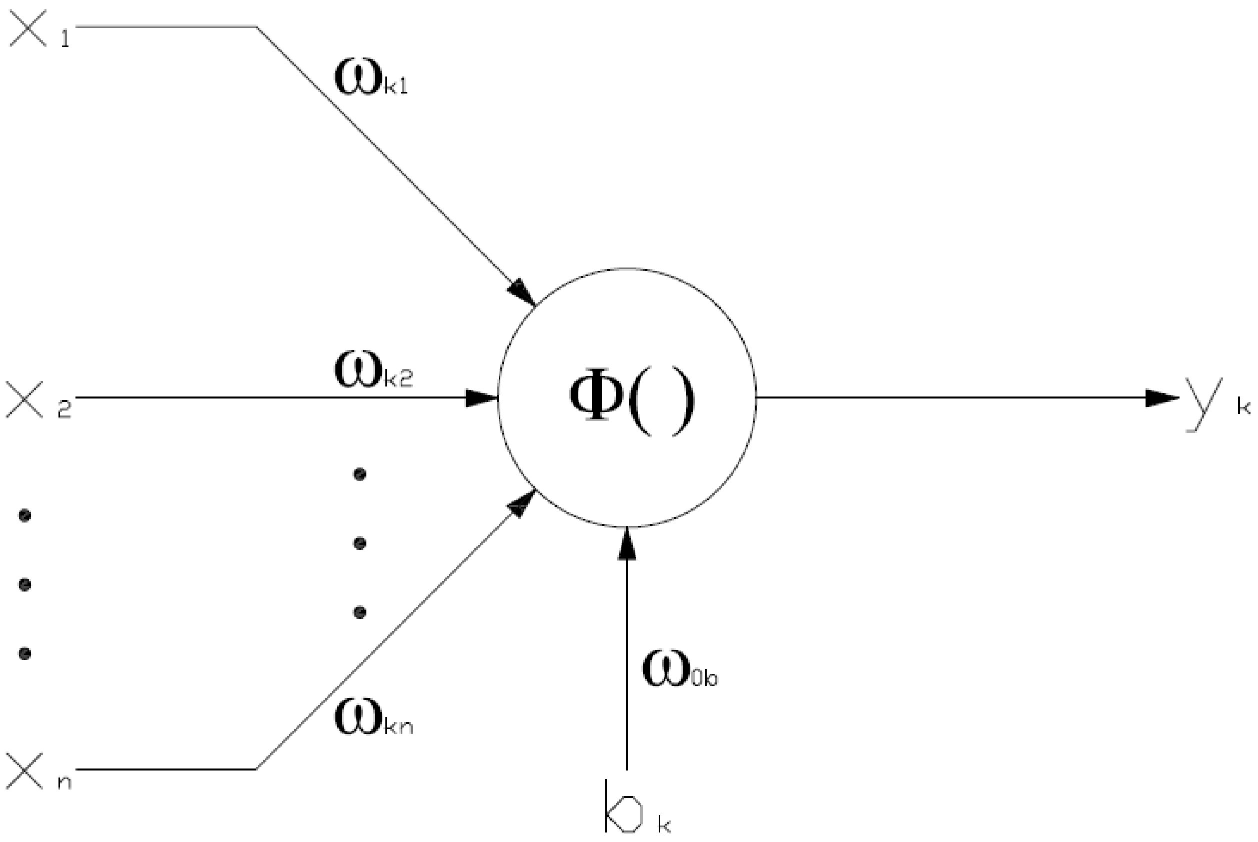
$$z_k = \left(\sum_{i=1}^{n} \omega_{ki} x_i \right) + \omega_{0b} b_k$$



$$y_k = \Phi(z_k)$$

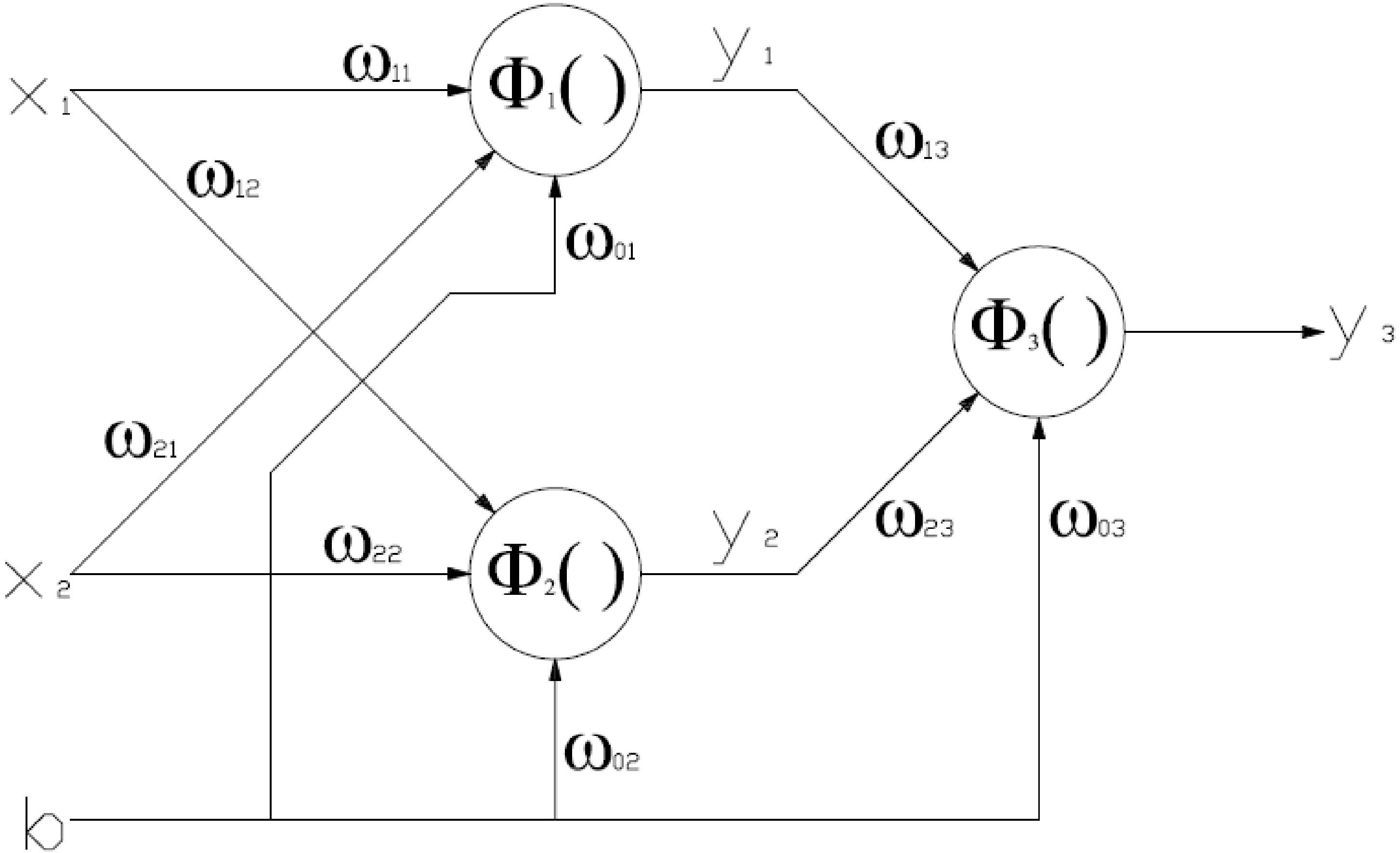
Artificial Neural Network Overview

- Neuron Shorthand Model



Artificial Neural Network Overview

- Neural Network Example



Activation Function Overview

- Activation Function can be any function
- Unipolar sigmoid has been chosen

$$\Phi = \frac{1}{1 + e^{-\alpha (z_k)}}$$

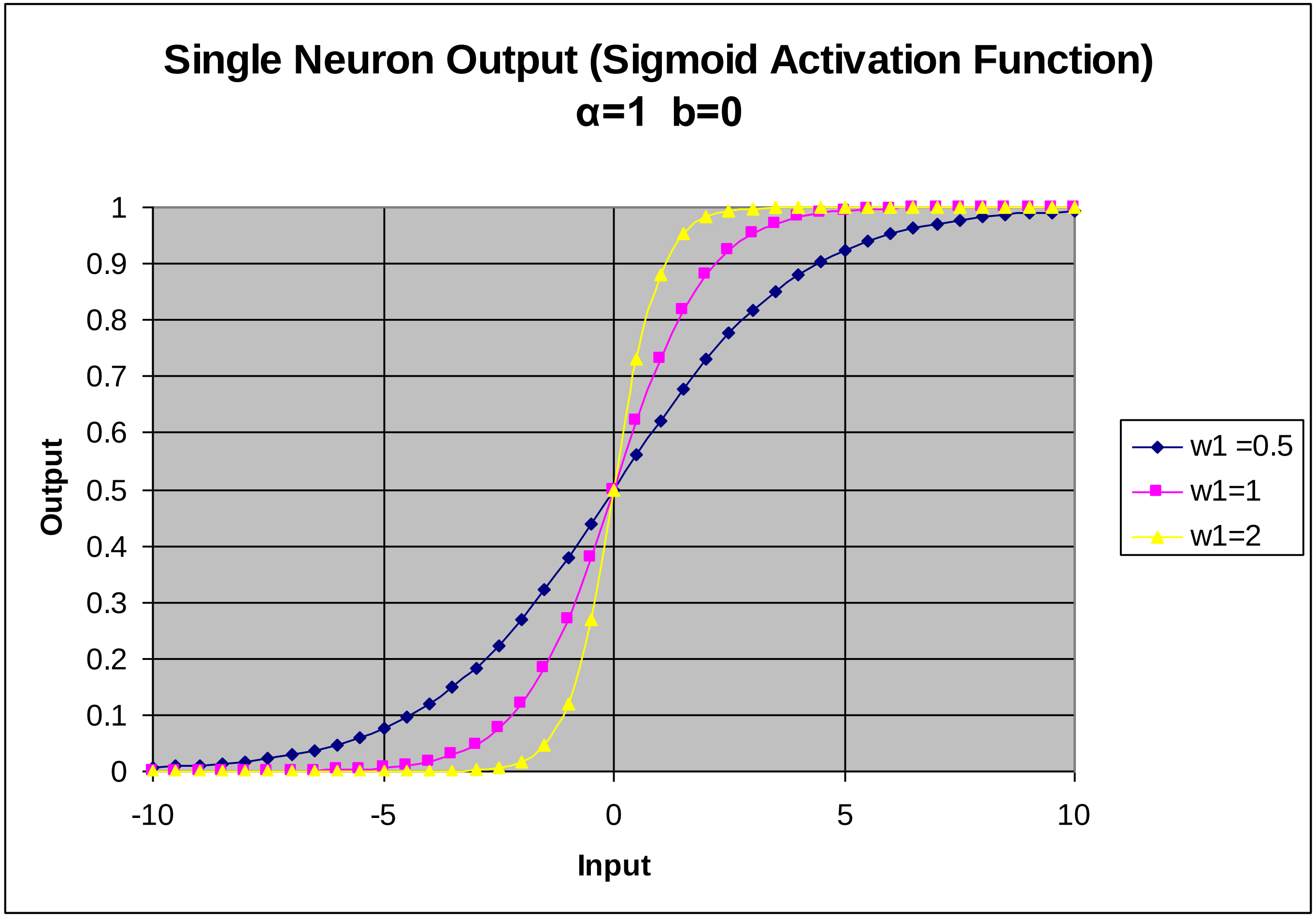
$$z_k = \left(\sum_{i=1}^{n} \omega_{ki} x_i \right) + \omega_{0b} b_k$$

Activation Function Overview

- α controls the slope
- ω controls the amplitude
- b controls the delay (left/right position)

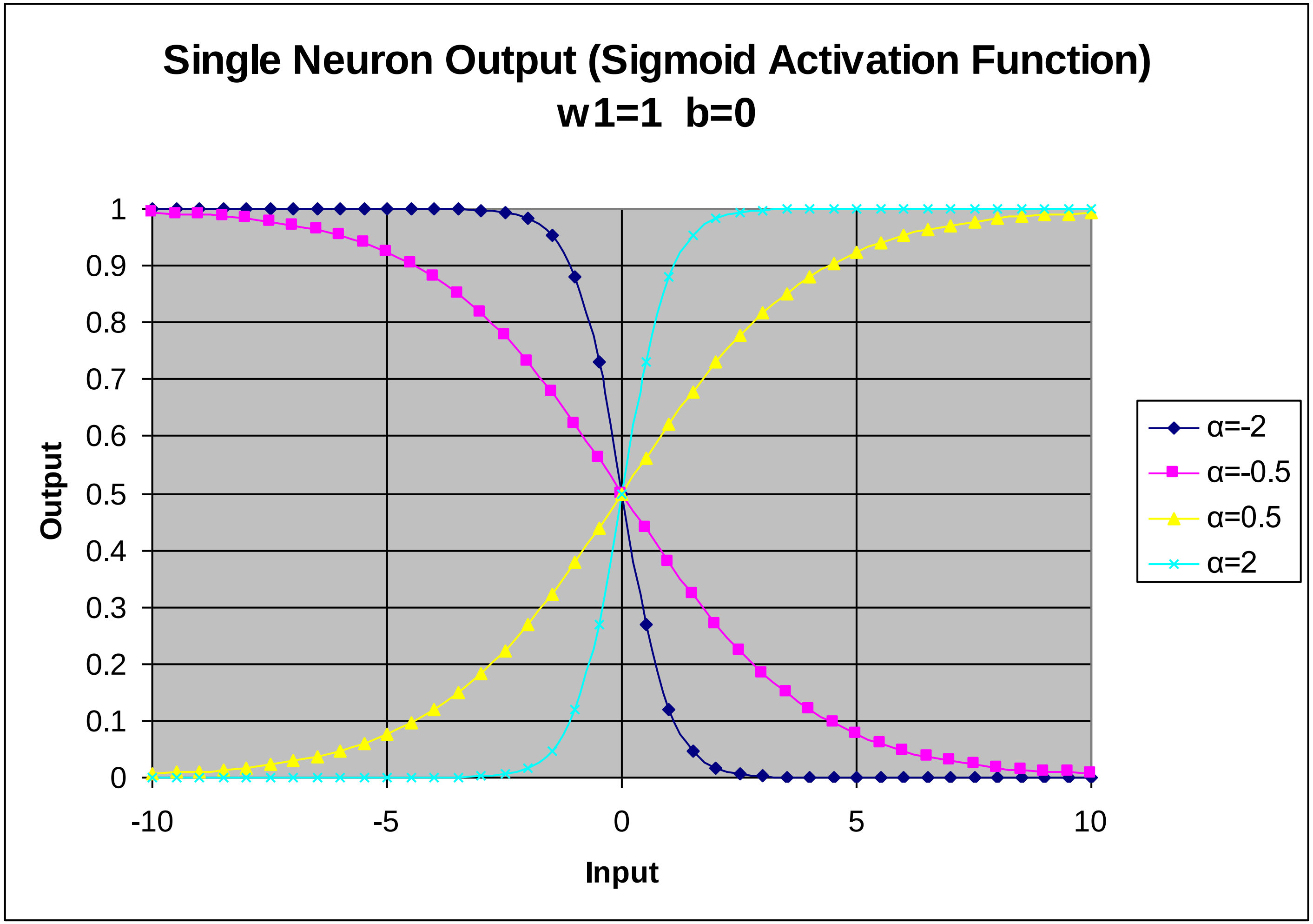
Activation Function Overview

- ω controls the amplitude



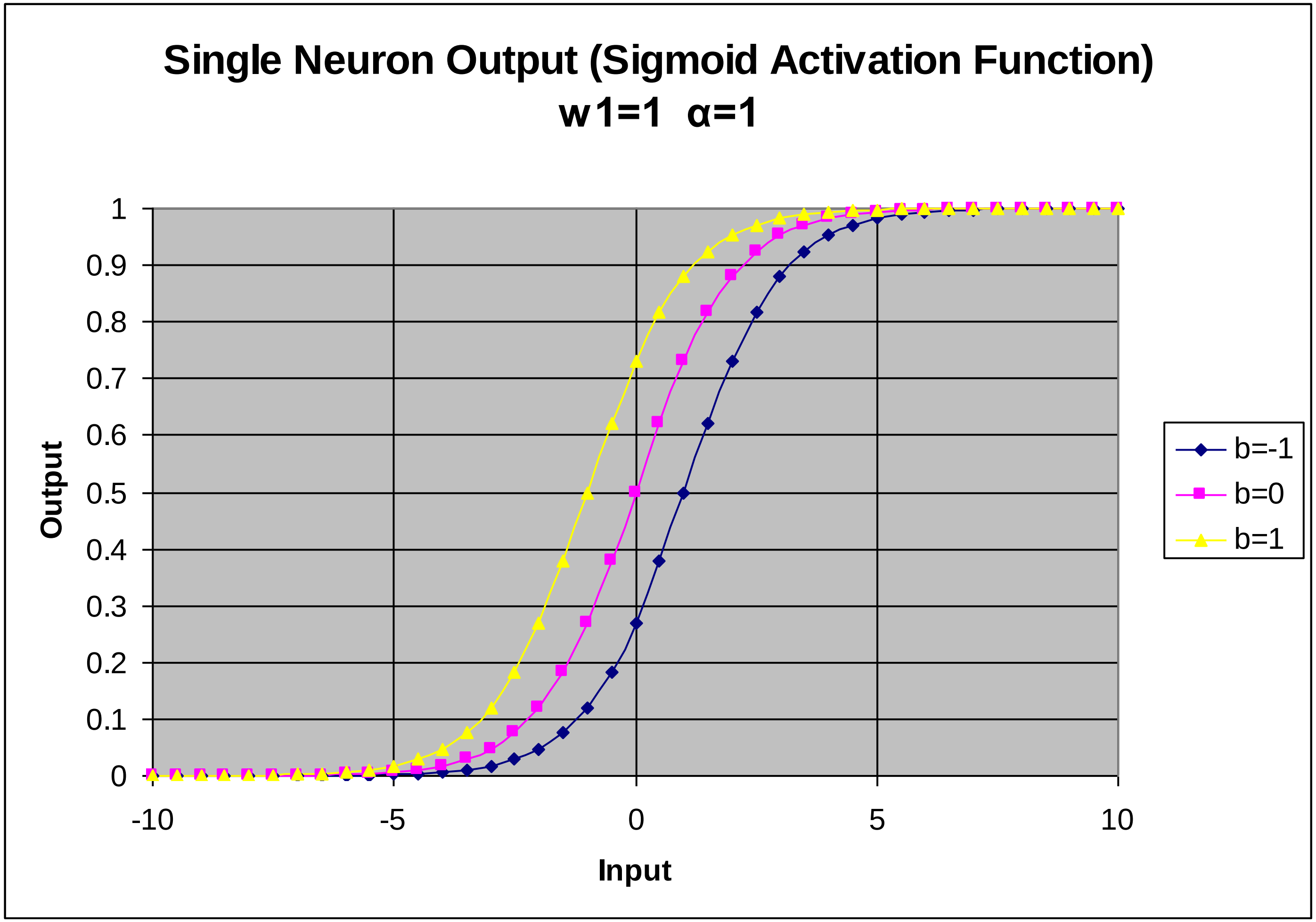
Activation Function Overview

- α controls the slope



Activation Function Overview

- b controls the delay (left/right shift)



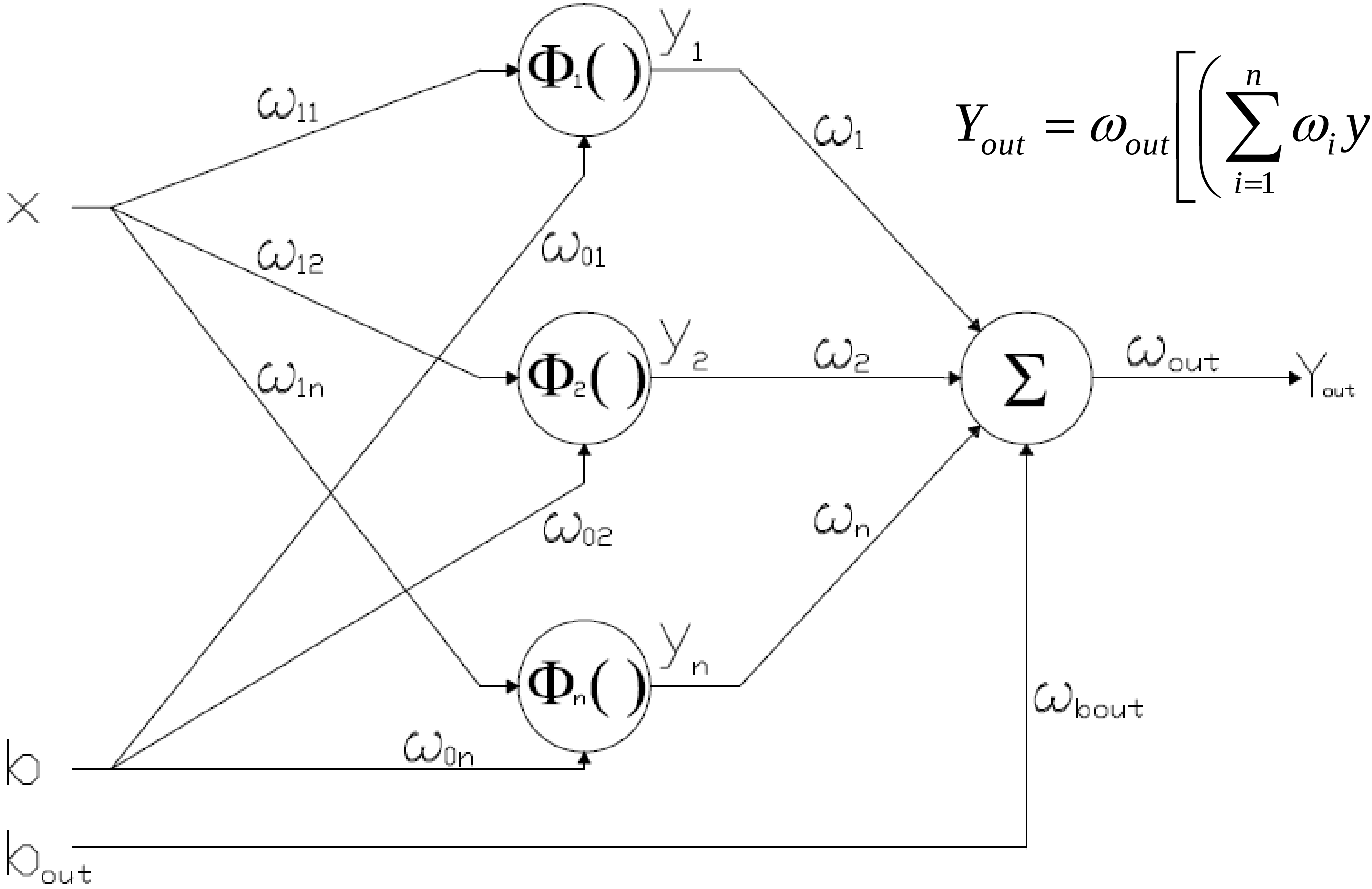
ANN Temperature Compensation

- TCXOs compensation (-40 to +85 C)
    - Thermistor resistor networks (+/-1.0ppm)
    - Polynomial function generator (+/-0.1ppm)

- ANN provides superior curve fitting
    - +/-0.005ppm (-40 to +85 C)

ANN Temperature Compensation

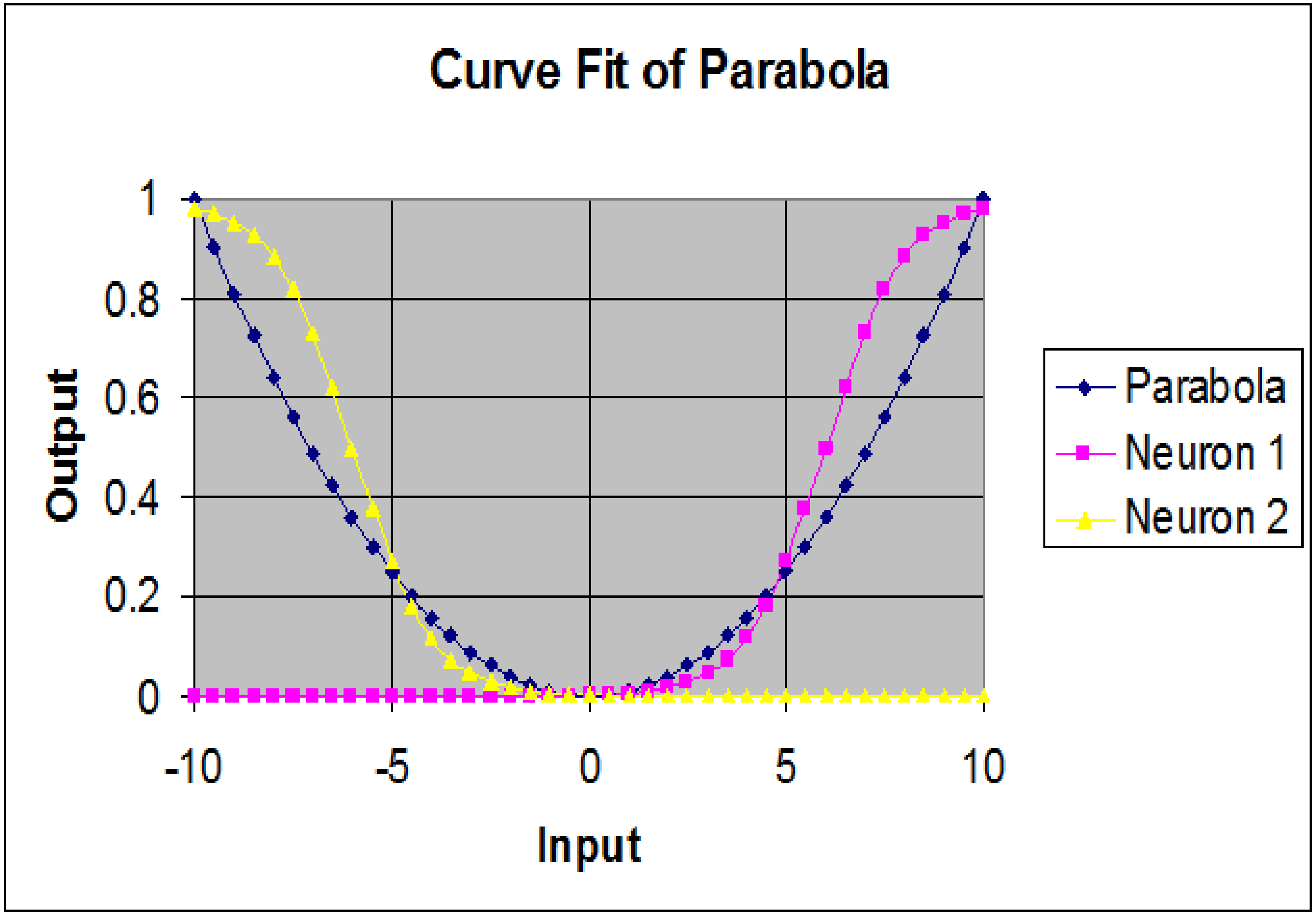
- Network Configuration



$$Y_{out} = \omega_{out}\left[\left(\sum_{i=1}^{n}\omega_i y_i\right)+\omega_{bout}b_{out}\right]$$

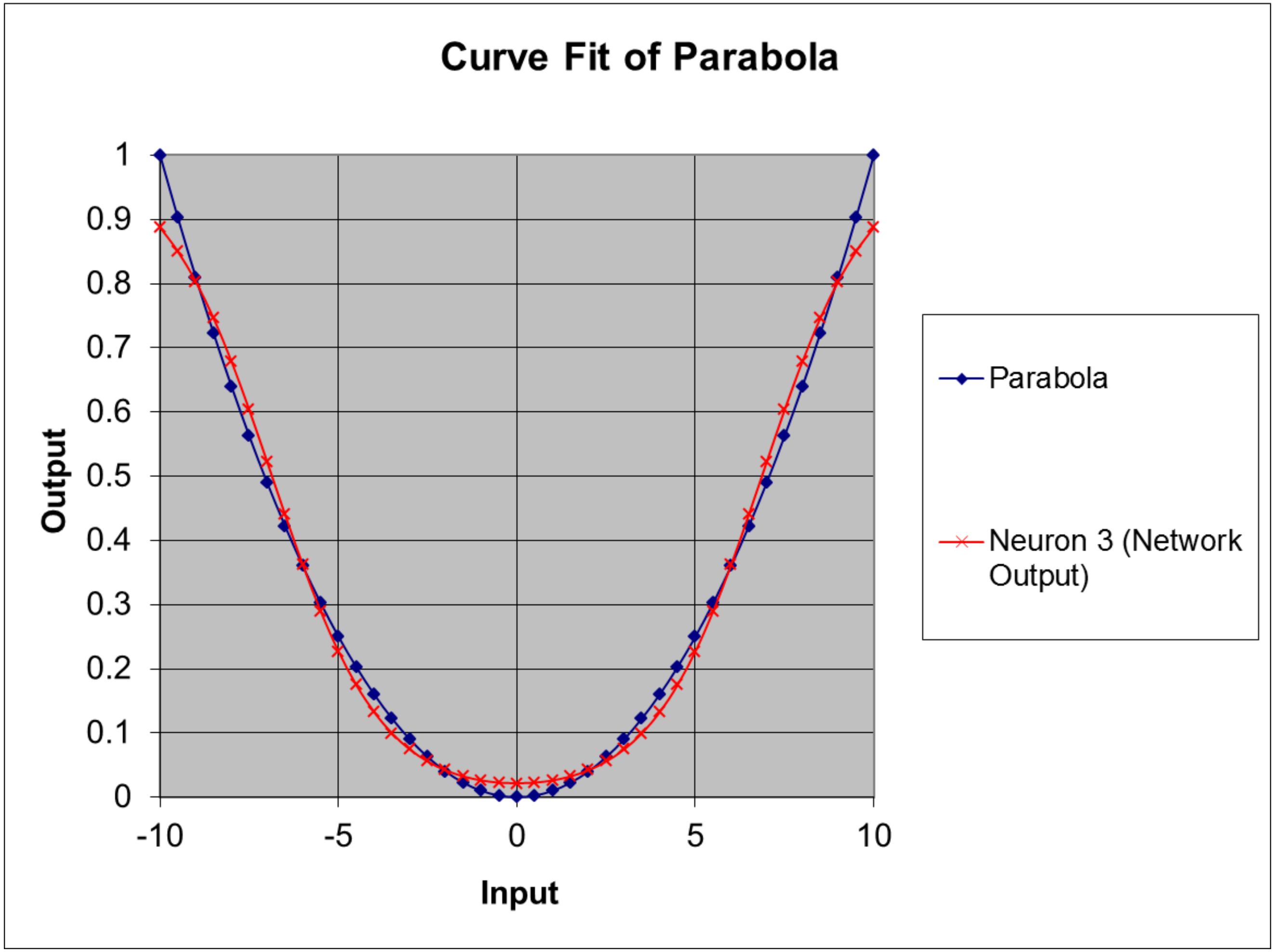
ANN Curve Fitting Example

- Two Neurons and Linear Summer



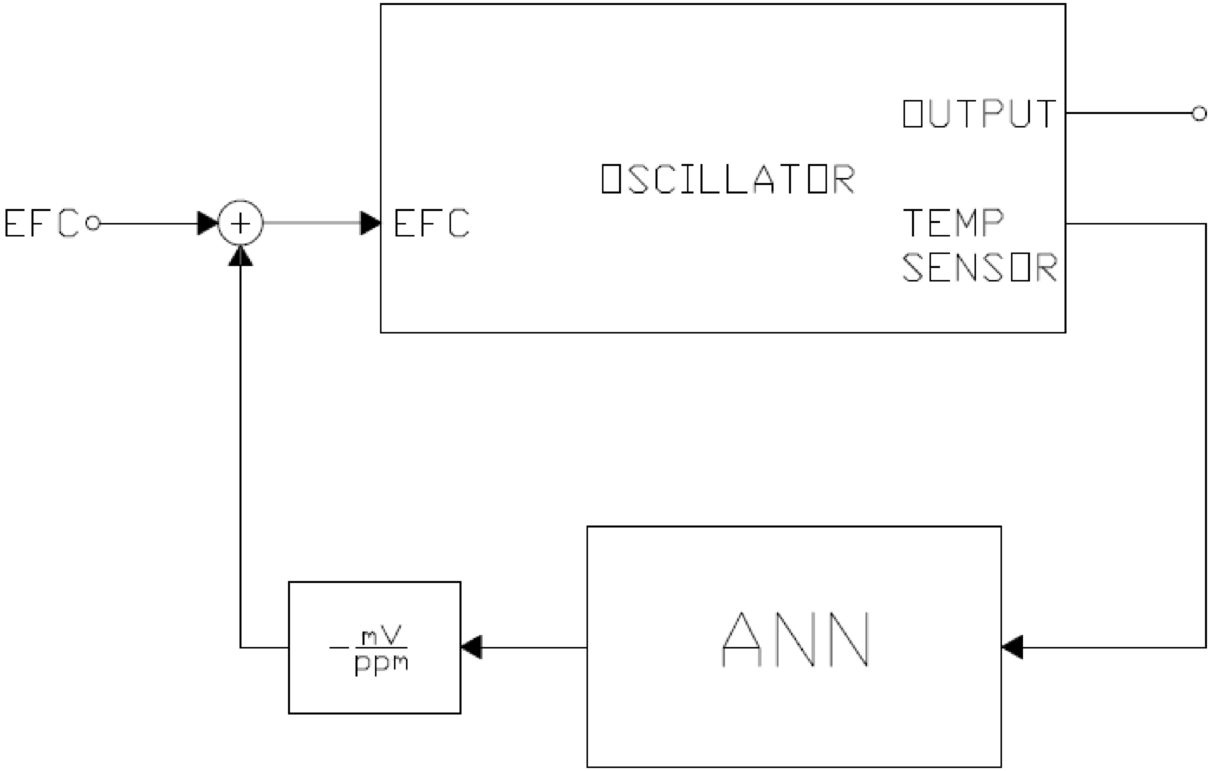
ANN Curve Fitting Example

- Two Neurons and Linear Summer



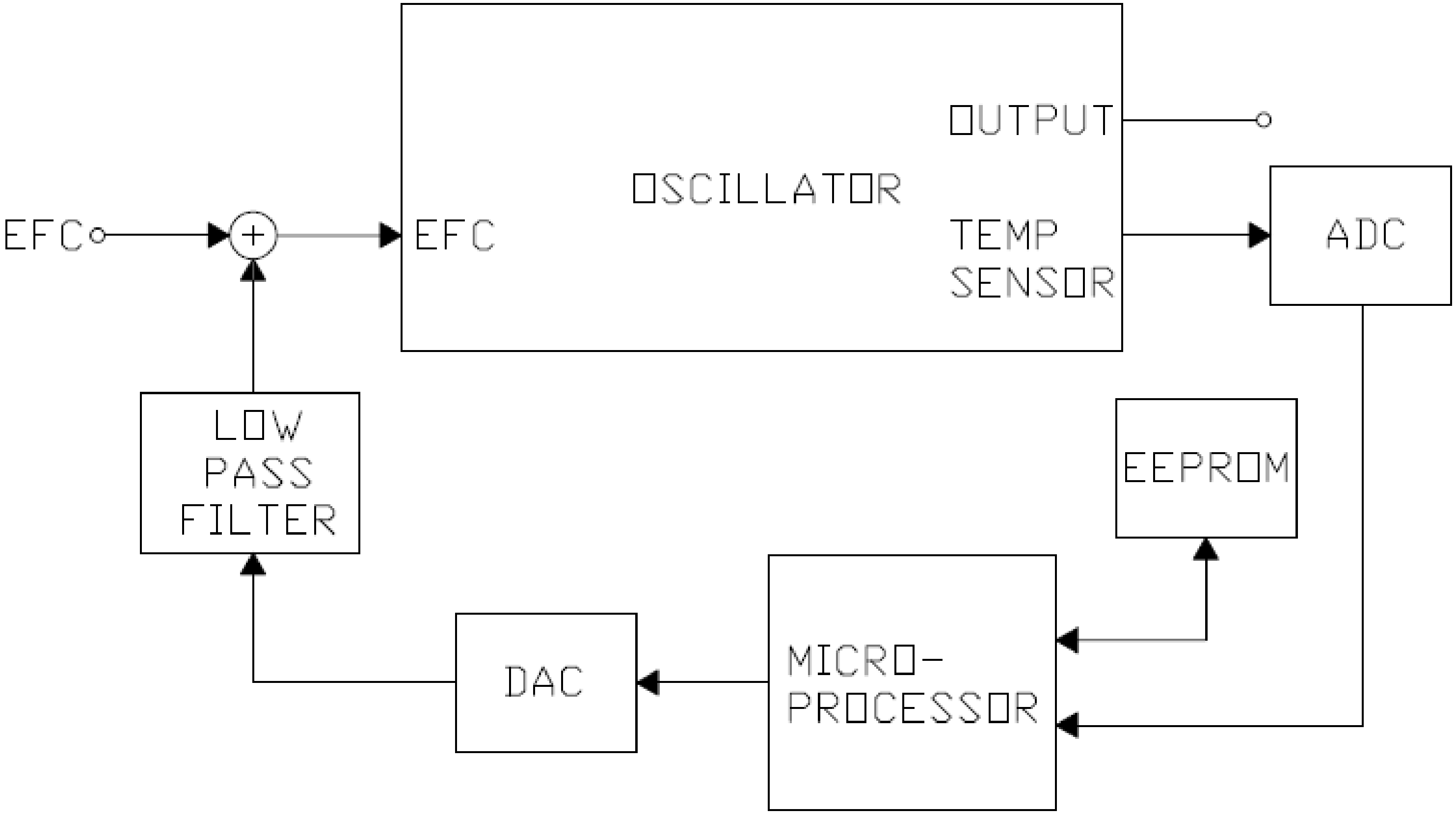
ANN Temperature Compensation

- Block Diagram



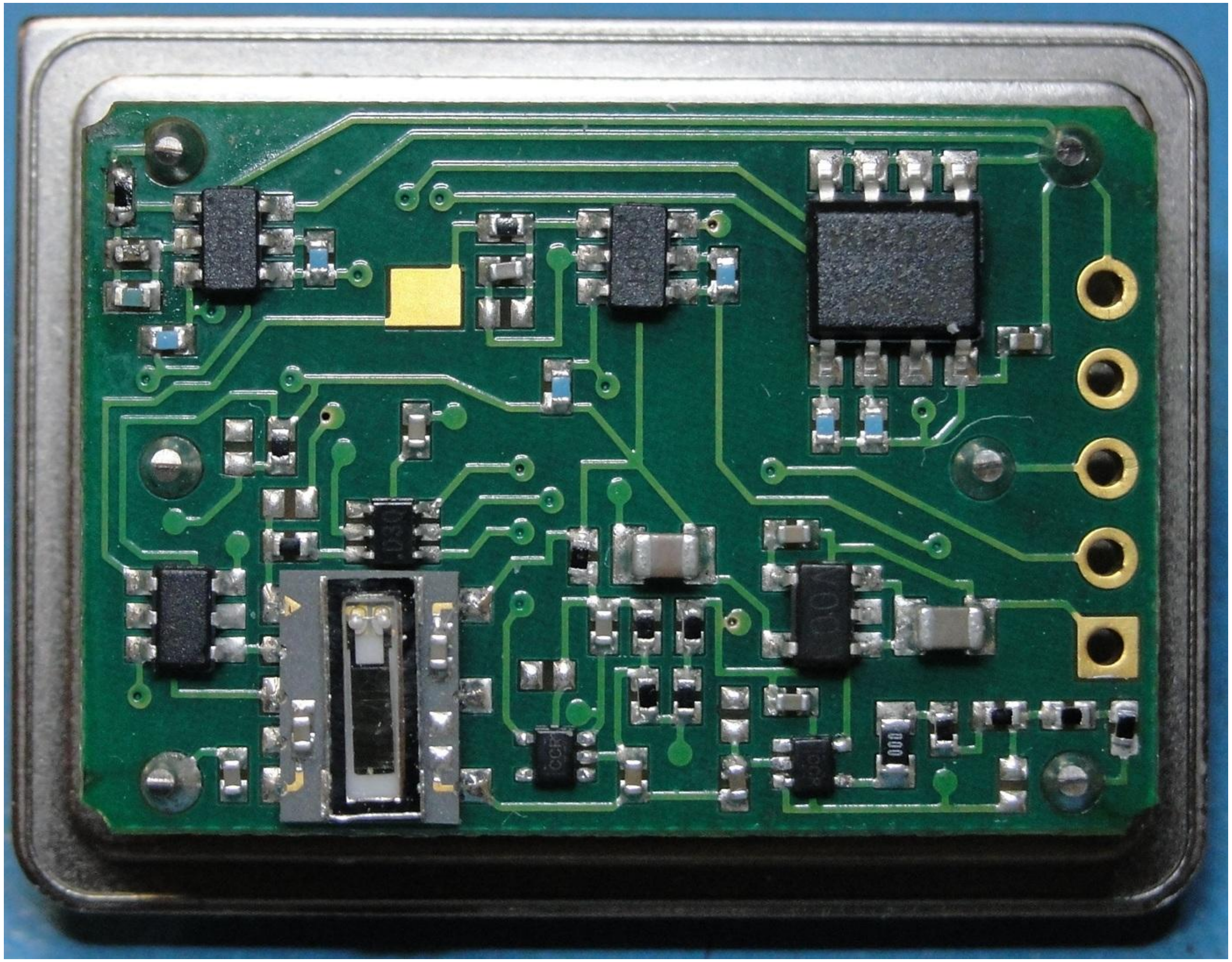
ANN Temperature Compensation

- Hardware Block Diagram



ANN Temperature Compensation

- Actual Hardware

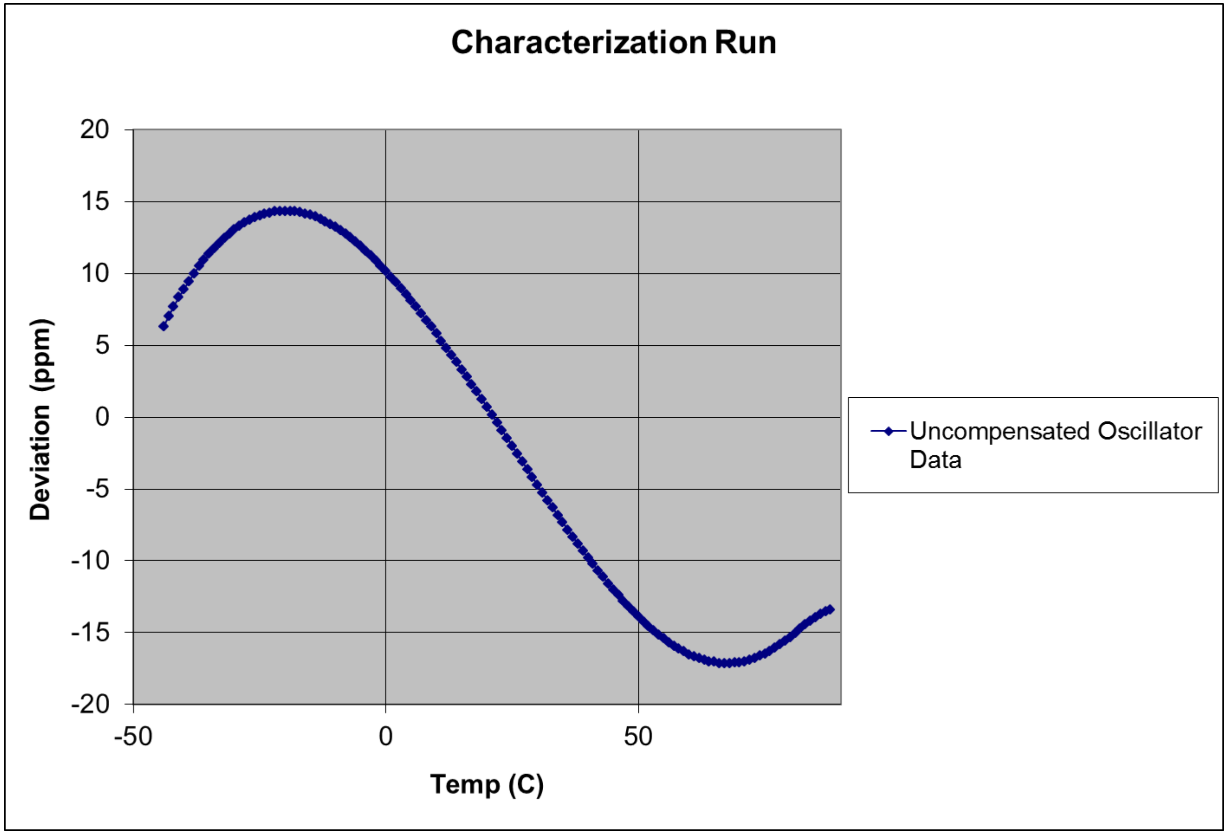


ANN Temperature Compensation

- Used GRI 5mm x 7mm TCXO
  - Ceramic package
- Uncompensated
  - ANN is primary compensation
- Compensated
  - ANN is secondary compensation

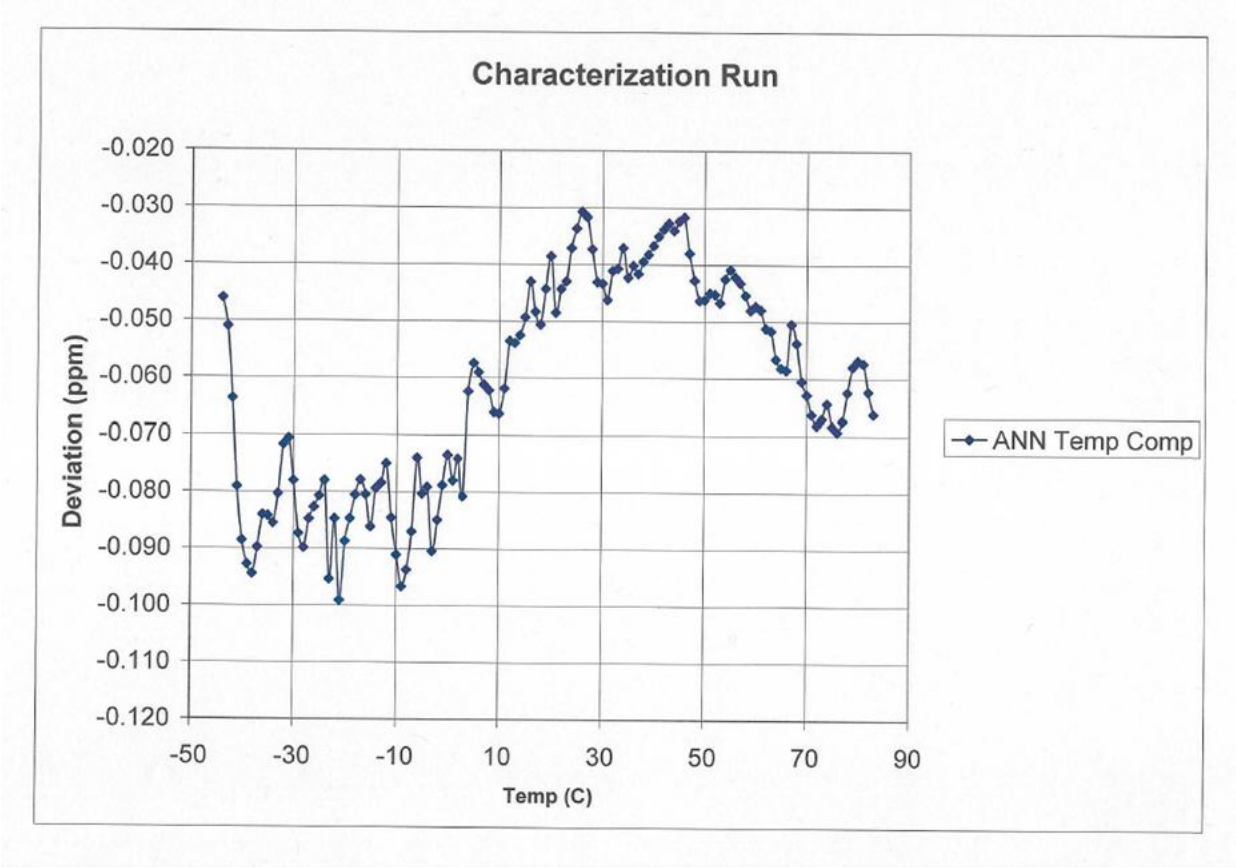
ANN Compensation Results

- Uncompensated performance
- Stability of +/-15.74 ppm from -42 to +86 C



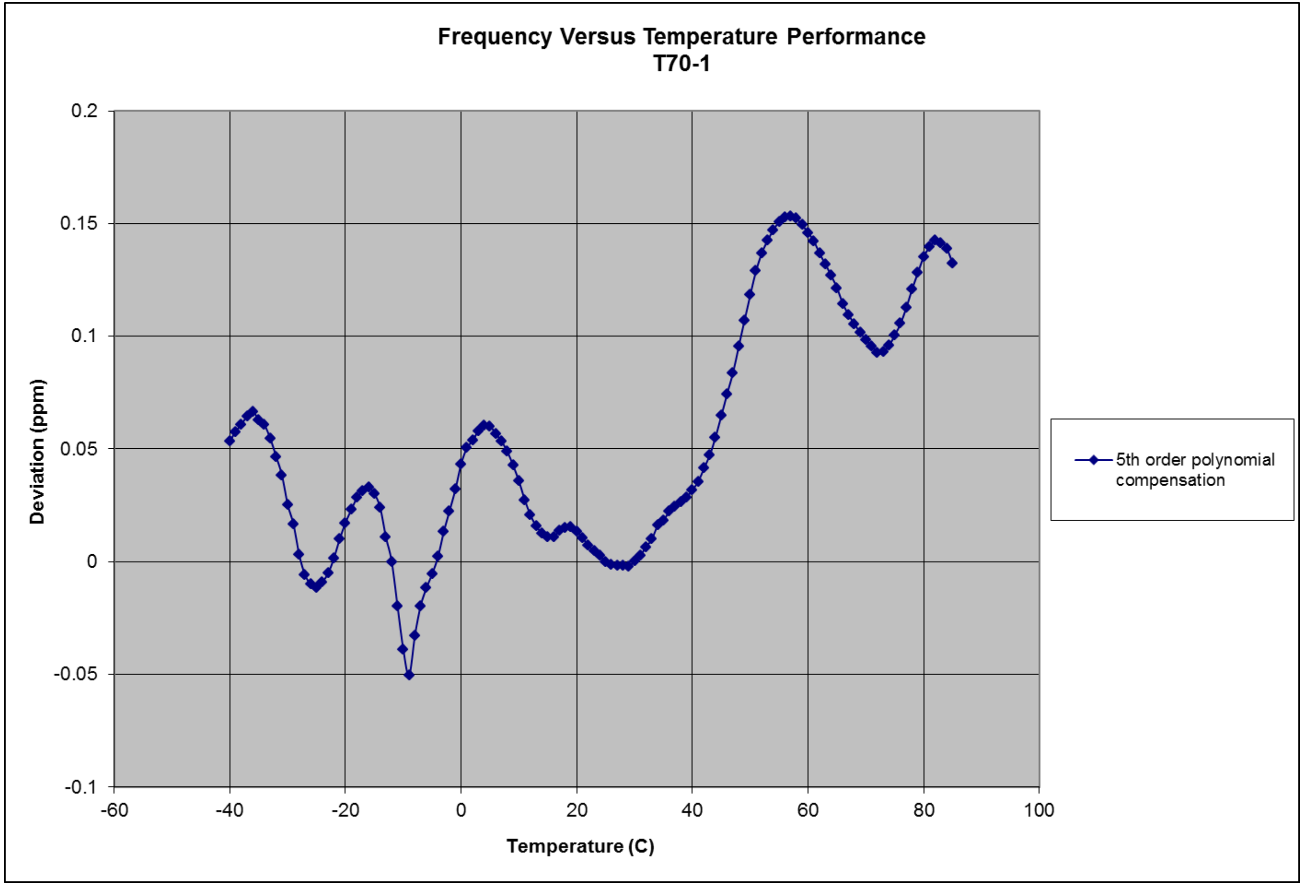
ANN Compensation Results

- ANN as primary compensation (25 neurons)
- Stability of +/-0.035 ppm from -42 to +86 C



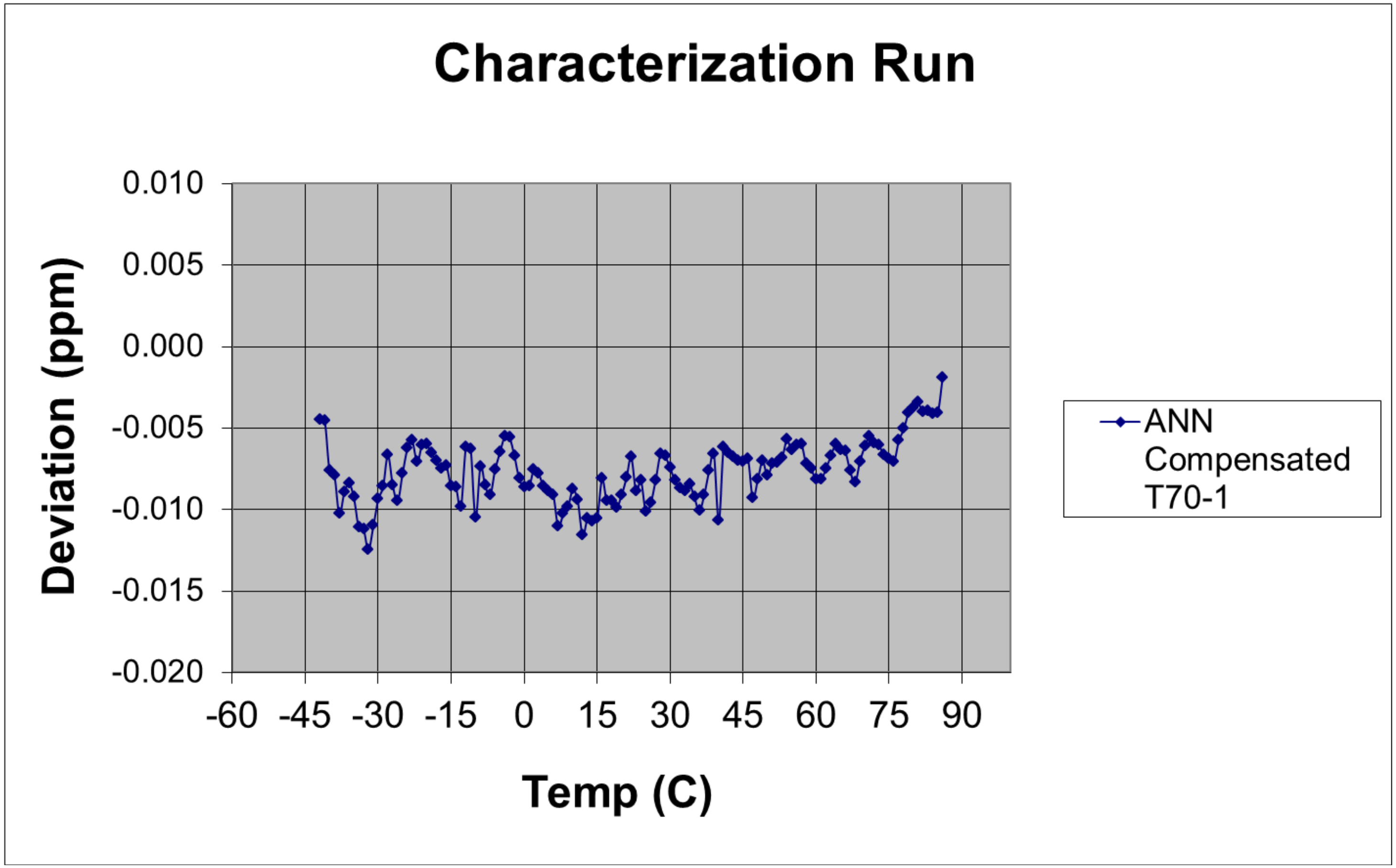
ANN Compensation Results

- 5th Order compensated performance
- Stability of +/-0.102 ppm from -42 to +86 C

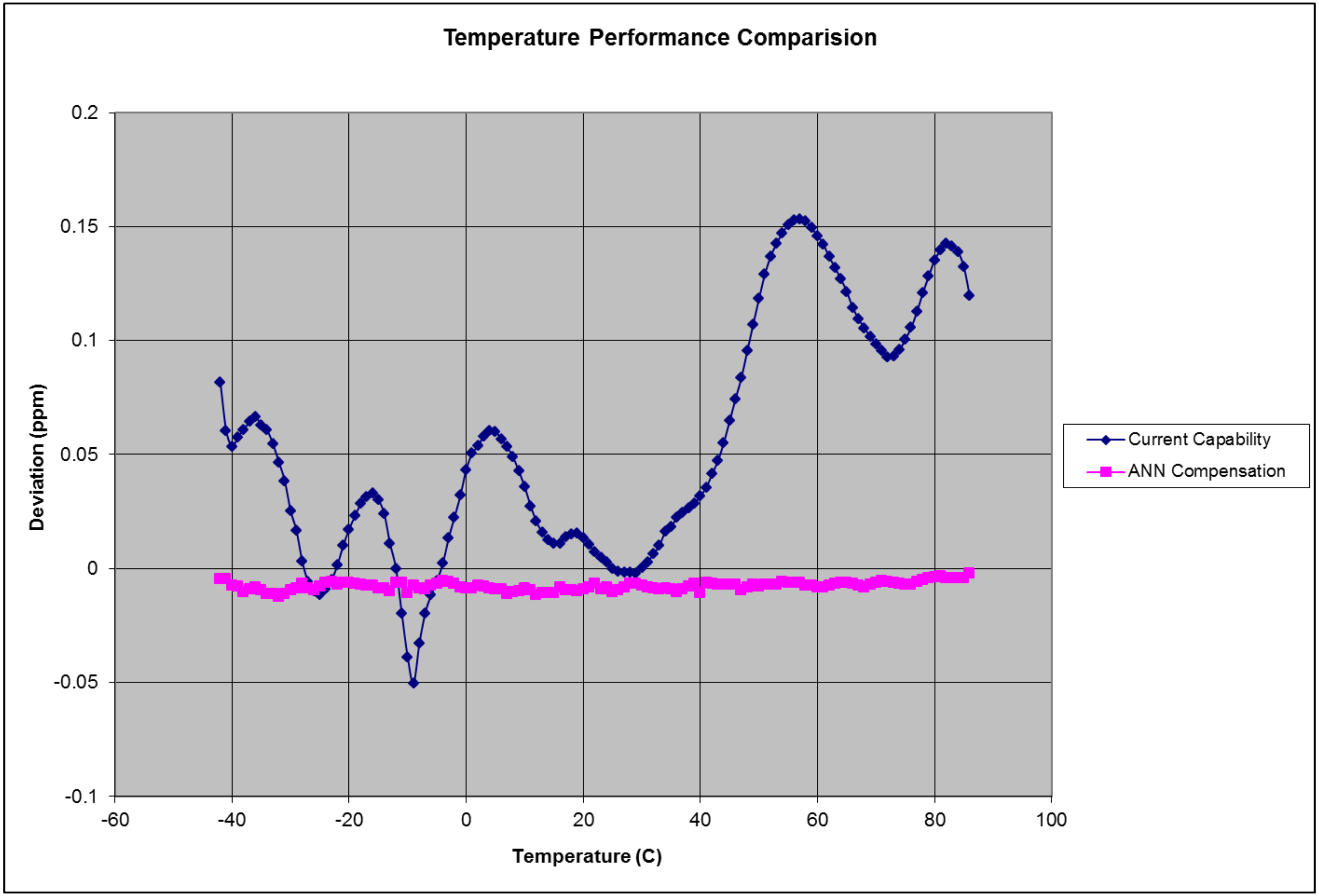


ANN Compensation Results

- ANN as secondary compensation (33 neurons)
- Stability of +/-0.005 ppm from -42 to +86 C



ANN Compensation Results



ANN Temp Comp Summary

- ANN as primary compensation needs new oscillator design

- ANN as secondary compensation has better stability than many small ovens

- Both have better stability than polynomial compensation

ANN Temp Comp Summary

- TCXO Phase Noise performance
- Multiple inputs could allow compensation of other environmental effects
    - Trim effect
    - Thermal Hysteresis
    - Warm-up
    - Aging

Trim Effect Compensation

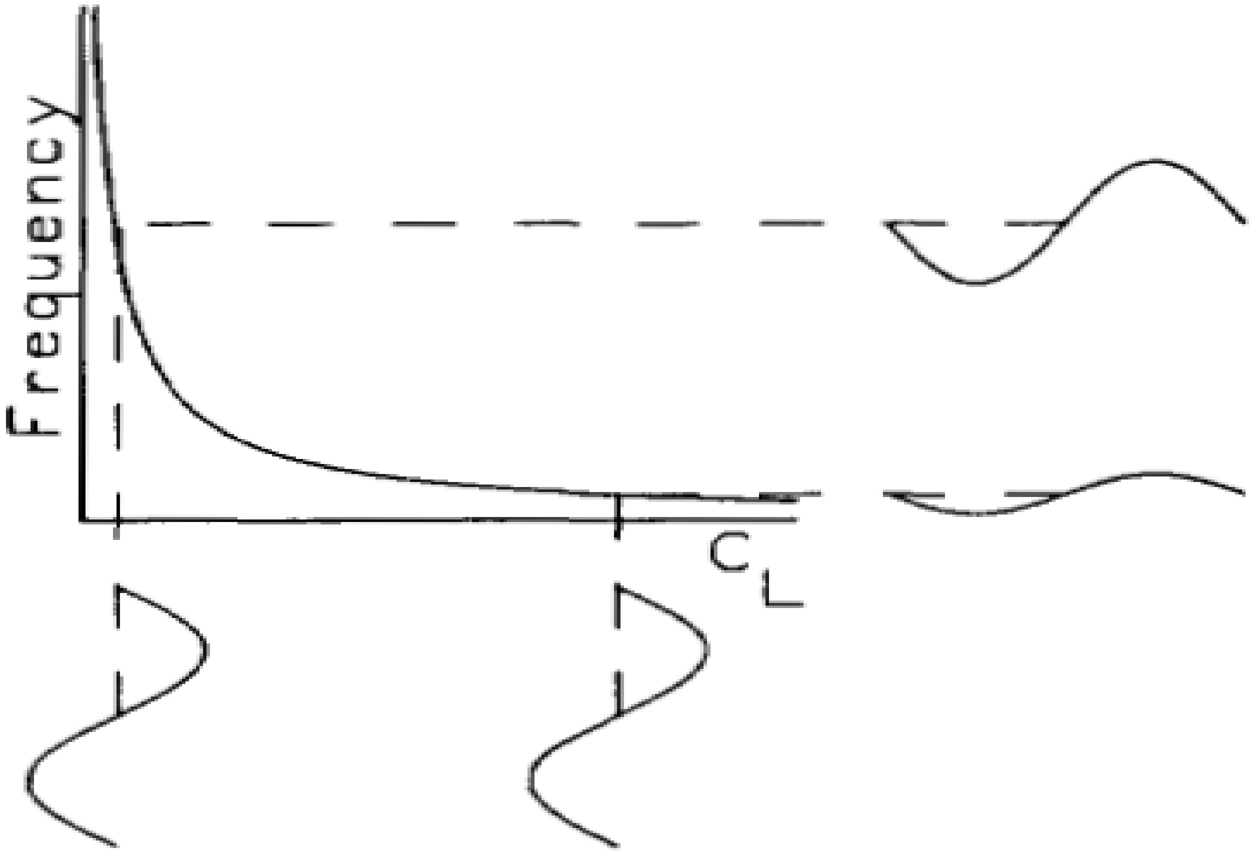
- Trim effect is a skewing of frequency versus temperature performance

- Caused by being at a different point on the varactor reactance curve than when compensated

- This degradation exists in all tunable xtal oscillators, but rarely specified anymore.

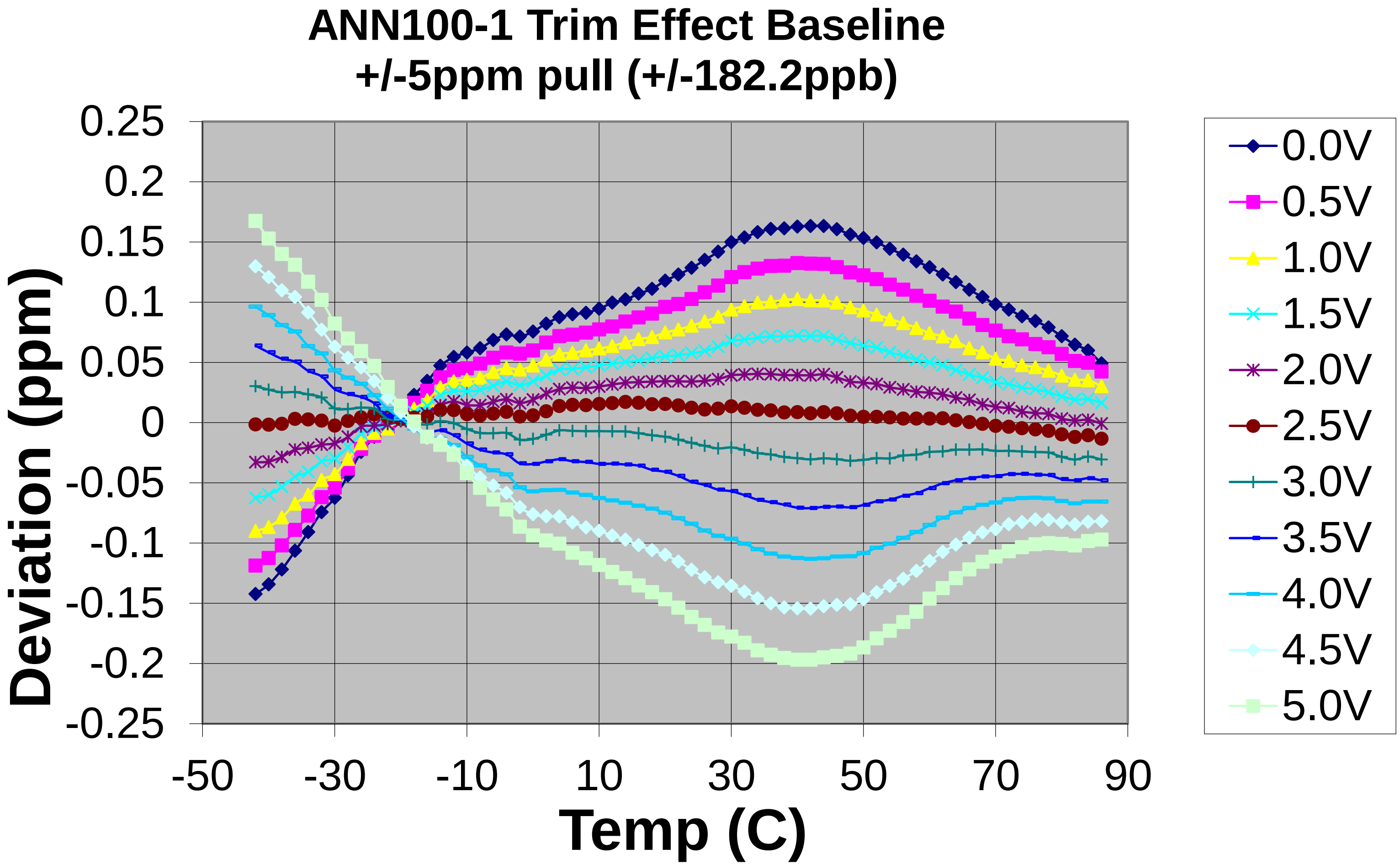
Trim Effect Compensation

- Frequency versus load capacitance



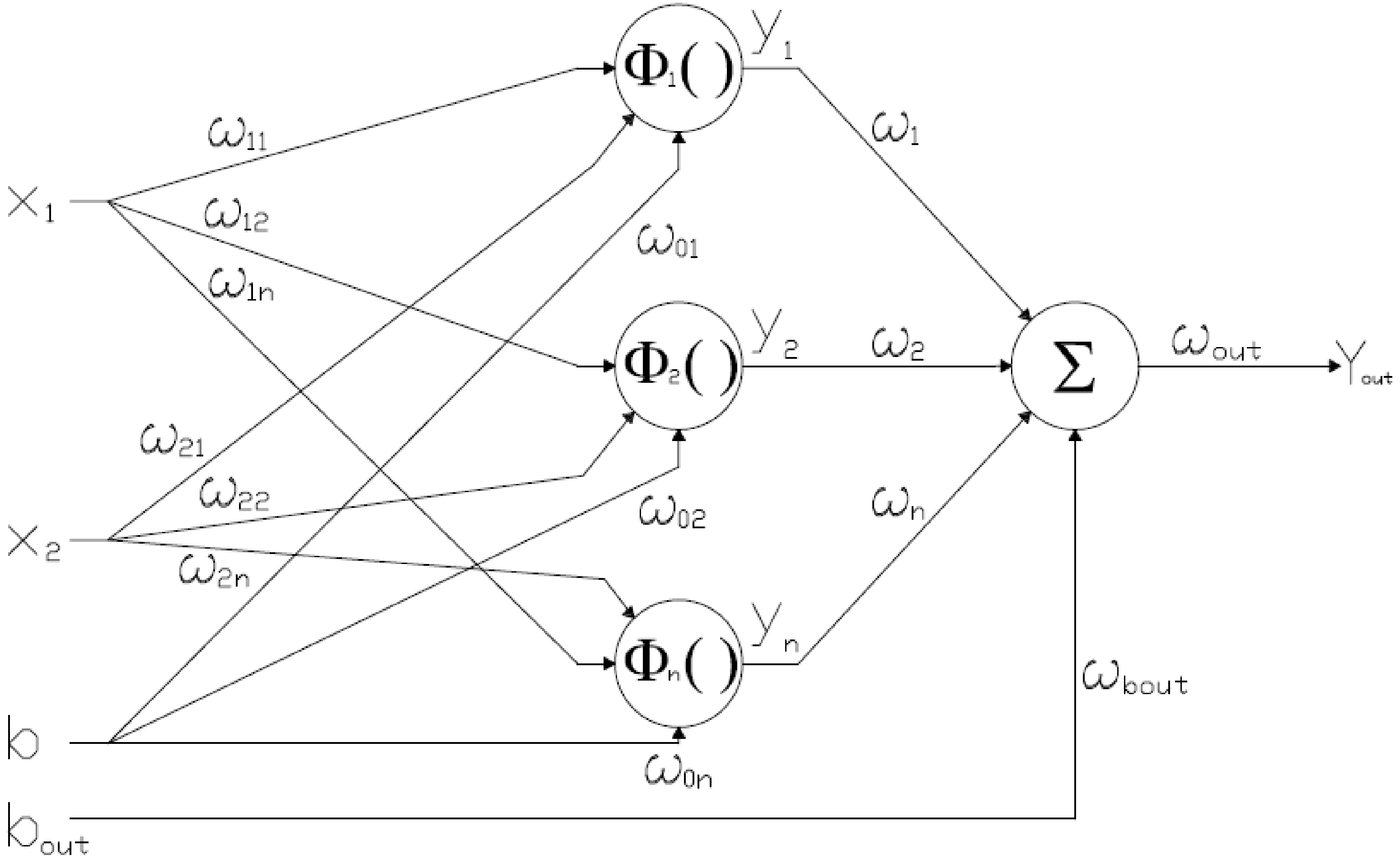
Trim Effect Compensation

- Trim Effect on Polynomial Generator



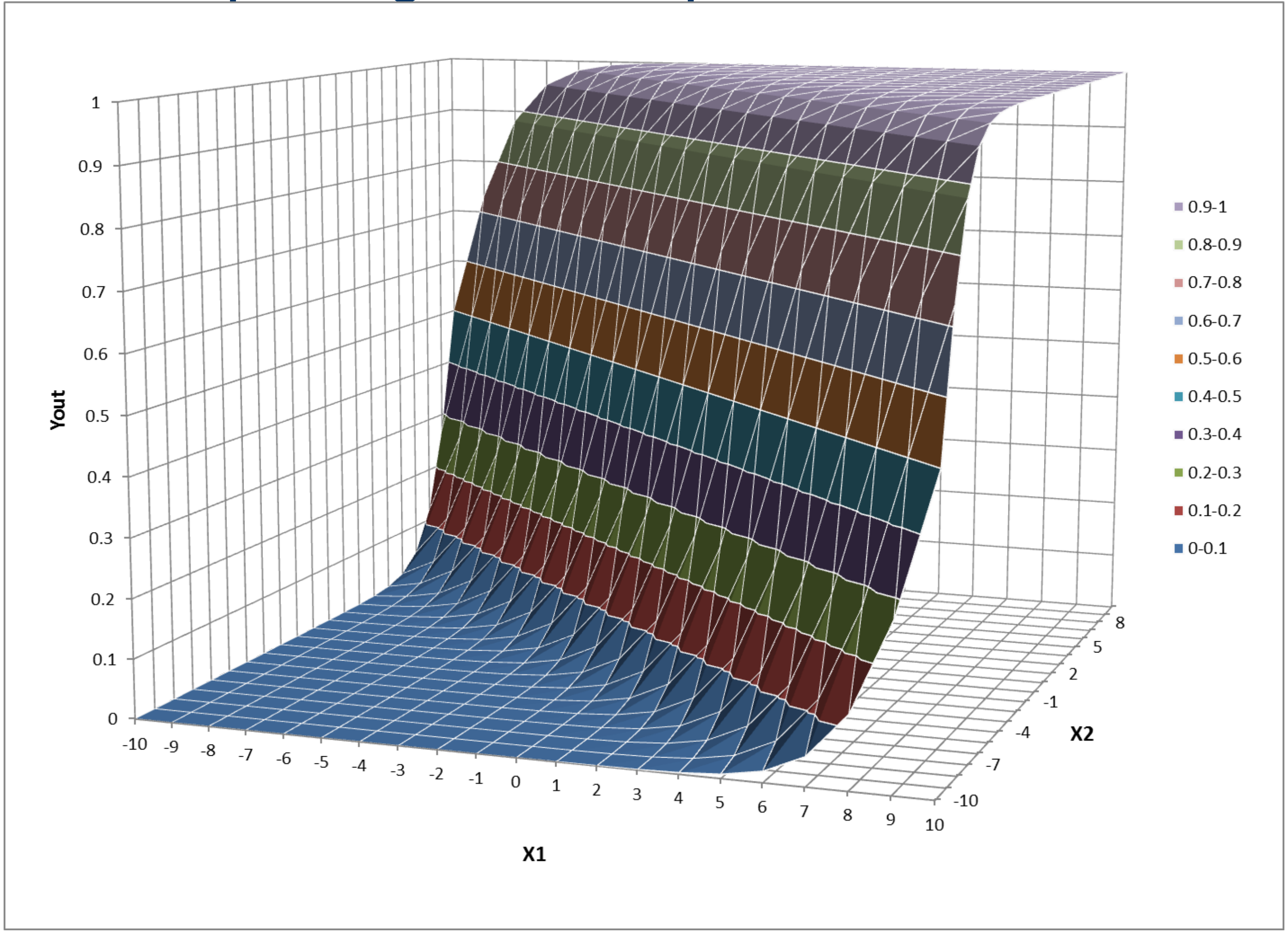
Trim Effect Compensation

- Two input ANN for trim compensation



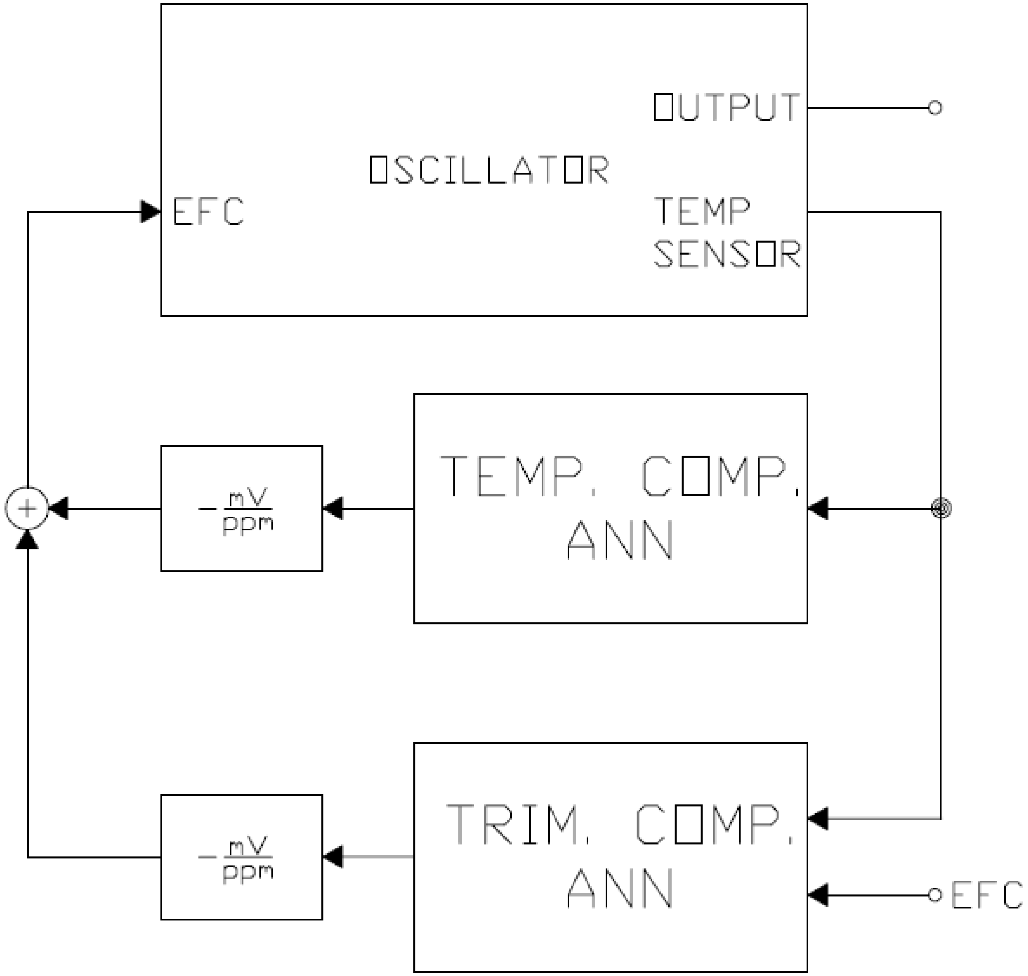
Trim Effect Compensation

- Two input sigmoid response



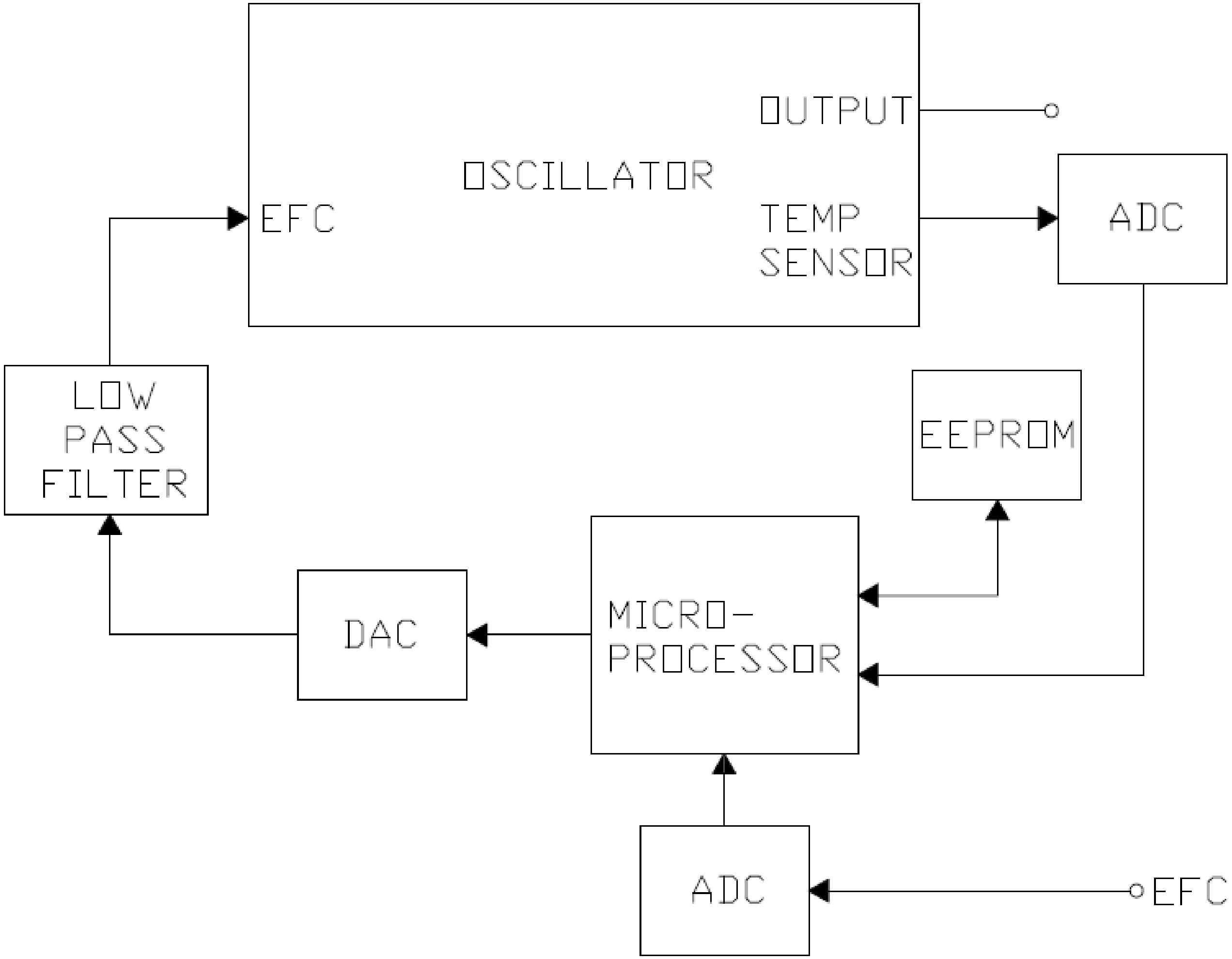
Trim Effect Compensation

- Trim effect compensation block diagram



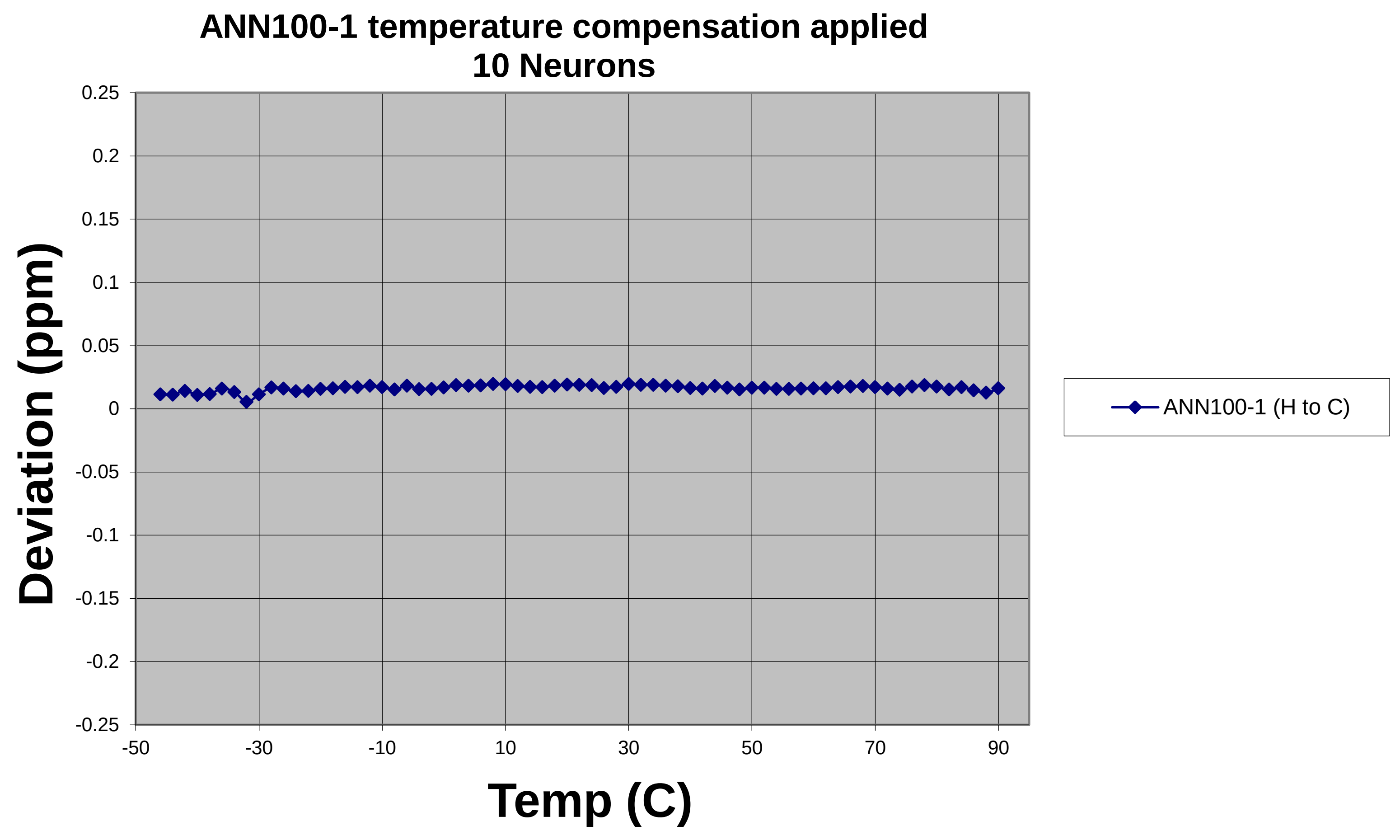
Trim Effect Compensation

- Trim Effect Compensation Hardware



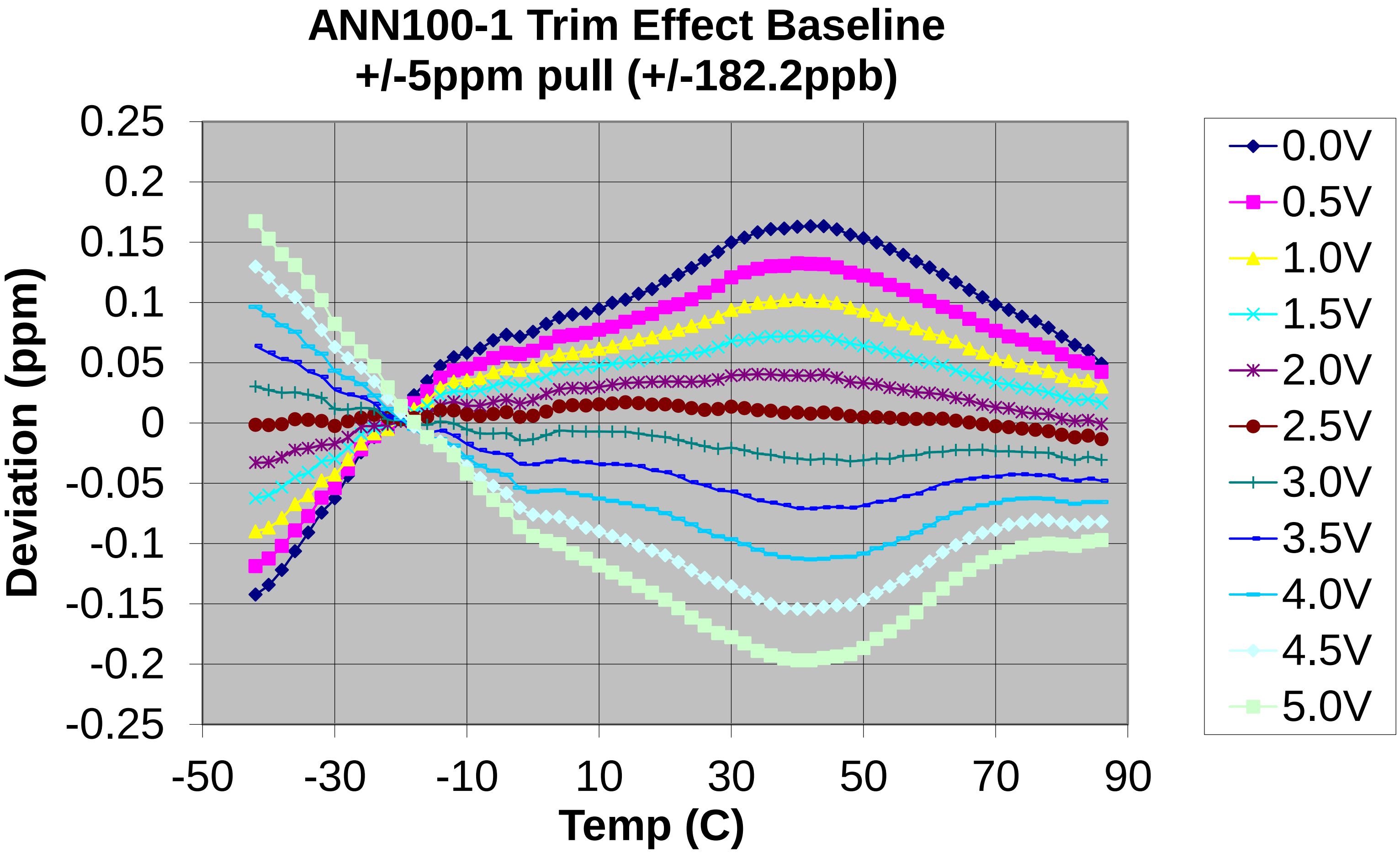
Trim Effect Compensation

- ANN temperature compensation applied first



Trim Effect Compensation

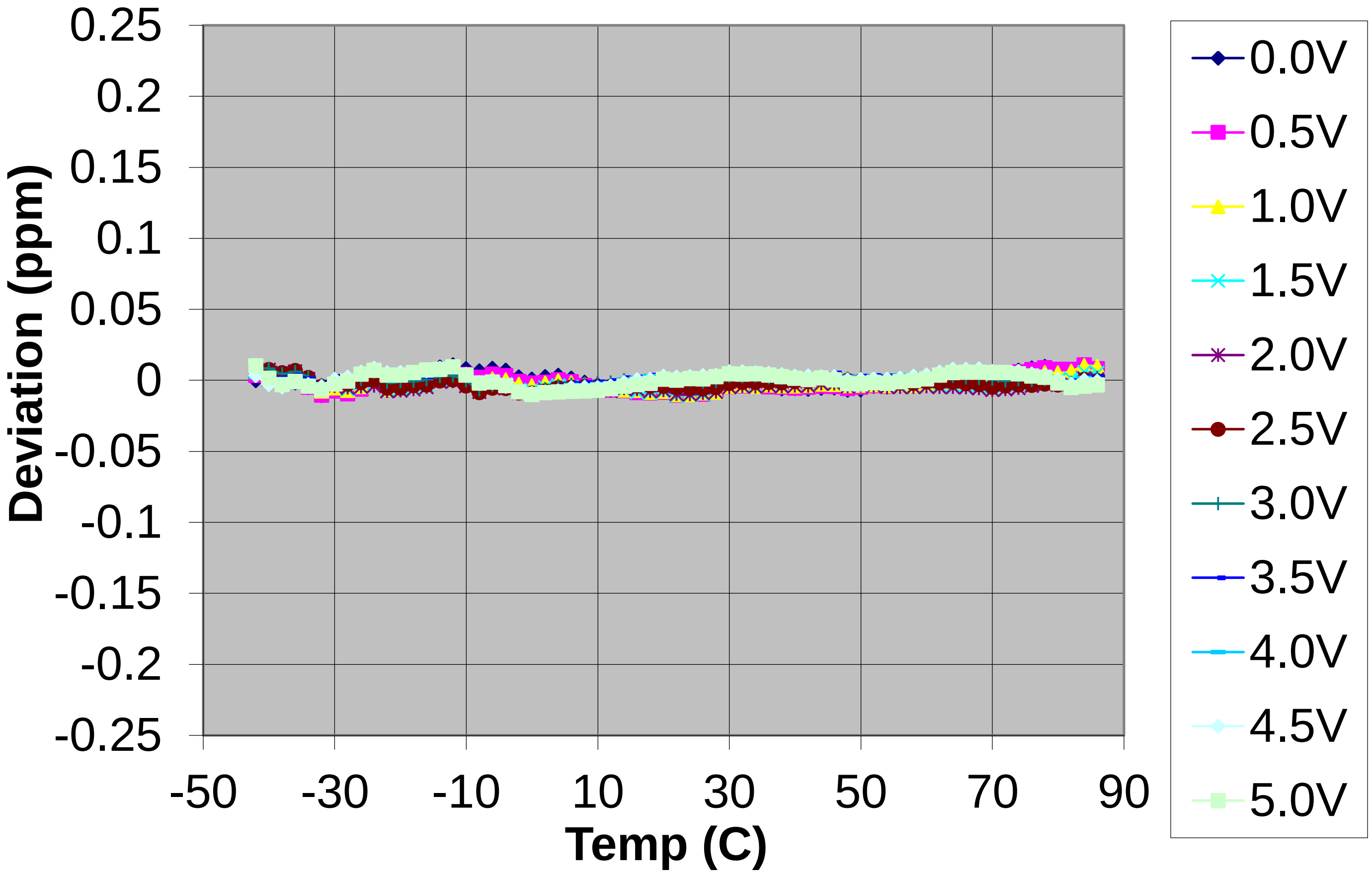
- Baseline trim effect



Trim Effect Compensation

- Trim Effect Compensation

ANN100-1 Trim Effect +/-5ppm pull
10 Neuron Compensation (+/-10.7ppb)



Trim Effect Summary

- ANN compensation of trim effect very effective
- +/-20ppb relatively easy to achieve
- Temp/trim compensation could be achieved as single ANN
- Practically easier to implement as a separate network

Hysteresis Compensation

- Thermal Hysteresis is a difference in the frequency versus temperature performance depending on thermal history
- Temperature change and rate are both factors in thermal hysteresis
- Rate causes an apparent hysteresis due to mismatch of the temperature sensor and the resonator
- Temperature change causes “true” hysteresis which is thought to be stress induced

Hysteresis Compensation

- TCXO’s are compensated by sweeping temperature and calculating solution, then repeating…

- Different manufacturers choose different profiles Hot to Cold versus Cold to Hot

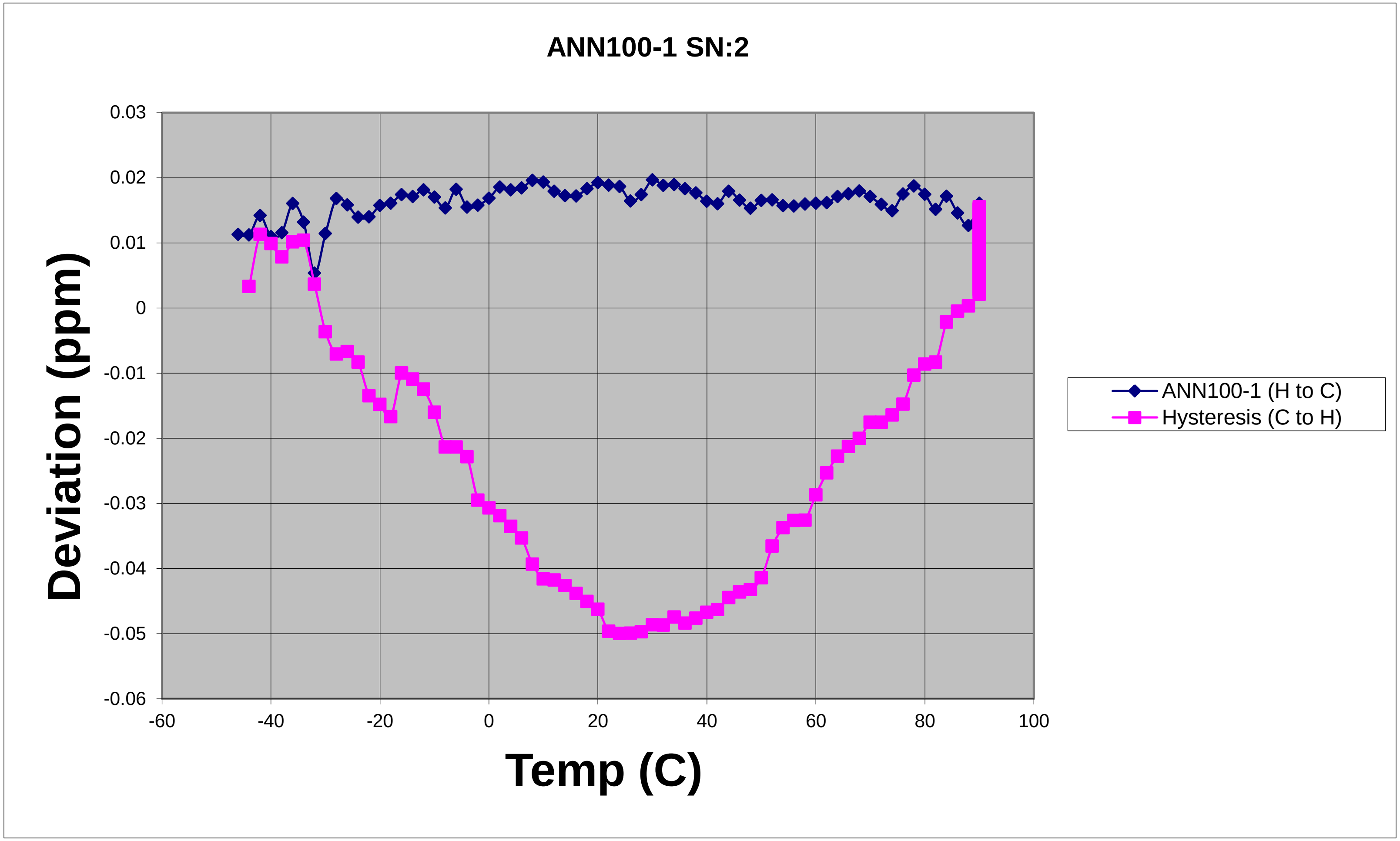
- Greenray compensates Hot to Cold to eliminate moisture issues

Hysteresis Compensation

- Both “true” and “apparent” hysteresis need to be compensated
- Very difficult because it is not trivial separating true from apparent hysteresis when various turn around points are encountered
- More research needs to be done to gain an understanding of the mechanics of hysteresis

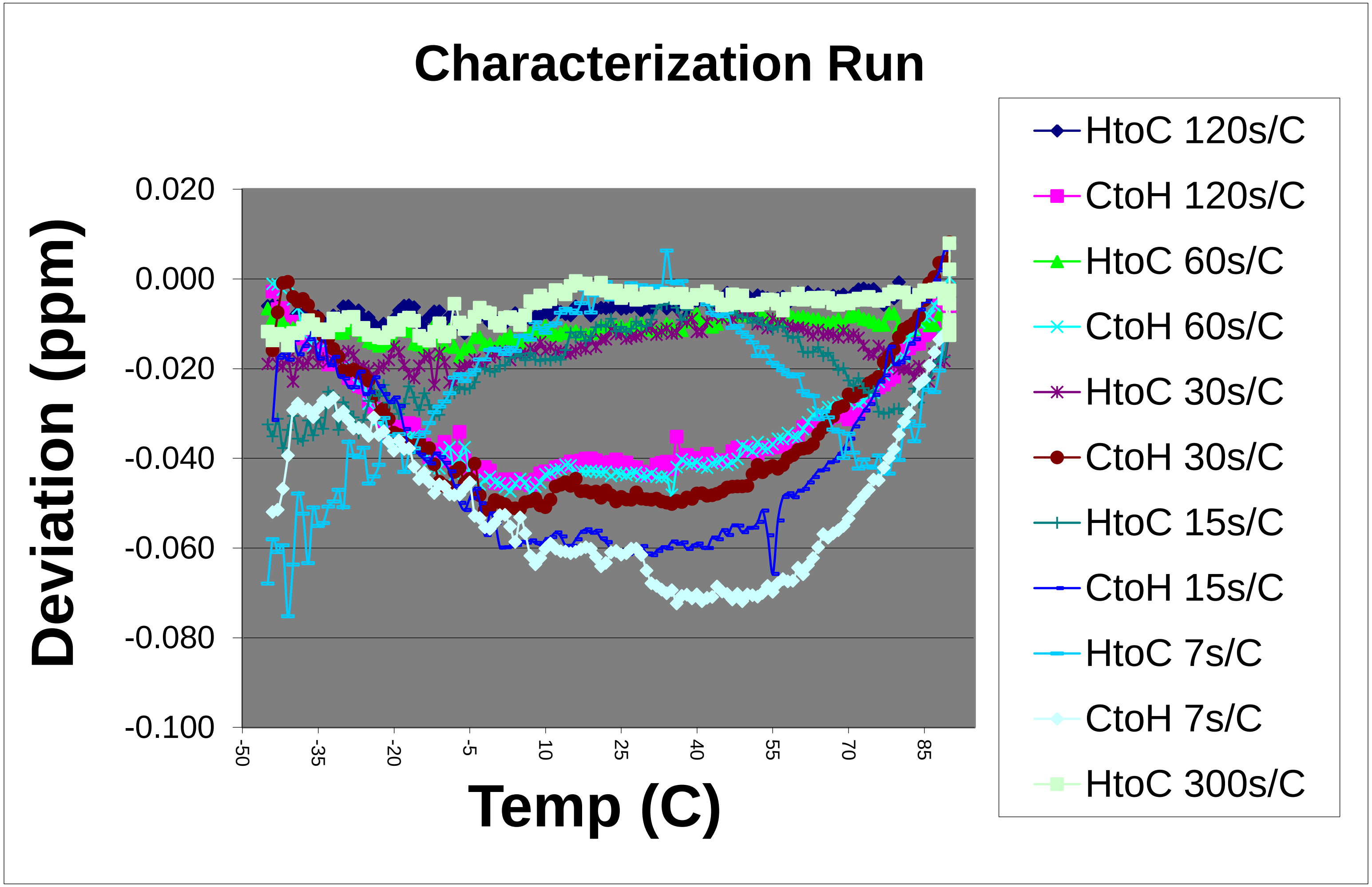
Hysteresis Compensation

- Example of quartz thermal hysteresis



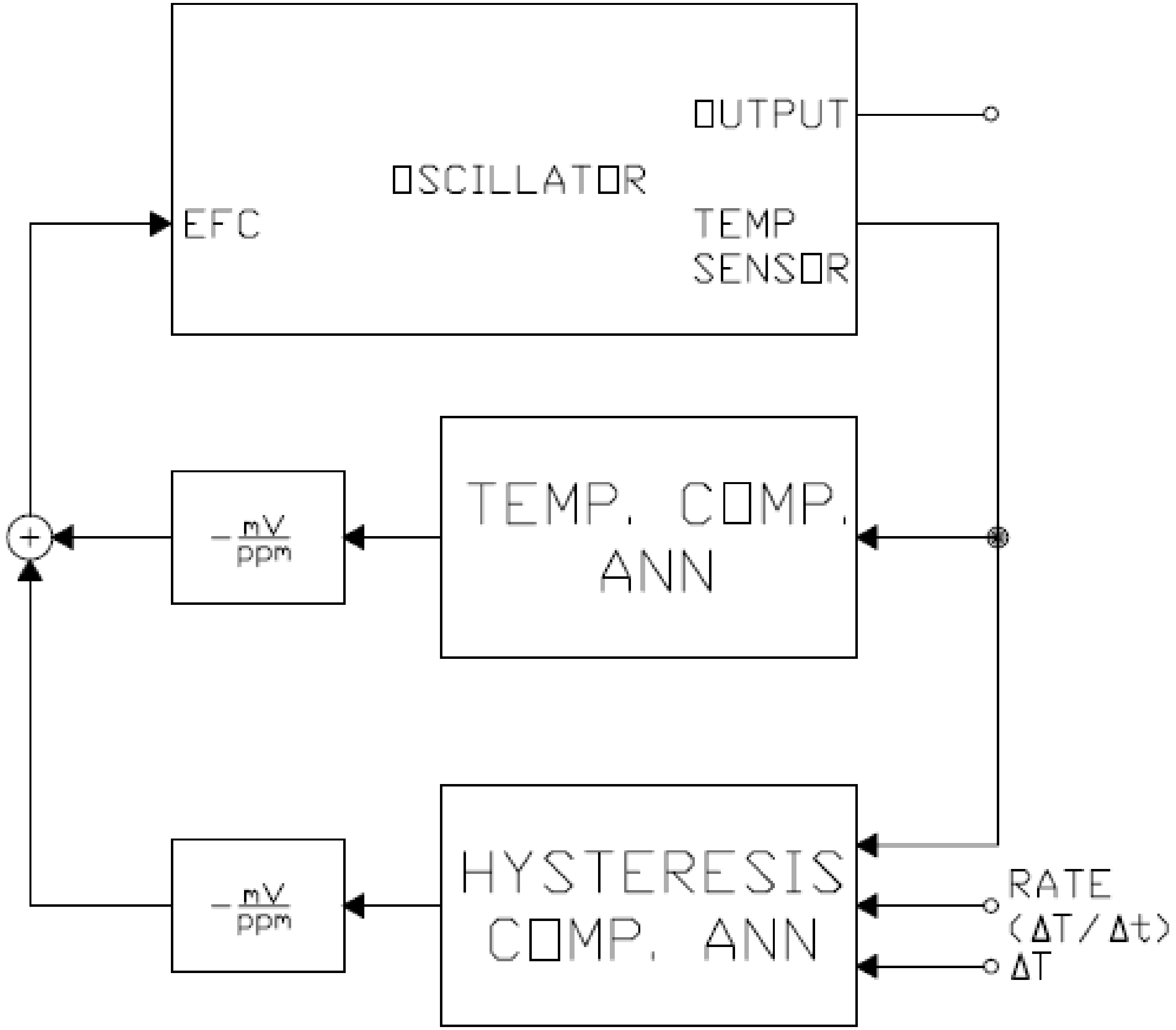
Hysteresis Compensation

- Rate Effects



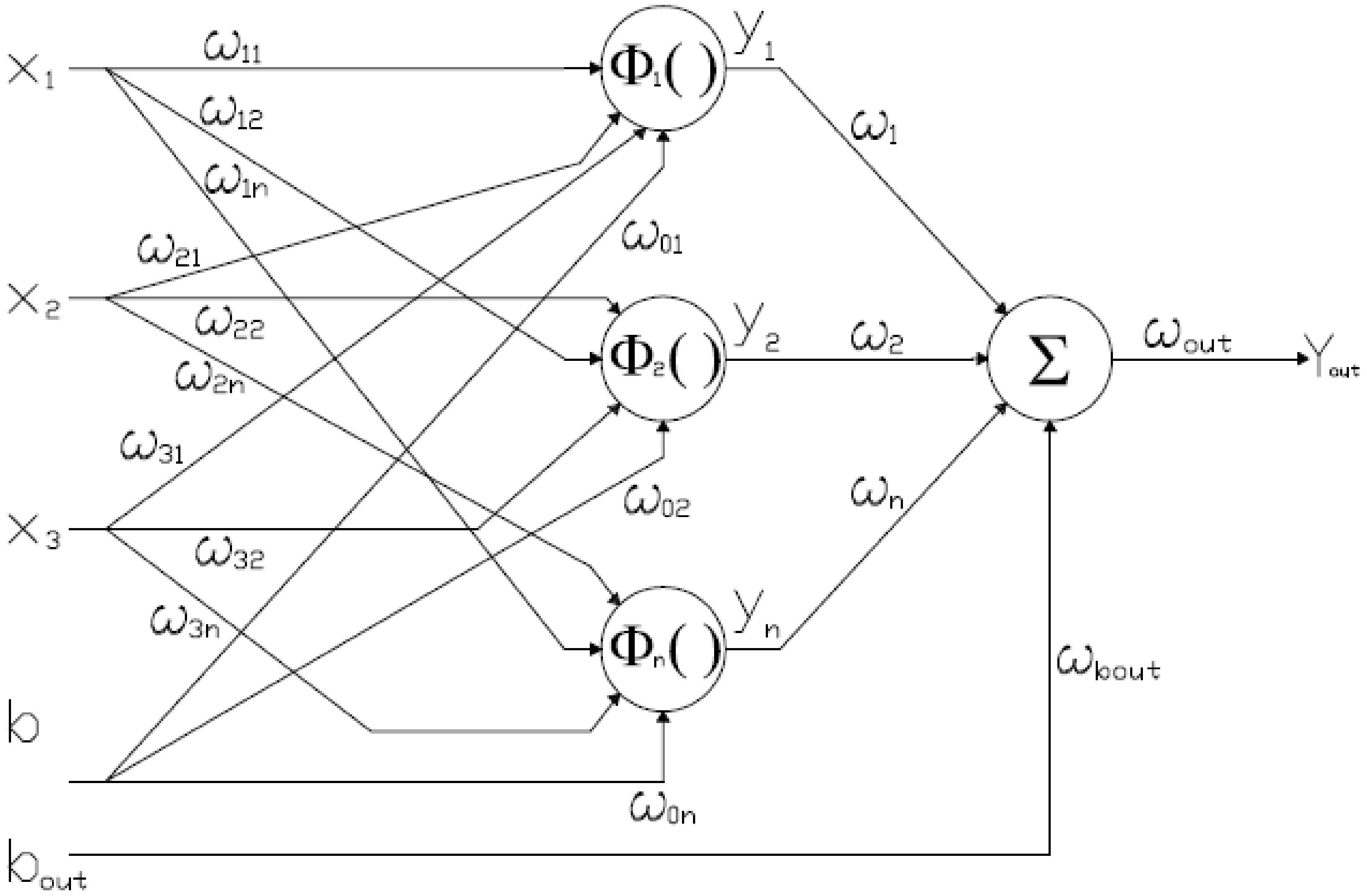
Hysteresis Compensation

- Hysteresis compensation block diagram



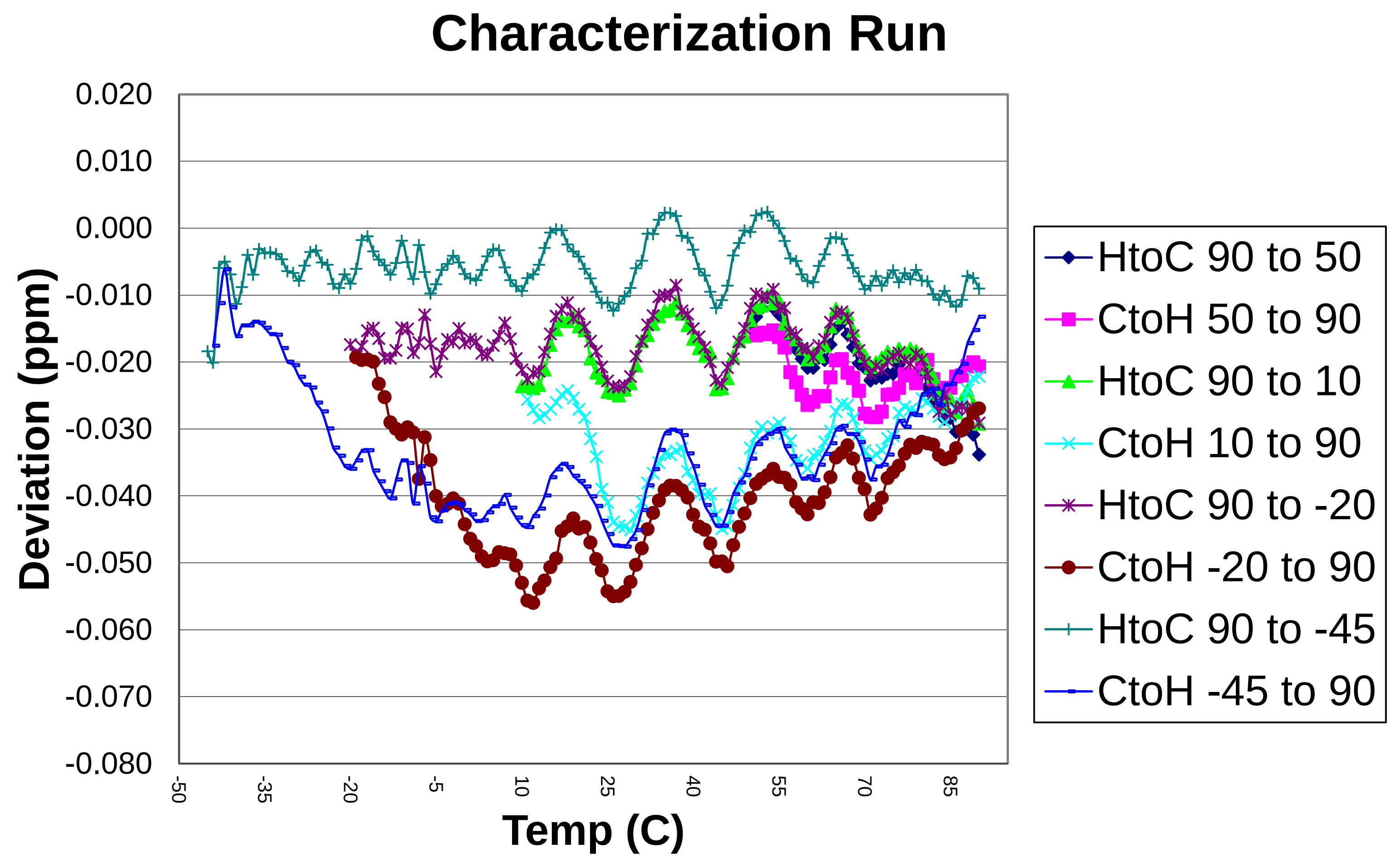
Hysteresis Compensation

- Hysteresis compensation block diagram



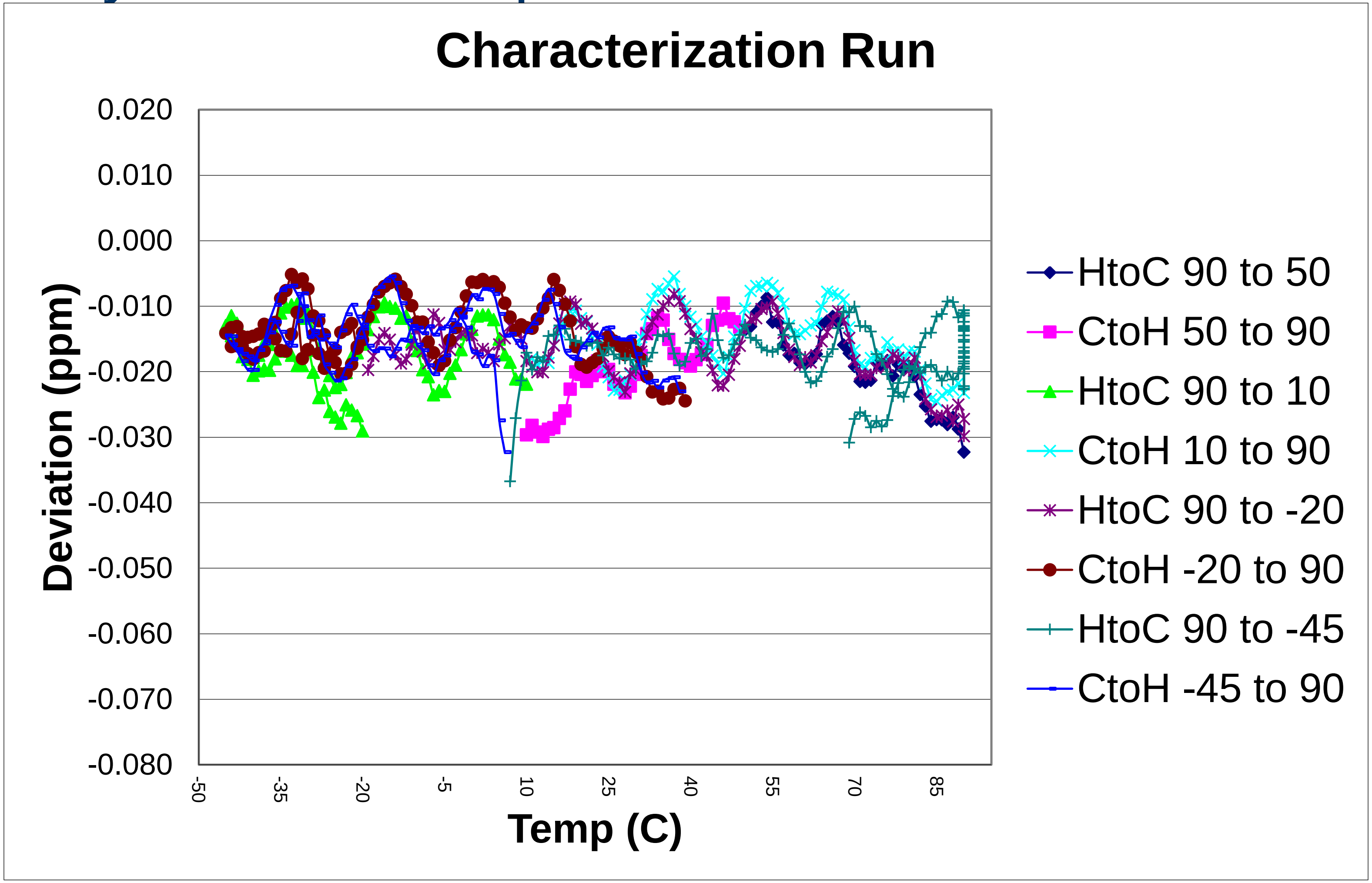
Hysteresis Compensation

- Hysteresis at different turn around points (same rate)



Hysteresis Compensation

- Hysteresis Comp



Hysteresis Summary

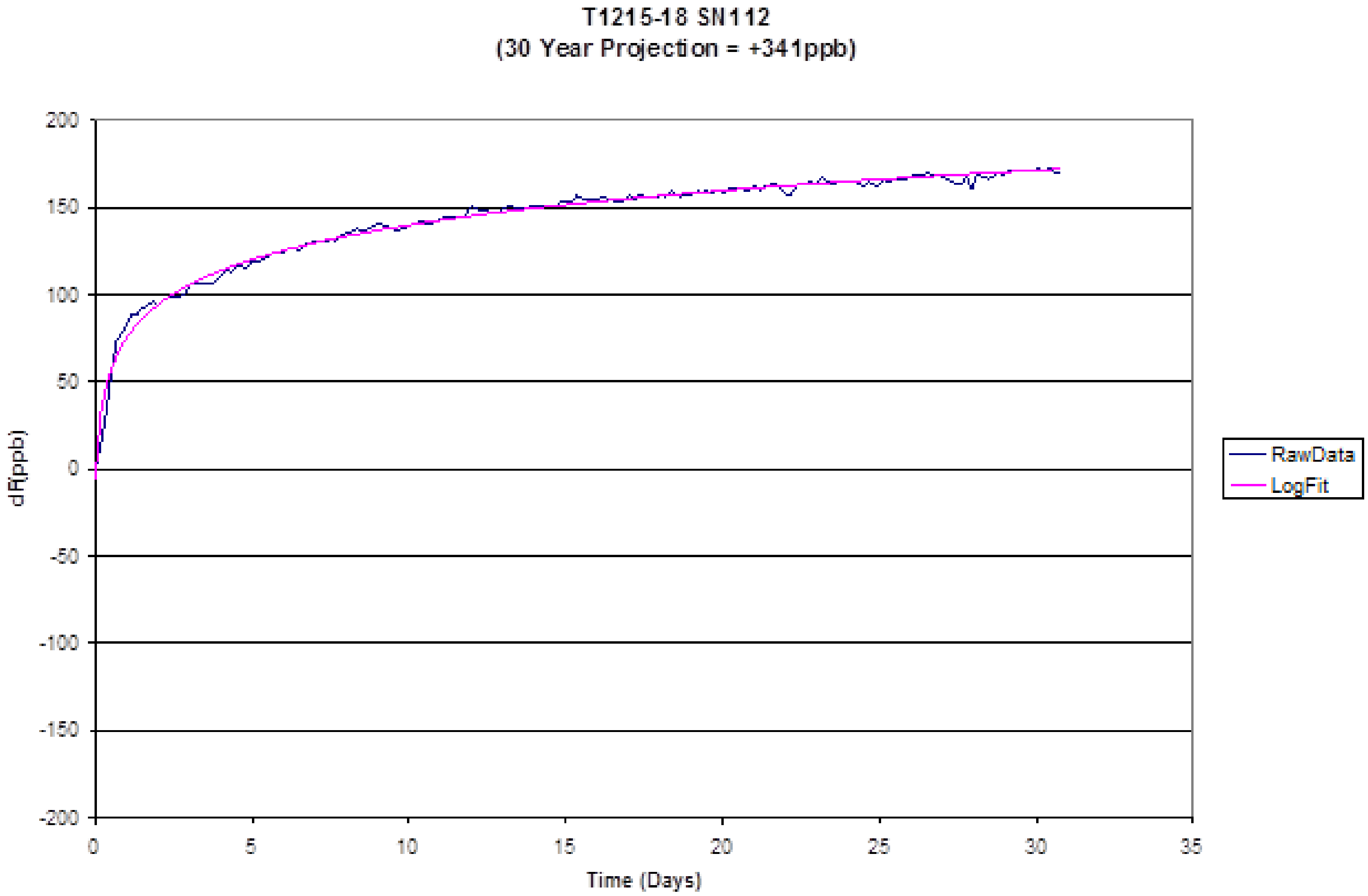
- Partially reduced to practice
- Need to better understand the effect thermal history has on frequency
- Need to isolate rate effects (apparent hysteresis) from hysteresis (true hysteresis)

Aging/Warm-up Compensation

- Aging is the long term frequency drift that takes place in quartz oscillators
- "Good" aging is a positive trending natural log function
- $f(t)=A(\ln(Bt+1)+f_o$
- "Bad" aging is a negative trending natural log function or negative linear function
- Bad aging can come from outgassing of contaminants that mass load the blank (mass to frequency relationship is inverse)

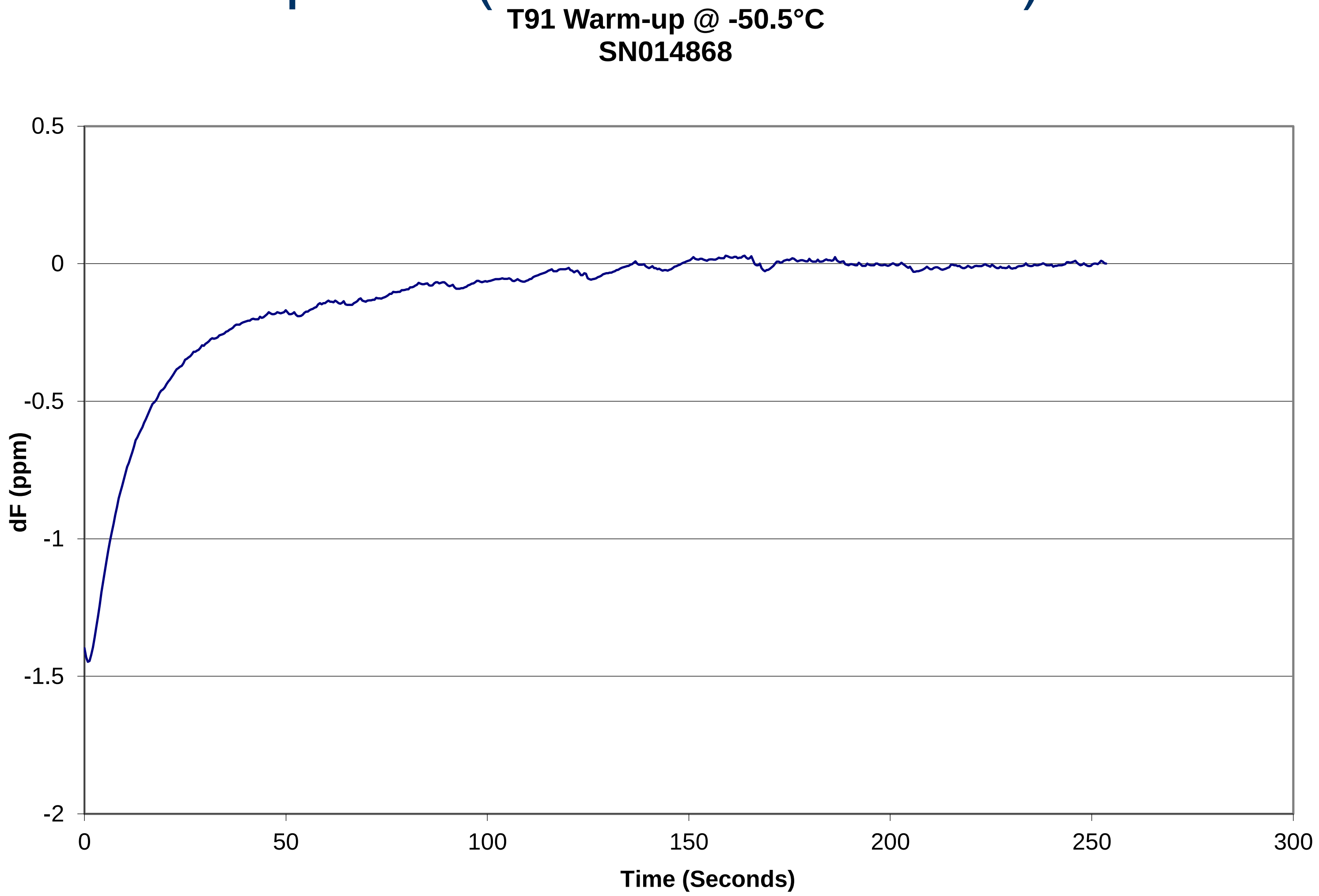
Aging/Warm-up Compensation

- Aging Plot (40MHz 9mmx7mm oscillator)



Aging/Warm-up Compensation

- Warm-up Plot (≈27MHz oscillator)

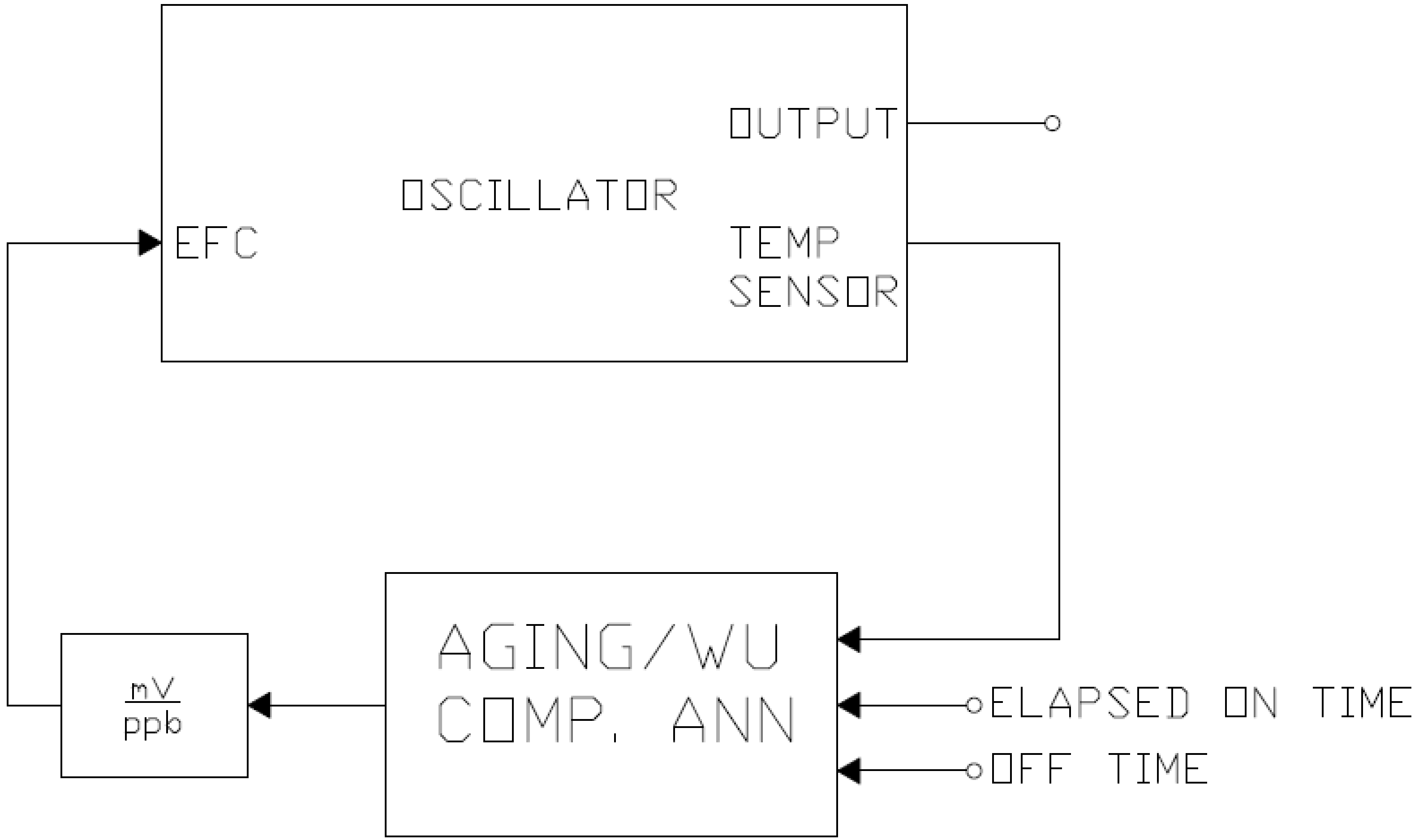


Aging/Warm-up Compensation

- Has not been reduced to practice
- Although different phenomenon aging and warm-up could use a common ANN structure for compensation
- Need to keep track of elapsed on time and off time

Aging/Warm-up Compensation

- Proposed circuit block diagram



Aging/Warm-up Summary

- Has not been reduced to practice
- Difficulty in keeping track of off time
- Might be viable for specific application with fixed amounts of off time

Conclusions

- ANN is a superior curve fitter to any method currently or previously used in frequency control
- For temperature compensation an order of magnitude improvement has been realized over other state of the art methods
- For trim effect it provides a compensation that makes the DUT virtually immune to trim effect (most manufacturers ignore it)
- Hysteresis is present on all crystal oscillators to some degree

Conclusions

- With the ANN temperature compensation the hysteresis dominates as the source of error
- Needs more research to better understand the phenomenon before compensation can be fully realized
- Aging/WU compensation is also desirable
- Difficulty in dealing with off time
- Maybe suitable for fixed off time applications

Conclusions

- ANN could be used for even more frequency control applications
- Very versatile due to its adaptive nature
- Not inherently limited in shape factor

Thank You

- Questions
- Comments
- Concerns

Works Cited

- [1] Steve Fry, “The Design and Performance of Minuature TCXOs,” RF Design, September 2006
- [2] B. Hivert, R. Brendel, “Neural Networks Trends For Frequency Control: A Review,” 1995 IEEE International Frequency Control Symposium, pp. 10-19.
- [3] D. B. Opie, “Operation of a Neural Network Controlled Crystal Oscillator,”1994 IEEE International Frequency Control Symposium, pp. 600-603.
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