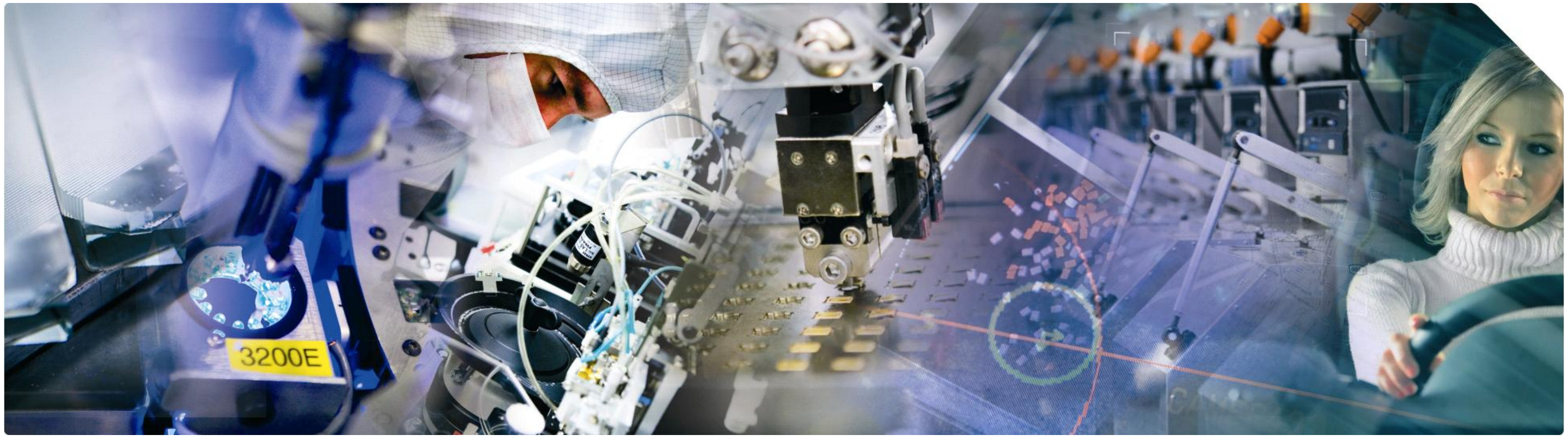



# Oscillator performance criteria for use in time lock loop applications

ITSF09
Dr Nigel Hardy

# The Local Synchronised Oscillator

- The local synchronised oscillator is increasingly moving from a phase or frequency locked loop, based on the physical layer to effectively a time locked system via secondary layer protocols.
  - Such as {weak signal GPS}, PTP (1588), NTP or a combination of these for redundancy or mutual assistance.
  - The time lock loop bandwidth can range greatly between these protocols varying from seconds for GPS to several hours for NTP.
- The longer time periods can impose particular challenges for the synchronised oscillator which provides the local time or frequency reference.  As the stability is now dominated by environmental changes during this time period.

# Oscillator Stability - Specification

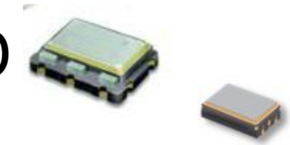
- The traditional oscillator stability specifications of
  - Phase Noise - short term, < 1 second
  - Allan Variance - medium term, 0.01 to 100 seconds
  - Ageing – long term, days to years
- Measured under idealised conditions:
  - constant temperature
- The effect of small temperature variations is not accounted for.
- A gap exists between Allan variance and ageing
  - In region of minutes to hours.
- Effectively the stability over the medium term time period from minutes to hours is poorly characterised …

# Presentation Plan

- Investigate different local oscillator types
  - TCXO, VCTCXO, TCOCXO, … OCXO
- How their oscillator stability is derived
  - Factors which improve or degrade the performance.
- Comparison between oscillator types
  - Detailed characteristics, limitations, for and against
  - Specifically over the medium term time period
- Ideas on how to characterise the stability over the medium term
  - From minutes to hours including thermal effects.

# Oscillator Types

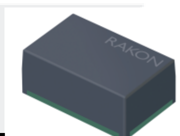
- Temperature Compensated Crystal Oscillator, TCXO



  - Fixed frequency and voltage control types, VCTCXO
  - High precision, ±0.1 to ±0.5 ppm over temperature

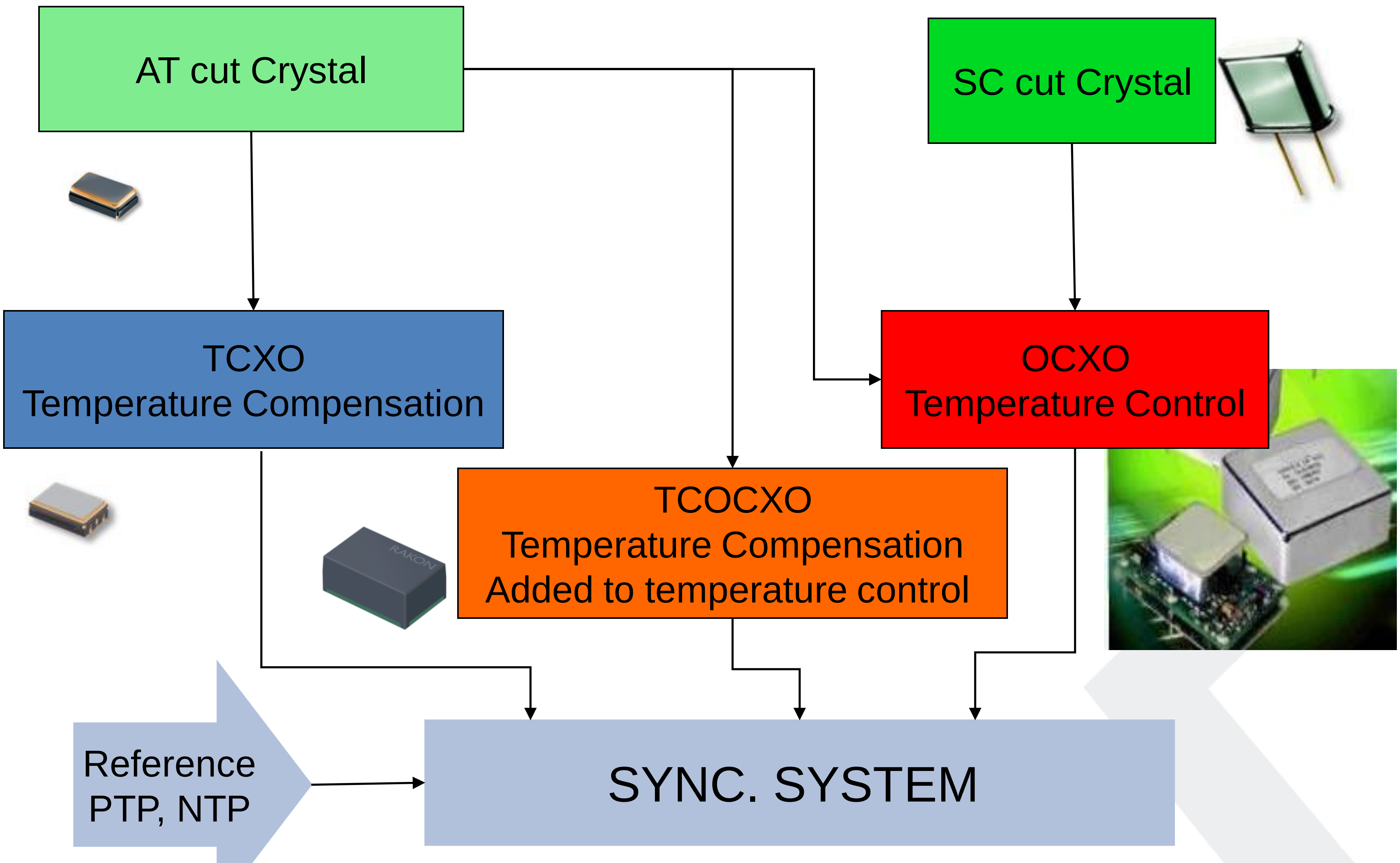
- Oven Controlled Crystal Oscillator, OCXO

- Hybrid: Temperature Compensated Oven Control crystal oscillator, TCOCXO
  - Enhances the OCXO performance and enables the realisation of a high performance miniature OCXO.



- All types exhibit multiple layers of compensation, and control

# Levels of frequency control



# AT-cut Quartz Resonator, TCXO

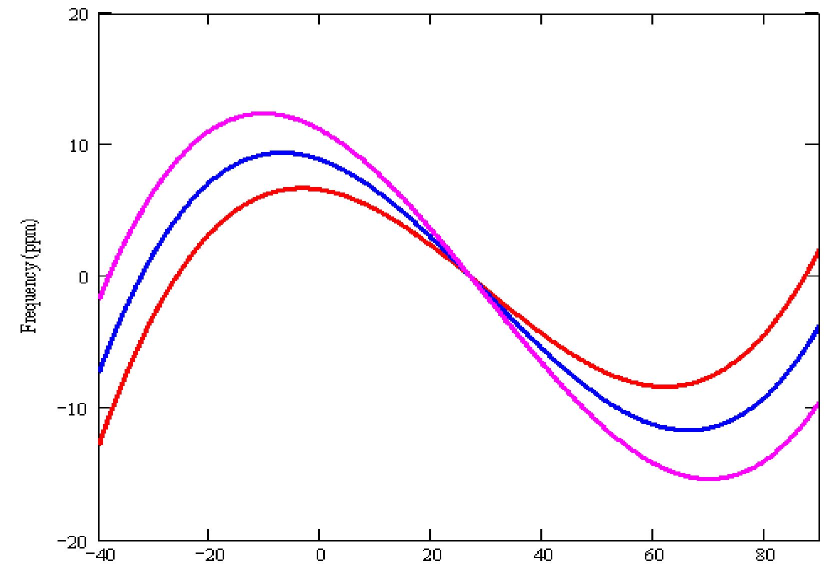
rakon

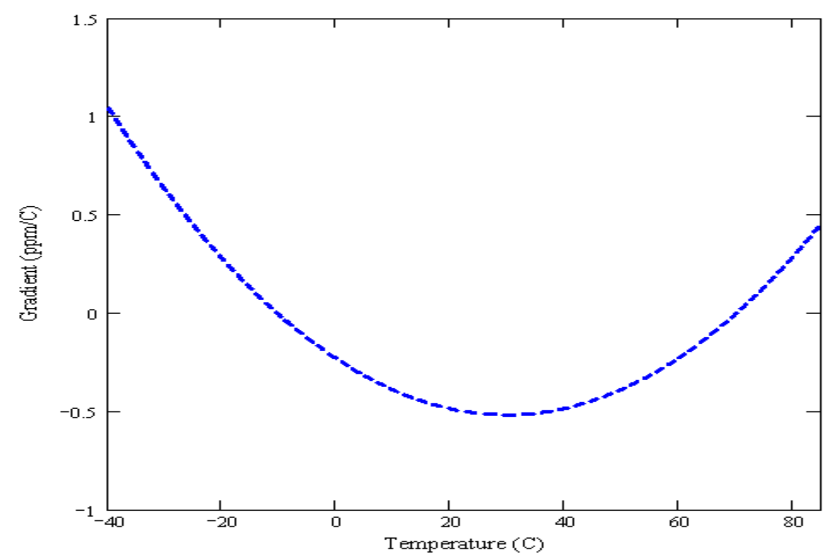
- +/-14 ppm frequency variation over –40 to 85°C , angle tolerance ± 1’
- Inflection temperature ~ 27 °C

$$F(\Delta T) = a + b\Delta T + d\Delta T^3$$

- with a max. slope ~1ppm/ °C

$$\frac{dF(\Delta T)}{dT} = b + 3d\Delta T^2$$



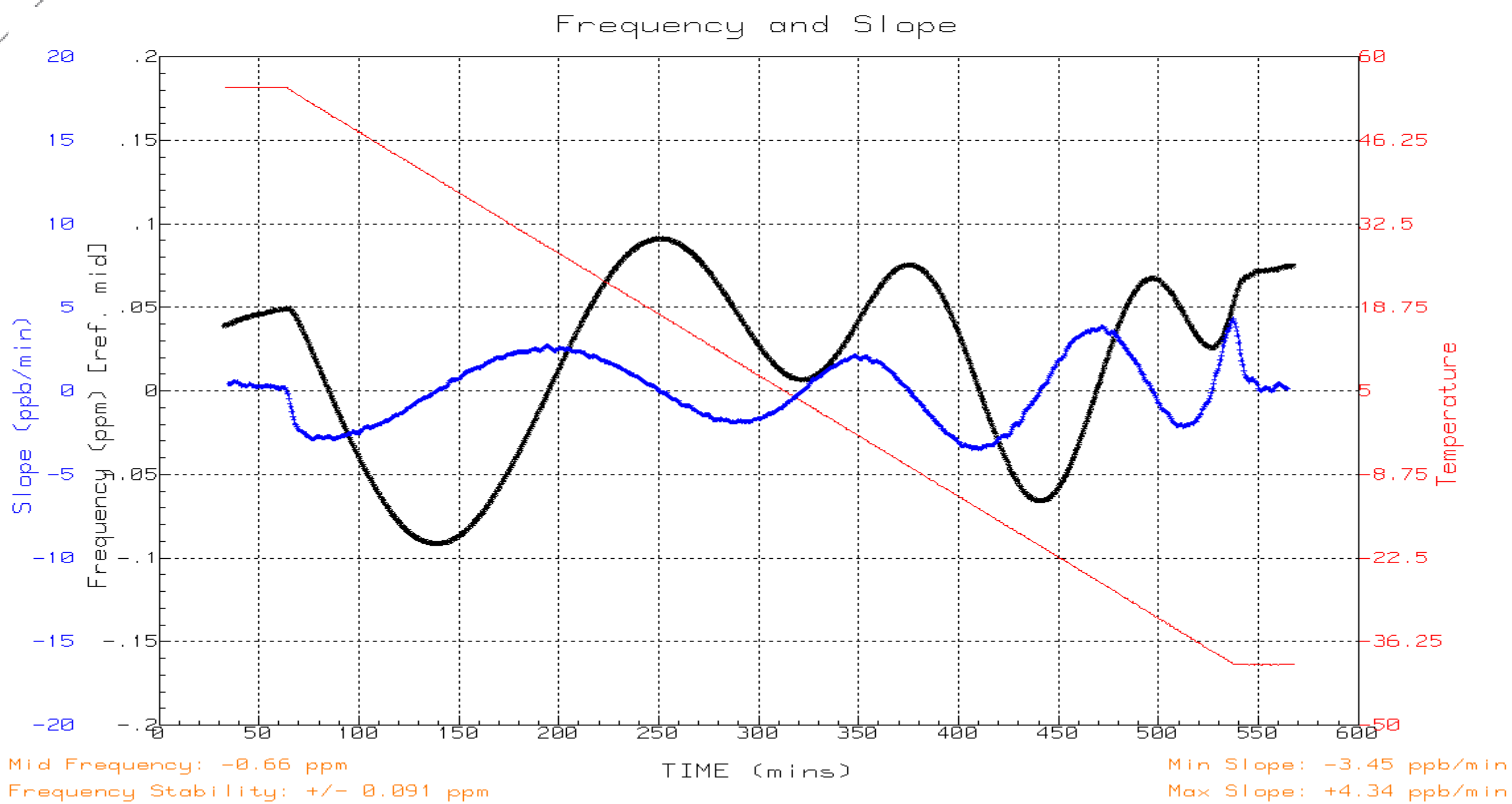



# TCXO stability specification

rakon

- Stability specified with reference to
  - Temperature, Supply voltage, Output load
  - Time, measured under idealised conditions
    - long term ageing, short term Phase noise and Allan Deviation.
- Frequency variation with temperature
  - Usually just specified as a maximum variation over the whole temperature range, ±(fmax-fmin)/2
  - Compensation achievable ~ 100 times, i.e.  ±0.14 ppm –40/85C.
- To assess the medium term stability over a few degrees requires knowledge of the incremental slope, $\Delta F/\Delta T$.

# TCXO ΔF/ΔT characteristics




Frequency stability is ± 0.091 ppm

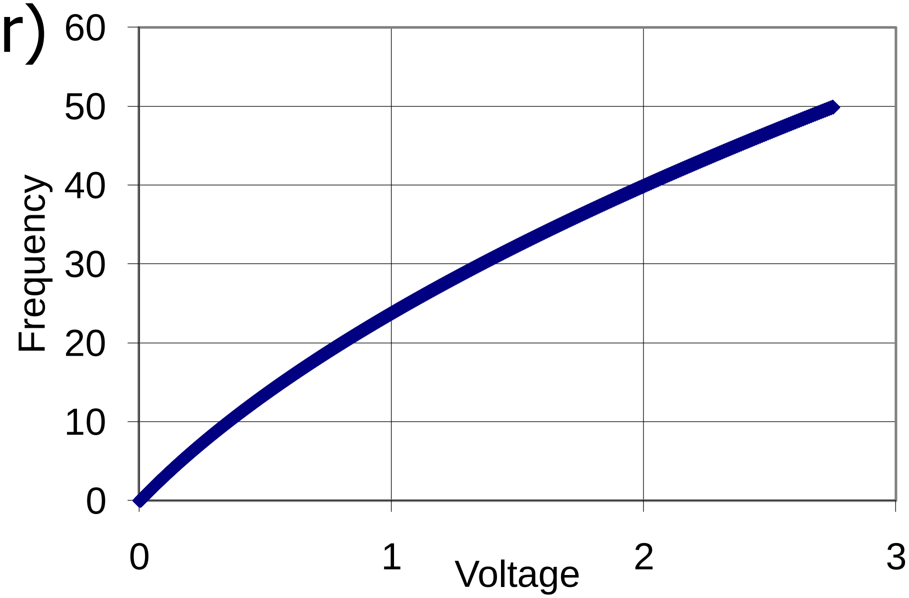
Max Slope ~ 4.3 ppb/min at 0.2 C/min gives **21.5 ppb/C**

# TCXO $\Delta F/\Delta T$ characterisitics

- Previous graph picked to illustrate potential pitfalls in just specifying the frequency variation.
  - Is possible to significantly improve.
- Where the high slope(dF/dT) comes from
  - high order residual error, compensation effects (tuning linearity)
    - Previous graph shows $8^{th}$ order error curve!
  - crystal perturbations, deviations from the ideal crystal F(T) curve also called activity dips, usually caused by interfering modes (e.g., by high overtone flexure modes).

# TCXO- VCXO characterisitic

- All standard TCXOs have at the heart a VCXO (Voltage Controlled Crystal Oscillator)




- Pulling curve

$$V(F) = a + bF + cF^2 + \ldots$$

- Compensation Required

$$-F(T) = a + bT + cT^2 + dT^3$$

- Non-linear Pulling leads to high order compensation

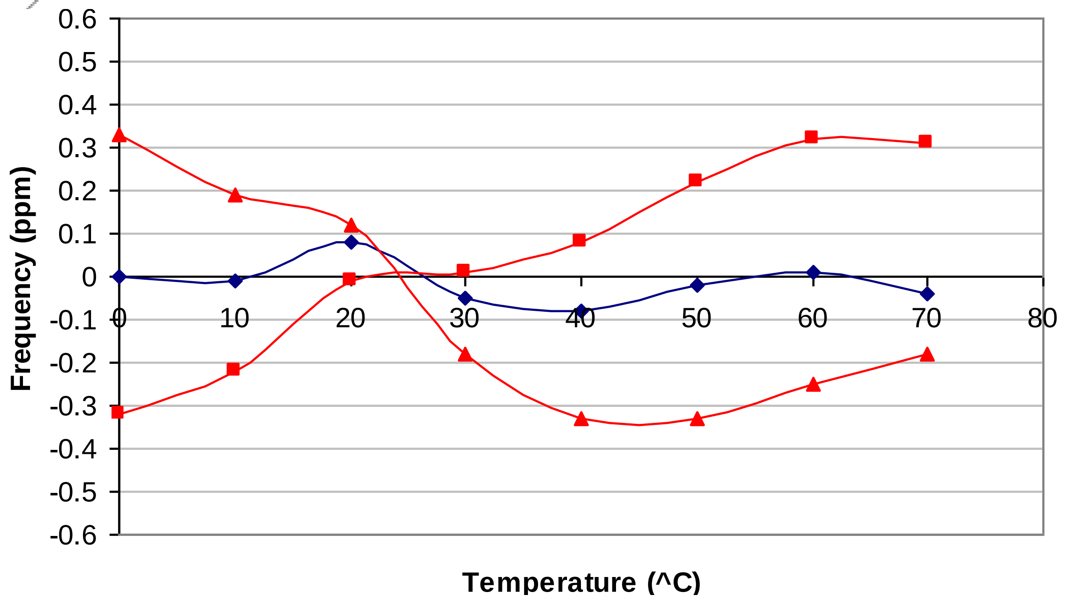
$$Vcomp(T) = V(-F(T)) = a_1 + b_1 F(T) + c_1 F(T)^2$$

$$= a_3 + b_3 T + \ldots\ldots\ldots\ldots\ldots\ldots + f_3 T^5 + g_3 T^6 + \ldots.$$

# VCTCXO characterisitics

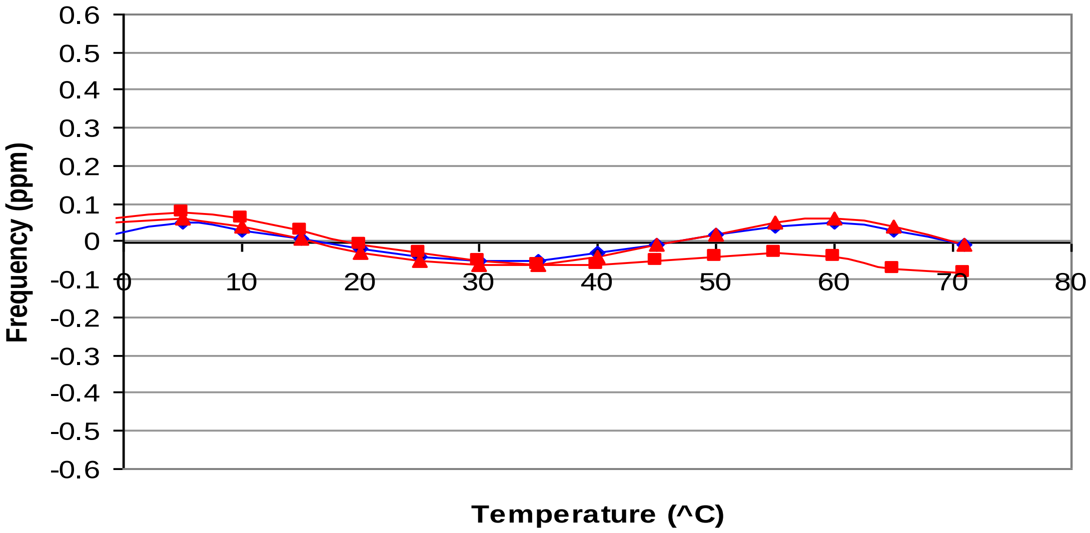
- Frequency vs Voltage control
  - allows direct control of the frequency via an external voltage
  - Possible system simplification, fewer oscillators.
- Requires a low noise, high resolution DAC
- Suffers from possible degradation due to the "Trim Skew effect"
  - degradation in the temperature compensation with variation in the voltage control. Caused by an interaction between the temperature compensation circuit and the external voltage control

# VCTCXO - Trim Skew effect




VCTCXO pulled +/- 7 ppm, degrades performance by a factor of three

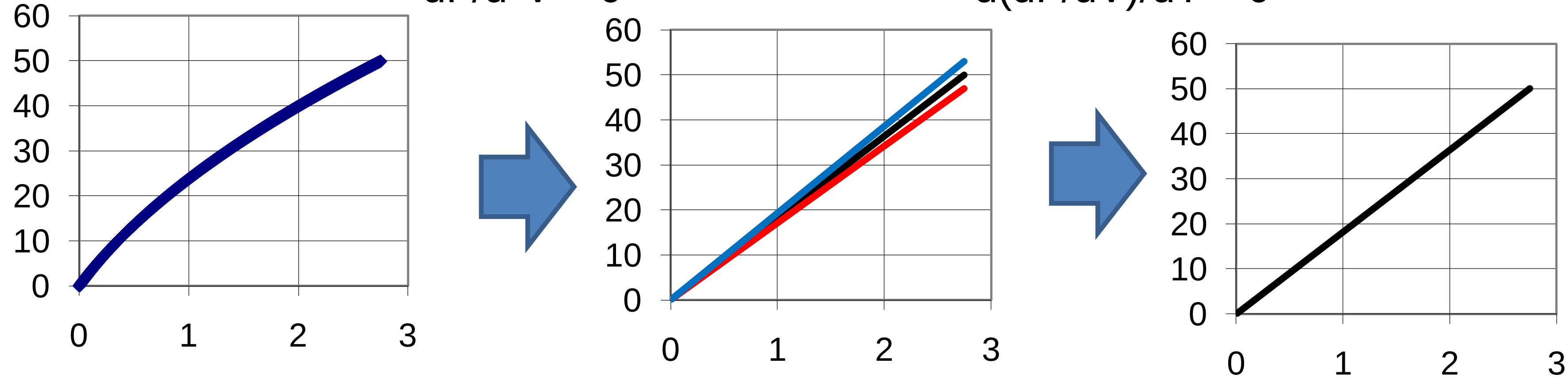
- How to minimise the effect to achieve this?

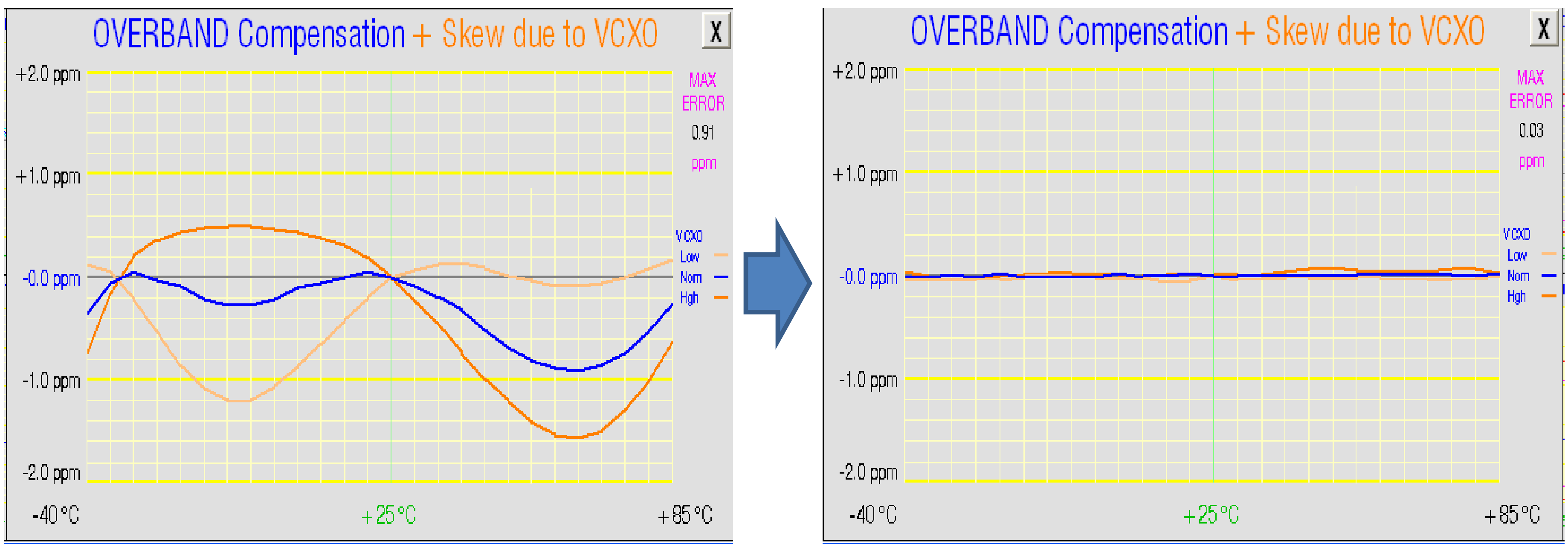


# VCXO Linearity and Trim Skew

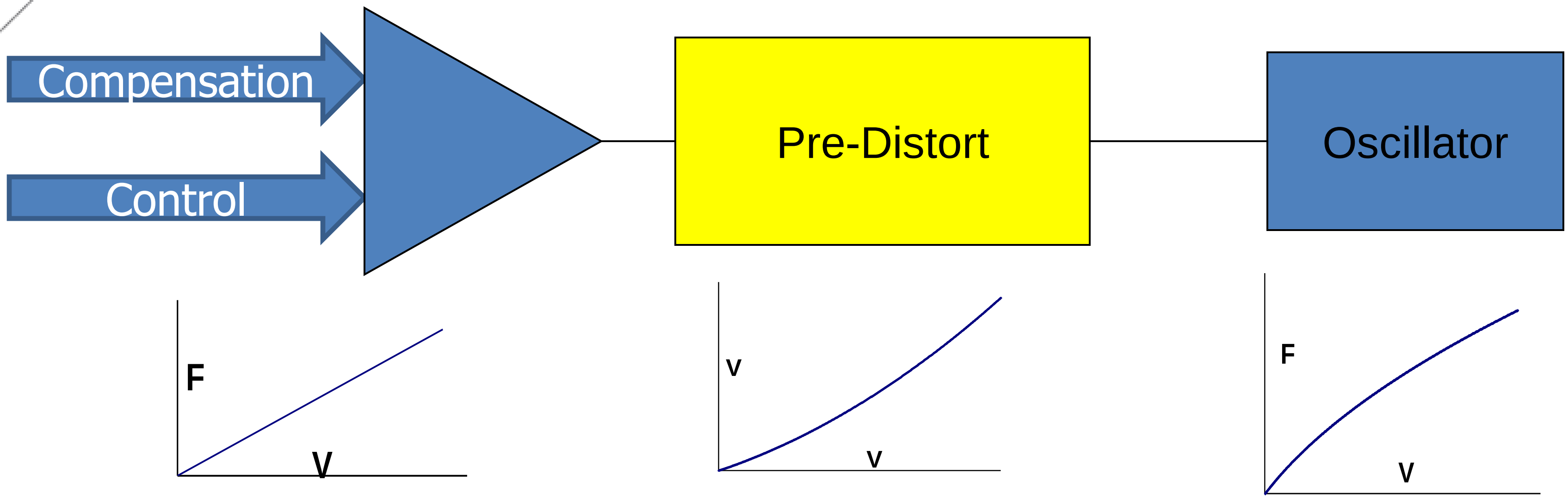
rakon

$dF/d^2V \sim 0$ $d(dF/dV)/dT \sim 0$



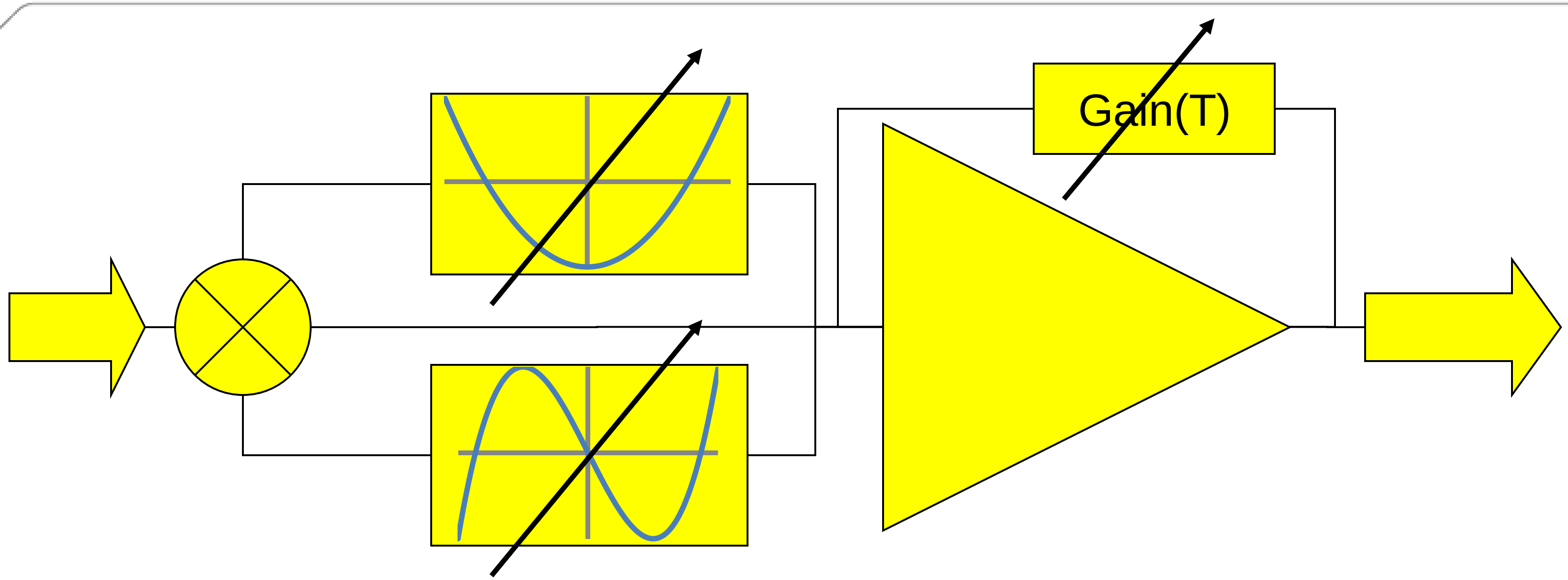



# Pre-distort circuitry




- Introduce a pre-distort circuit between compensation + control voltage and oscillator.
- To linearise pulling and add temperature dependent gain.

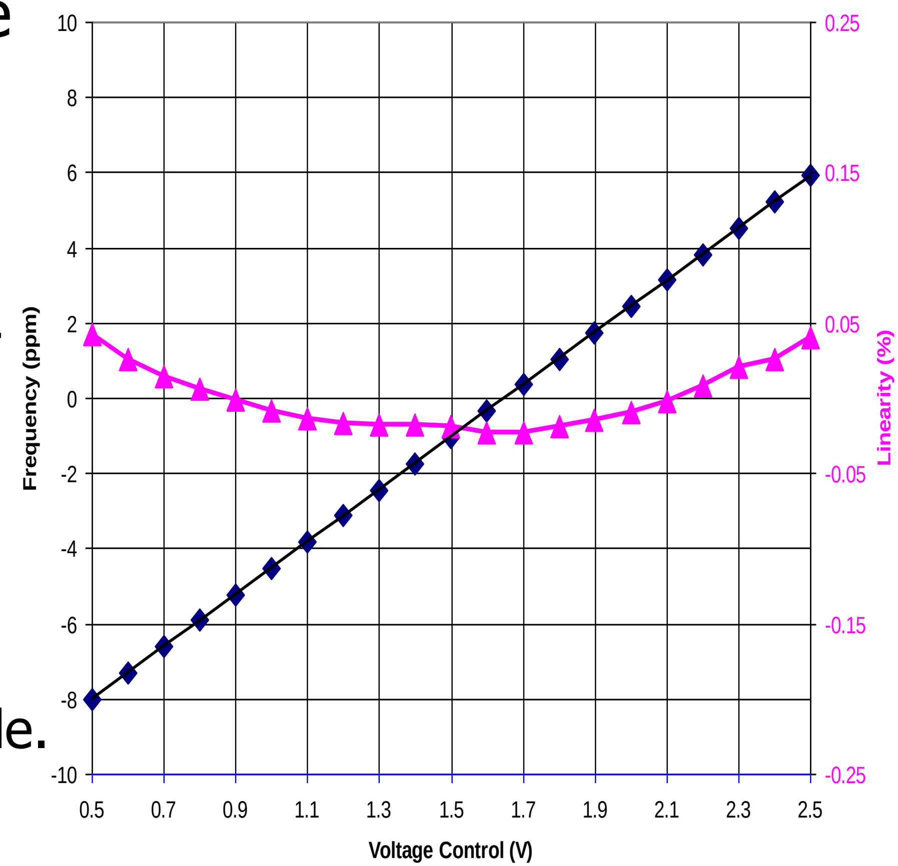
# Pluto's Pre-distort circuitry




- Rakon's TCXO ASIC "Pluto" provides Programmable
  - Second and third order distortion
  - Temperature dependent gain
- Pulling dF/dV is made constant with changing voltage and temperature
  - $dF/d^2V \sim 0$, $d(dF/dV)/dT \sim 0$

# Benefits of Constant dF/dV

- Linearity <0.1% is achievable with pre-distort circuitry.
- Improves compensation by significantly reducing
  - High order residual error (lower slope)
  - trim skew effect (VCTCXO)
- Improves system lock behaviour
  - Slope is constant and predictable.
  - Reduces iteration cycle, locking time.



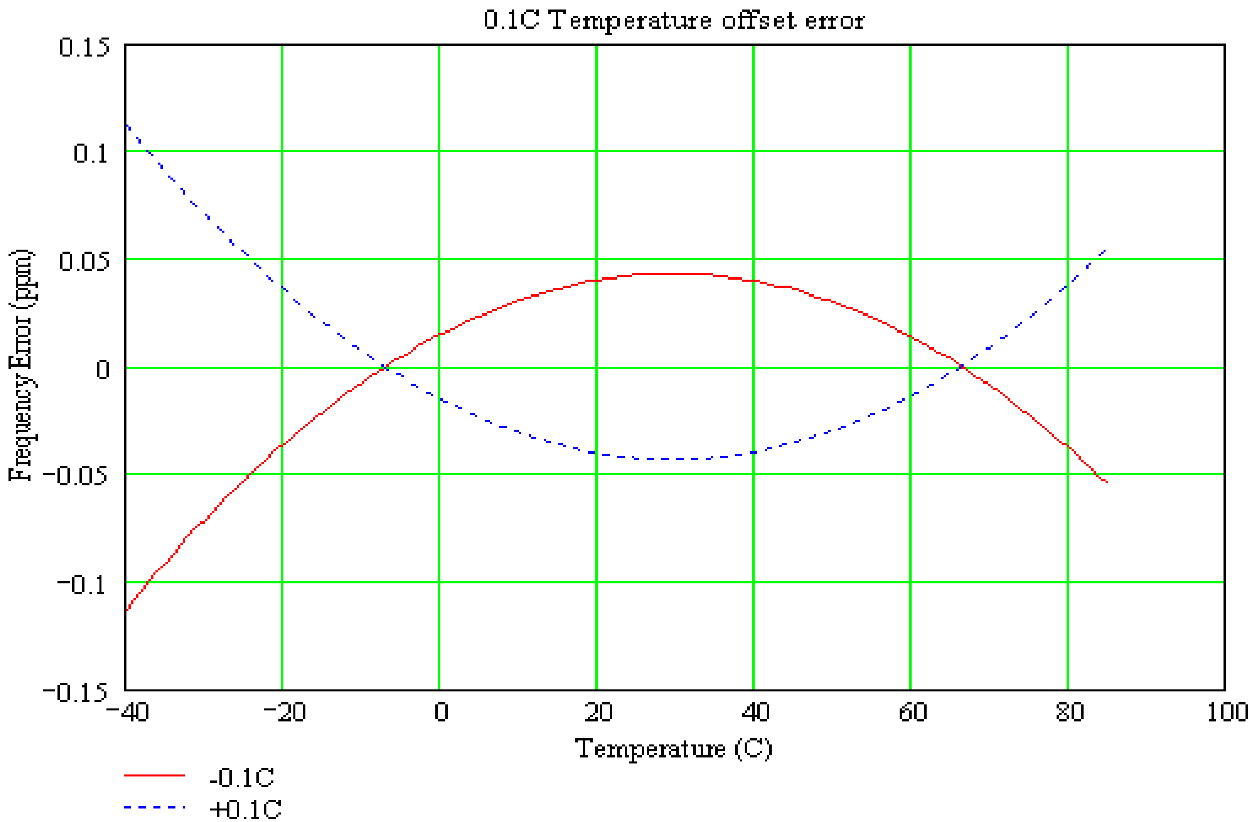
# Frequency Perturbations

rakon

- Continuous improvements in the control and processing decrease occurrence especially at established frequencies
  - become more troublesome at higher frequency, smaller dimensions
  - Can be reduced, but hard to eradicate
- Compliance testing of crystal and/or finished oscillator every 1C or less over entire temperature range.
  - High resolution measurement.
  - At a High sampling rate.
  - In a high volume ATE.
  - With a dF/dT limit.

# TCXO Dynamic thermal effects

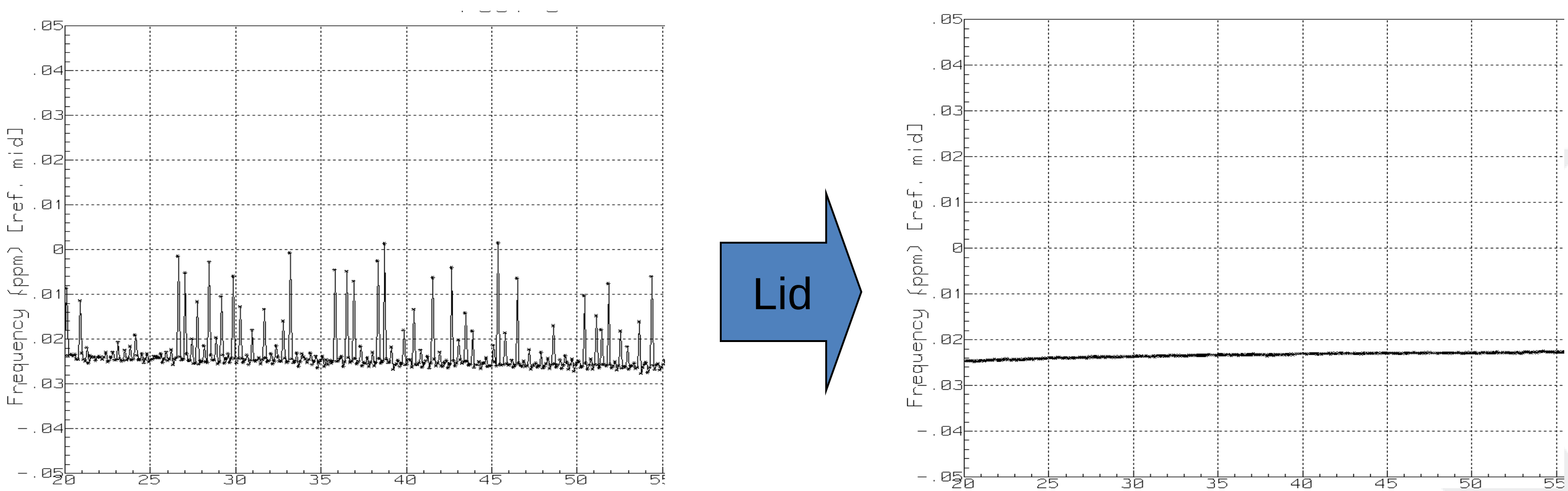
- TCXO relies on the temperature sensor tracking the crystal
  - Introduction of a thermal gradient between crystal and TCXO sensor of 0.1C can degrade up to 100ppb.



# Environmental influence

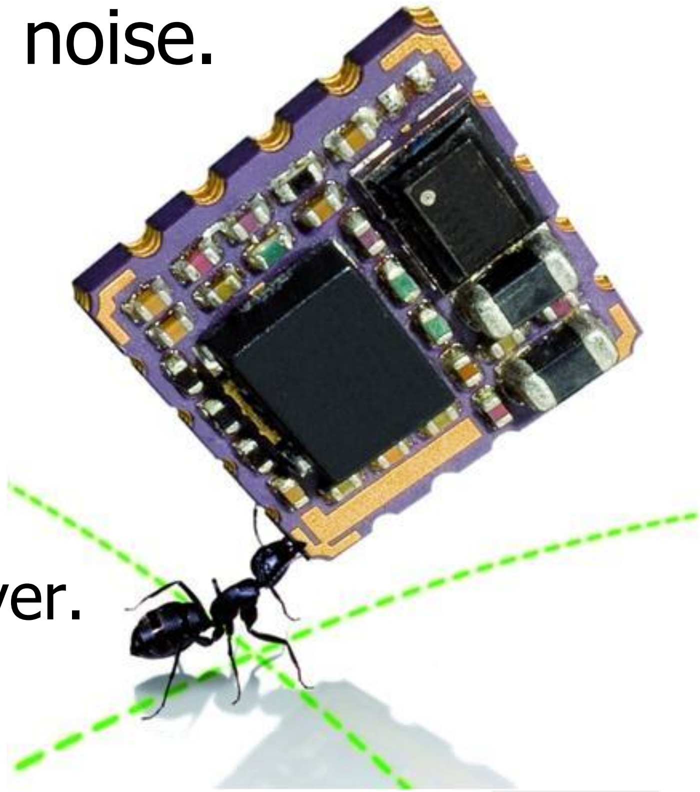
- Small ceramic packages provide a good thermal connection between ASIC and Crystal
  - Little degradation up to 10C/min ramp rates
  - but the top of Crystal package is exposed so can be particularly sensitive to airflow.

- Operational environment
  - Forced cooling, fans etc. Variable speed or on/off
- Test environment
  - Test chamber cooling, Liquid $CO_2$ , example below shows 20ppb spikes when exposed directly to chamber airflow.



# Indoor GPS TCXO requirements

- For indoor GPS, high sensitivity required
  - To achieve levels –160dBm
- Long correlation time required to raise the signal above the thermal background noise.
  - 2.5 second correlation time
  - 0.4Hz frequency bucket
    - 0.4Hz at 1.5GHz is ~ 0.3 ppb
- Oscillator stability
  - Allan variance(2.5s) < 0.04 ppb
  - Very high stability TCXO with cover.
- Assisted GPS also required.



# Summarise TCXO - dF/dT

- Minimise TCXO dF/dT by
  - Reduce high order error curves via Linear pulling
  - Screen for crystal perturbations over entire temperature range.
  - Protect oscillator from thermal gradients and airflow.
- State of the art TCXO figures, Rakon “Pluto” TCXO
  - ~ 4ppb/C typical to 12 ppb/C max. over, 0 to 70C
  - ~ 6ppb/C typical to 20 ppb/C max. over –40 to 85C
- For lower dF/dT figures and hence better medium term stability then need look at OCXO type product.

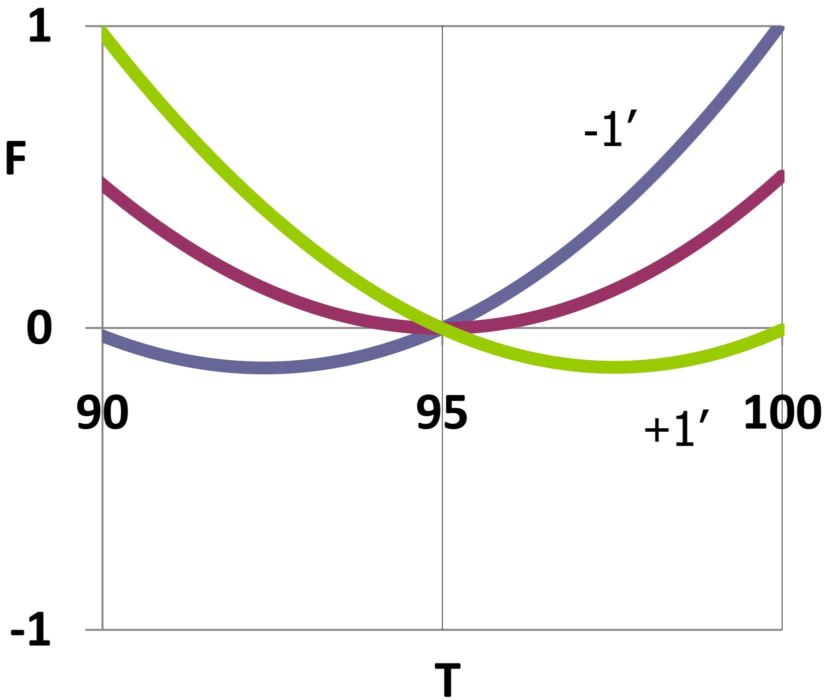
# OCXO - characteristics

- Operating over a narrow temperature range
  - Crystal perturbations unlikely, almost eliminated
  - No high order compensation effect
  - No significant Trim skew effect for VCOCXO
  - Significantly lower dF/dT achievable.
- Disadvantages to be offset in a OCXO
  - High component count, complicated manufacture
  - Large Size, especially height, difficult to surface mount
  - High power consumption, Longer warm up time

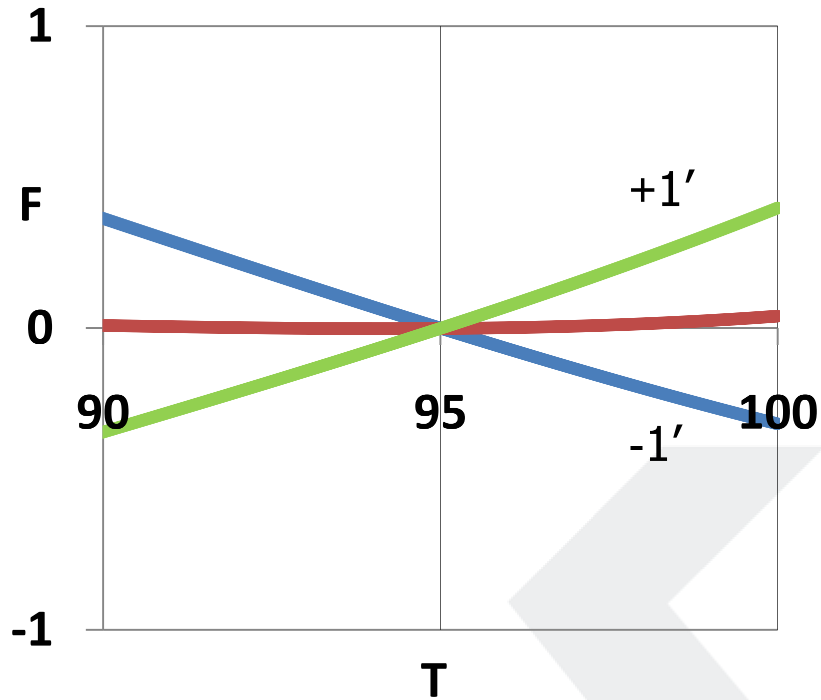
- SC cut crystal vs AT cut
  - ~10 times better stability for same oven control range.
  - But very much larger, not commonly available as strip resonator.
  - Needs B-mode trap, external LC circuit
  - More complex manufacturing and relative lack of volume manufacture, makes it significantly more expensive.

# OCXO Crystal – AT or SC cut

- Comparison including crystal batch variation, angle tolerance ±1′
- AT cut upper turn point, SC cut inflection temperature ~ 95C



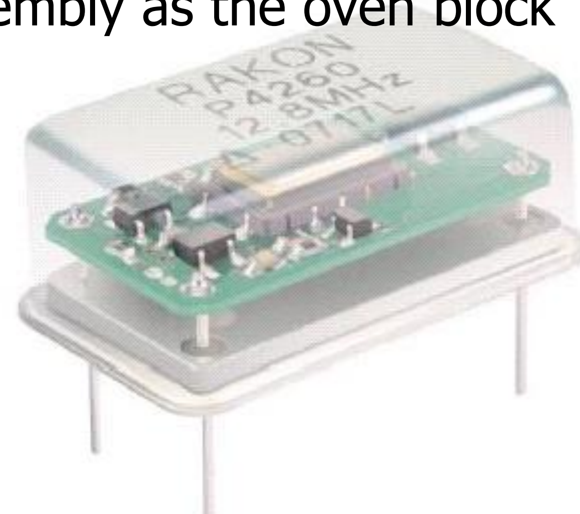

AT-cut Quadratic error, turnover moves with angle tolerance




SC-cut linear error, can be very small at the optimum angle

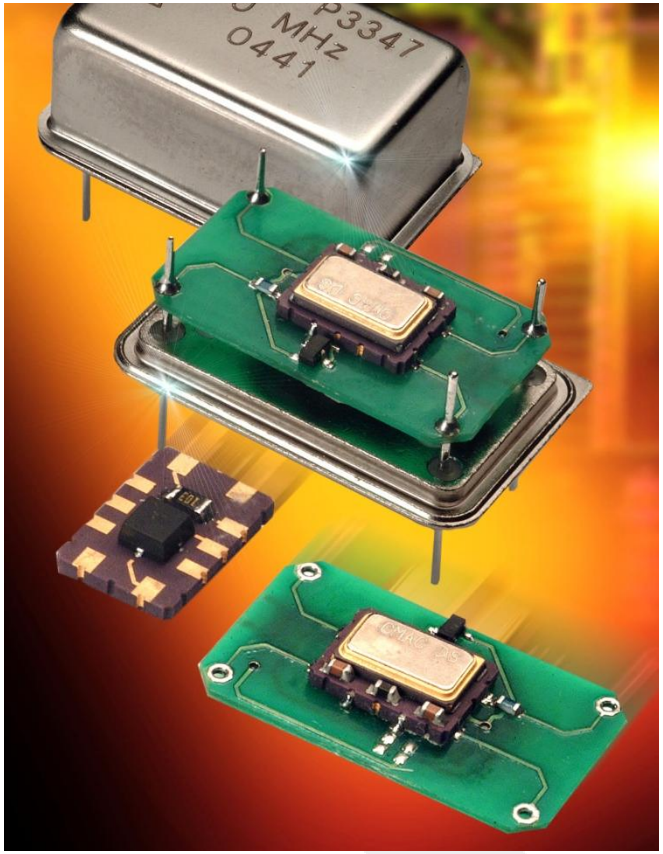
# Miniature OCXO (TCOCXO)

- SC cut type stability from AT cut crystal?
  - Make the oven more stable.
  - Or add compensation to a simple oven.
- Temperature compensated oven controlled crystal oscillator (TCOCXO)
  - Can not just ovenise a TCXO as the thermal gradient generated by attaching the heater degrades the performance.
  - Compensation has to be performed after the device is ovenised.
- Miniature and low cost.
  - Basic ceramic TCXO strip crystal assembly as the oven block
  - Add heater and Temperature Sensor
  - External heater control circuitry
- Rakon "Triton" product range



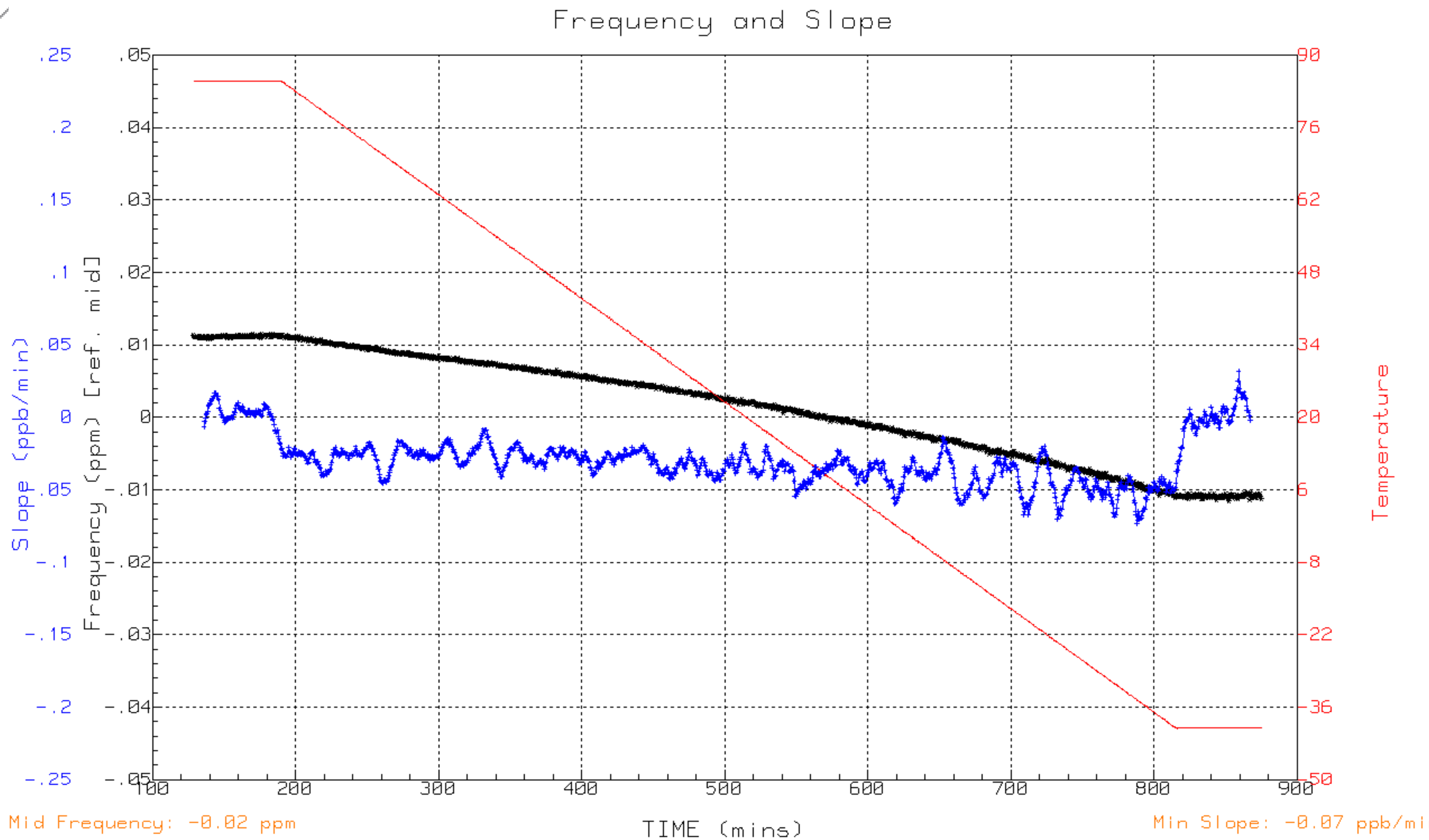
# Rakon's TCOCXO "Triton"

- Triton TCOXCO product range incorporates Rakon's TCXO ASIC "Pluto"
- Particularly suited to TCOCXO
  - Versatile compensation features
  - Good short term stability
- ASIC communication shared with VCXO input and RF output.
  - Minimum number of connections for low power
  - Allows compensation of completed assembly.



# TCOCXO - Characteristics

rakon




Frequency stability +/- 11 ppb -40 to 85C

Slope - 0.07 ppb/min. at 0.2 C/min. equates to 0.35 ppb/C.

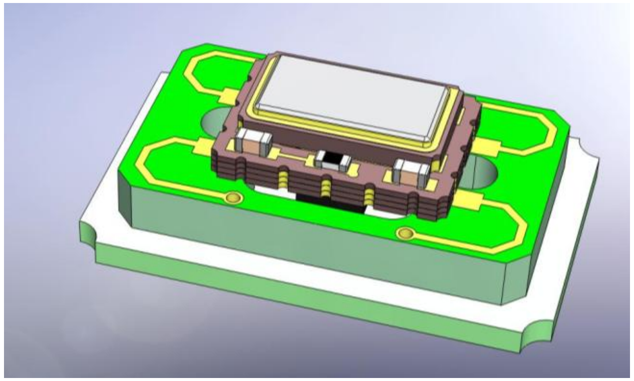
# TCOCXO - Characteristics

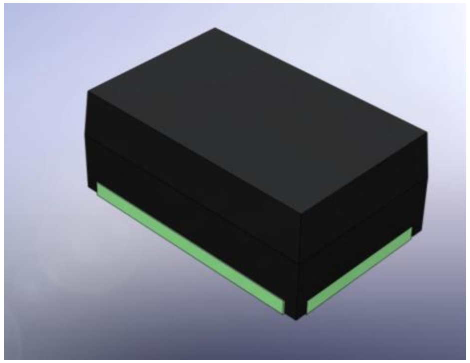
› Increased Stability with temperature
  - Variation five to ten times better than a TCXO, typically ±10 ppb
  - dF/dT ten times better, typically 1 ppb/C

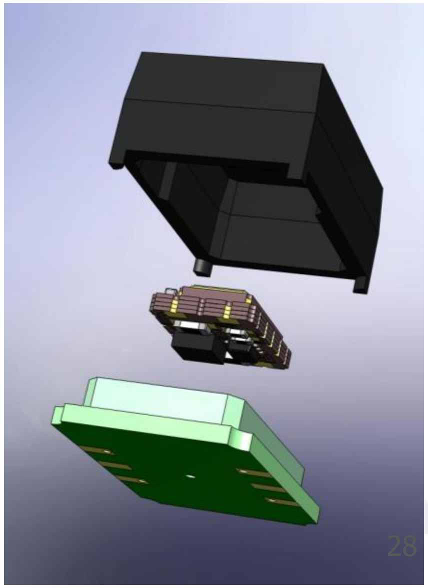
› Miniaturisation of the oven assembly also leads to:
  - Lower Power consumption, 300mW @ room
  - Faster start-up, 30 seconds @ room

› Mounting all the oven control circuit onto the ceramic oven block allows a true surface mount device to be constructed in a 14x9x6 mm package size.

› Surface mount "Triton"



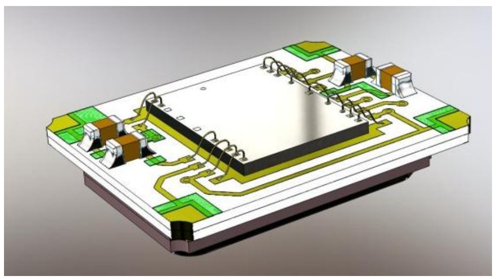


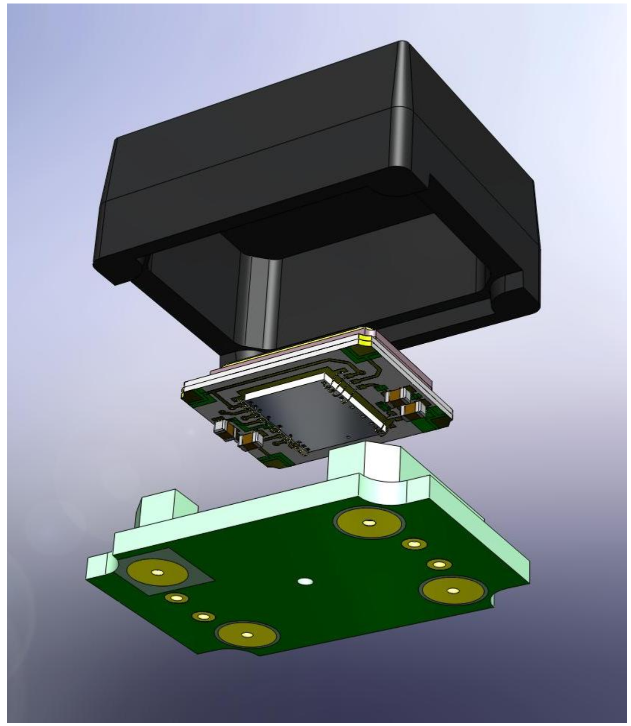


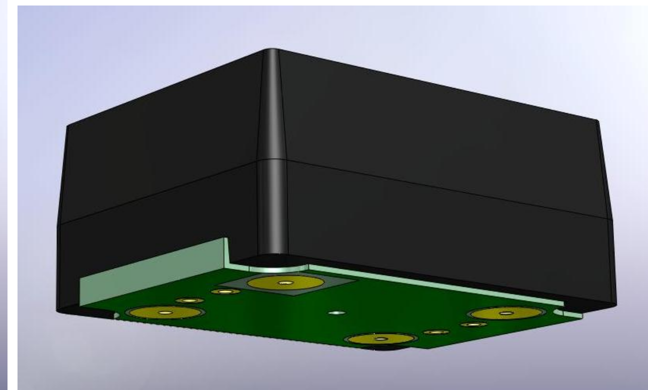
# TCOCXO - Mercury ASIC

- Fully integrated into one ASIC, “Mercury”
  - Oscillator, compensation, heater, and oven control circuitry
- Fully controllable oven features:
  - The oven set point temperature.
    - Individually match to the AT-cut crystal turnover temperature.
  - The thermal gain and the current limit during warm-up
  - Power control so that supply voltage change does not change the oven temperature.
    - Improved frequency vs. supply stability
- Optimised compensation for OCXO application
  - Second order compensation centred on turnover temperature.
- Good VCXO linearity < 0.5%

# Mercury TCOCXO Assembly

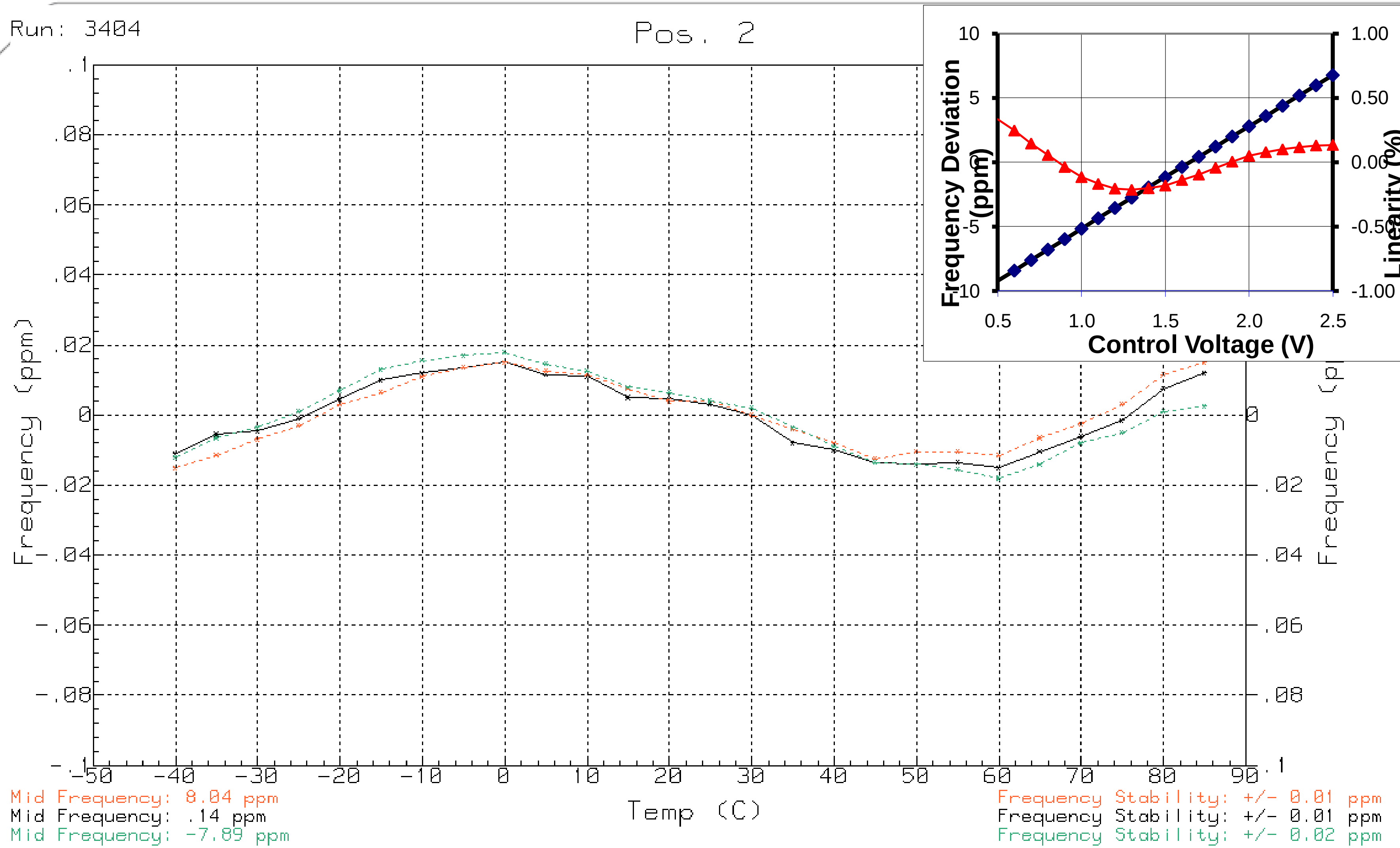






- Small size, especially height, of internal oven block allows improved performance in established outlines or further size reduction to 9.5x7.5x4.1mm.
  - Power consumption ~250 mW @ room temperature

# TCOCXO - Mercury

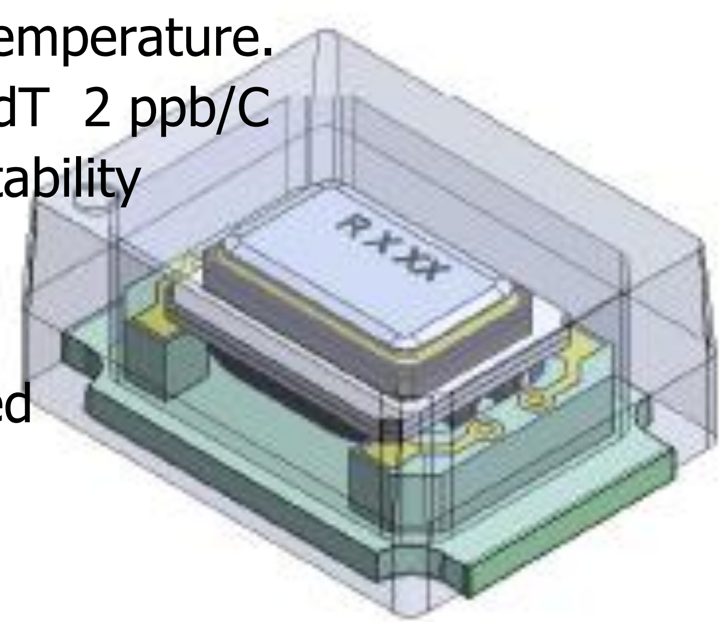



Typically < ±20 ppb -40/85C, including +/- 7ppm pulling. dF/dT ~ 1.5 ppb/C

# TCOCXO - Mercury

rakon

- Low cost high performance OCXO
  - Single integrated ASIC - Low component count - Higher reliability
  - Simple construction -- Automated assembly
  - AT-cut strip crystal -- miniature low cost crystal
  - Compensation and control -- high performance
- Very good stability
  - Frequency variation 20 ppb over temperature.
  - Frequency temperature slope, dF/dT 2 ppb/C
  - Leads to excellent medium term stability
- Smallest OCXO
  - < 0.3 cc volume
  - Very low height < 4.5 mm mounted
  - 9.5 by 7.5 mm footprint



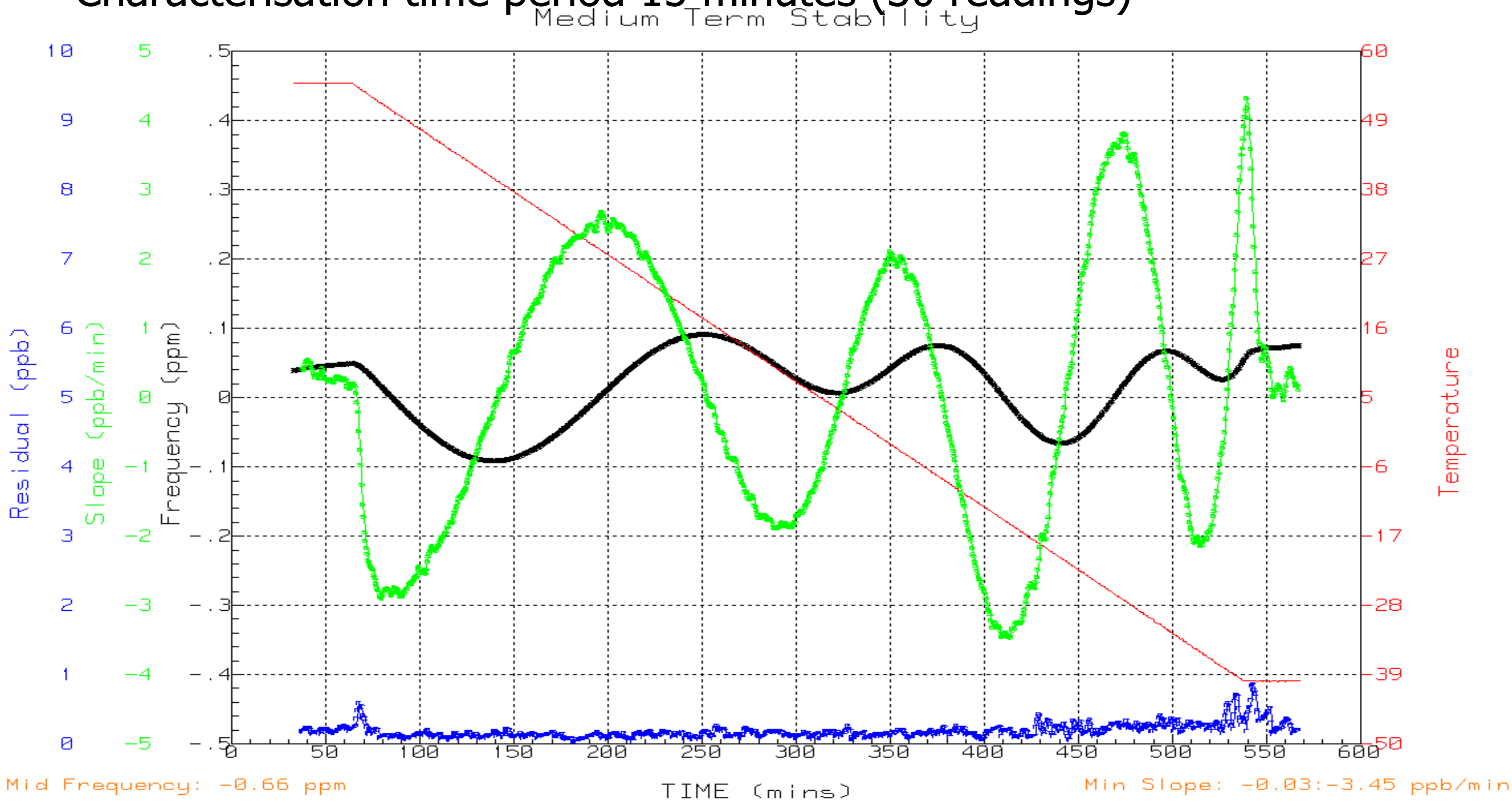
# Characterisation – Medium Term

- A measure of the stability over the characteristic time period corresponding to the synchronisation loop.
- Can be roughly estimated for small temperature changes
  - Frequency change with time, dF/dt = dF/dT * dT/dt
- Directly measure stability under variable temperature conditions
  - Under a defined temperature ramp rate.
  - At a measurement rate sufficient to accurately characterise the average frequency variation rate and noise within time period of interest.
- Example measures:
  - The average rate of frequency change with time over the characteristic time period.
  - The residual error about this average value.

# Medium term characterisation

TCXO example:  Ramp rate 0.2C/min, measurement rate 2 per min

Characterisation time period 15 minutes (30 readings)




Maximum slope  4.34 ppb/min

Maximum Residual  0.87 ppb

# Conclusion

- The medium term stability needs to be determined over the respective synchronisation loop time period.
  - Simple estimate from knowledge of dF/dT
  - Full characterisation from
    - Defined temperature ramp and measurement rate
    - Detailed analysis over the characterisation time period
- a TCXO can perform very well given:
  - Good design with linear temperature independent pulling
  - The correct characterisation
  - and if necessary environmental protection
- For higher performance, an OCXO is required
  - The TCOCXO gives OCXO performance without the usual size and cost penalty.  As with Rakon's "Triton" product range.
  - Further optimised with the fully integrated solution, "Mercury".