

Oscillator specification and performance testing for tomorrow's sync architecture

ITSF12
Dr Nigel Hardy

- › The sync architecture of today's telecom network is rapidly evolving in response to demands for higher bandwidth, lower cost and the need for time and frequency synchronisation. This is especially true at the rapidly expanding edge network, with LTE rollout and Small Cells playing an important role in expanding the capacity of wireless networks. This imposes particular demands on the local oscillator, usually in terms of longer loop time constants which amplify its sensitivity to environmental effects.
- › Apart from holdover (where the oscillator dominates the stability of the system), it is the oscillator, control loop and reference signal or signals combined, which define the system performance. So to understand the stability effects of the oscillator on the whole system we must attempt to assess the oscillator as it would be in the system.

Oscillator Assessment Testing

- › Measurement requires continuous Phase information.
 - We take continuous frequency measurements
 - Counter takes time stamps internally and converts to frequency.
 - Frequency expressed as fractional frequency offset(ffo), in parts (ppb etc)
 - continuous ffo information converted to Phase

- › A lot of specifications reference requirements under:
 - 'Constant Temperature'
 - 'Variable Temperature'

- › But what does this actually mean?



What is Constant Temperature?

› GR-1244-CORE issue 4:

Note that in the “constant temperature” cases, Telcordia considers $\pm 5^{\circ}\text{F}$ ($\pm 2.8^{\circ}\text{C}$) to be a reasonable limit for the ambient temperature changes that occur during a test measurement interval. On the other hand, this resulting window may be anywhere within the specified operating temperature range for the equipment (e.g., equipment

› ITU, ETSI etc +/-1K

- To hold to this temperature stability then a temperature controlled chamber is required, which usually implies in practice nearer +/-0.1K.

› Dilemma, What do you test?

- Hold the temperature constant, $\sim \pm 0.1\text{C}$
- Or do you force the temperature to move +/-1C or +/-2.8C
 - and if so at what rate, how often???

› Most specifications are looking for the result without the influence of temperature variation. So if small temperature movements do have an effect, the temperature should be held constant.

› Constant temperature applies anywhere in temperature range

- Test at room and temperature extremes

What is Variable temperature?

› Requires information on:-

- Temperature Range
- Rate of change of temperature with time
- Temperature change profile

› Standards:-

- For example ETSI EN 300 019-1-3 V2.3.2 Environmental conditions and environmental tests for telecommunications equipment. Extracted from section 5.1 table 1:-

Class	3.1N	3.1E	3.2	3.3	3.4	3.5	3.6
	Temperature controlled	Temperature controlled	Partly temperature - controlled	Not Temperature controlled	3.3 + Sites with heat trap	3.3 + Sheltered	Control room
Low temp (C)	+5	-5	-5	-25	-40	-40	+15
High temp (C)	+40	+45	+45	+55	+70	+40	+30
Rate (C/min)	0.5	0.5	0.5	0.5	1.0	1.0	0.5

› No temperature Profile or thermal test regime(set of temperature profiles) defined.

› Airflow effects

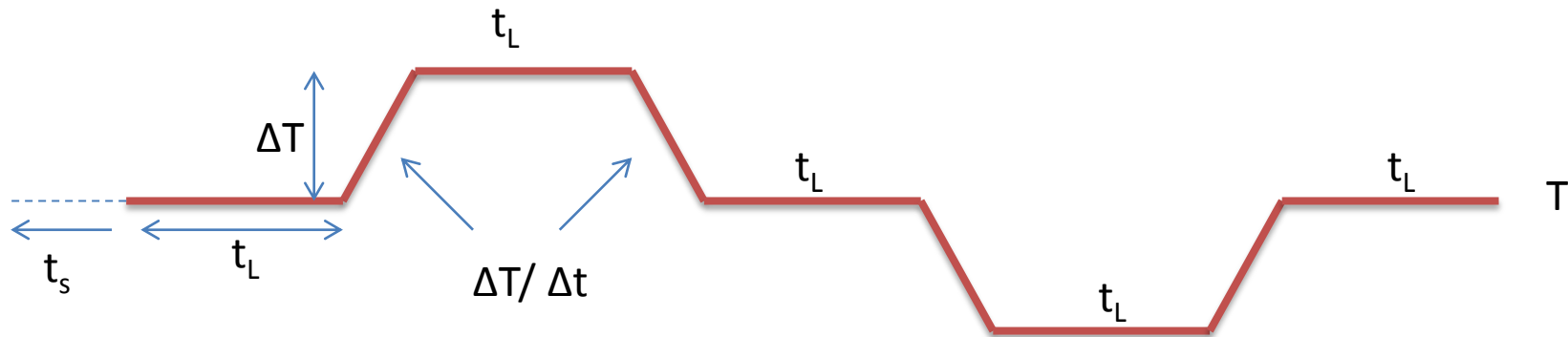
- A change in Airflow causes an apparent change in ambient temperature.

Thermal Test Regime

- › The long time constants now envisaged for some slave clocks, in association with variable temperature testing, cause problems which previously did not have to be addressed.
 - The longest loop time constants were previously associated with the stratum3E level and its 1 mHz wander filter bandwidth, which equates to a time constant of 160 seconds.
 - At 1C/min the stratum 3E time constant only equates to 2.7C,(~5F) little more than some definitions of constant temperature (GR1244).
 - However if the loop time constant is 5000 seconds then the temperature movement equates to **83C**, clearly far in excess of any actual observed movement during operation.
- › Manufacturers design and test systems over a wide temperature range to cover all possible uses
 - ambient temperature ranges and also internal equipment temperature rises
 - all uses are not simultaneous, each equipment is only used under one set of conditions at one time.
 - Hot or cold country, summer or winter, inside or outside, temperature controlled etc..

Thermal Test Regime

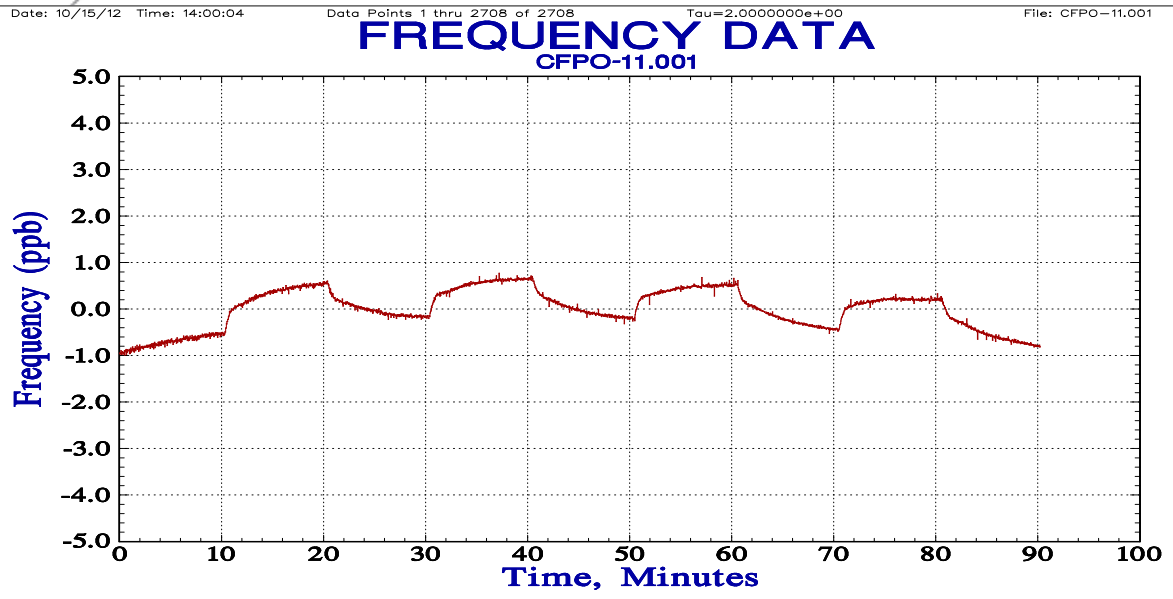
- › The problem comes down to one of establishing a test methodology or regime which covers the required temperature range without involving an onerous amount of test variations. The test methodology should also still allow the system specifications to dictate the minimum and maximum temperatures and rates of change etc.
- › A temperature profile of the type shown below has been proposed



- › Where t_s is the test stabilisation time, t_L is the time required for the loop to recover, ΔT is the maximum temperature excursion, $\Delta T / \Delta t$ is the ramp rate, and T is the test reference temperature.
- › Realistic value assigned to ΔT the maximum temperature excursion (~15 to 20C for example). This Profile can be run several times to cover the whole temperature range
 - conducted at room temperature and the temperature extremes.

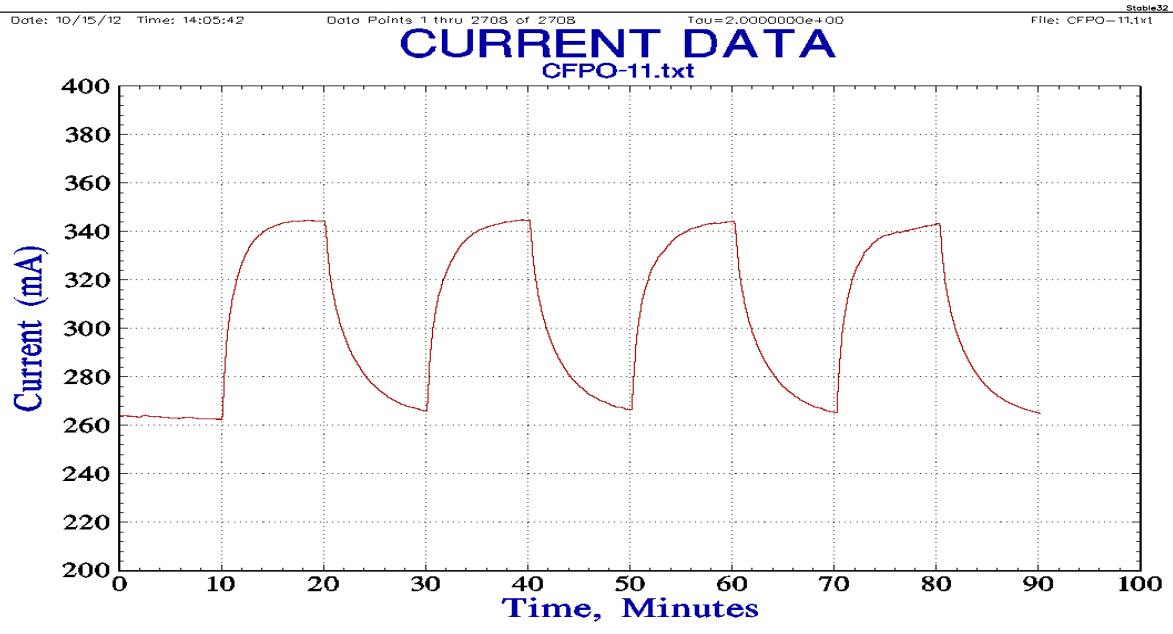
- › For any oscillator airflow has an impact, but especially for any OCXO
- › OCXO internal circuitry reacts to heat loss rather than ambient temperature directly, so any change in the heat loss is equivalent to a change in ambient temperature (similar to the wind chill effect)
- › In operation: Airflow is determined by cooling fans.
 - On/off fans present the worse case, Variable speed less so.
- › During test: the test chamber is normally designed for very high airflow, as it is has to force a temperature on the equipment. Imposing this airflow directly on the OCXO will cause the apparent temperature range to be significantly extended, at the low end.
 - -40C at low airflow can easily look like -65C or lower at high airflow.

Airflow Stratum 3E OCXO



SMD: 25*22*12 mm
Volume: 6.6 cm³
Stratum 3E OCXO
+/-5ppb -40/85C:-
Crystal: SC-Cut, Third Overtone

Airflow varied from 0 to 1m/s,
10 minutes off followed by 10
minutes on.



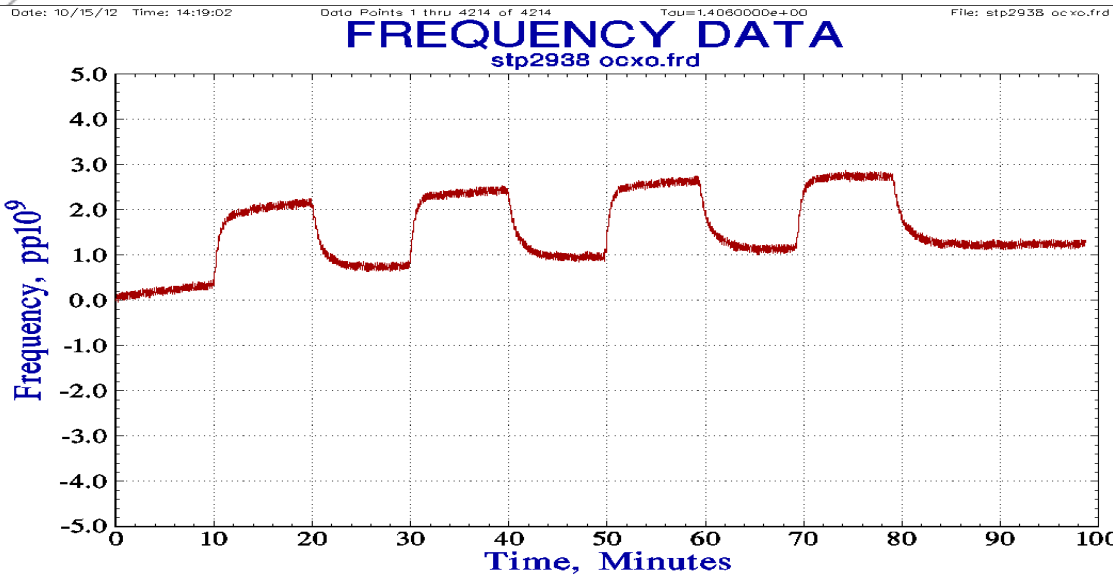
Change in frequency 0.9ppb

Change in current 80mA
Equivalent to ambient
temperature change of

~24°C!

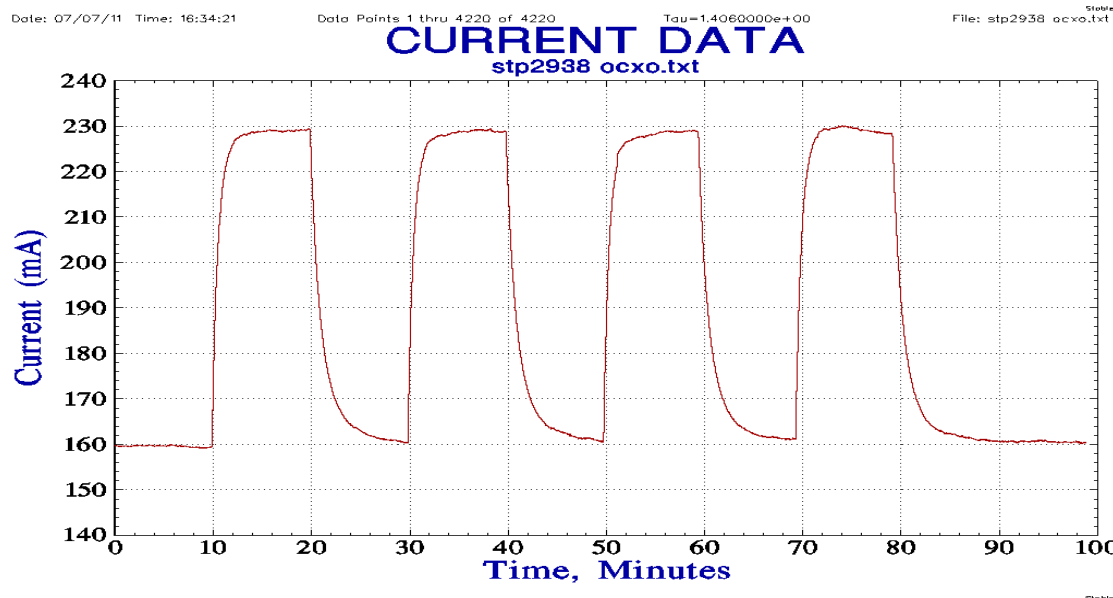
Airflow Stratum3e DIL type OCXO

rakon



DIL: 21*13*13 mm
Volume: 3.55 cm³
Stratum 3E Mini OCXO
+/-10ppb -40/85C:-
Crystal: SC-Cut, Third Overtone

Airflow varied from 0 to 1m/s,
10 minutes off followed by 10
minutes on.

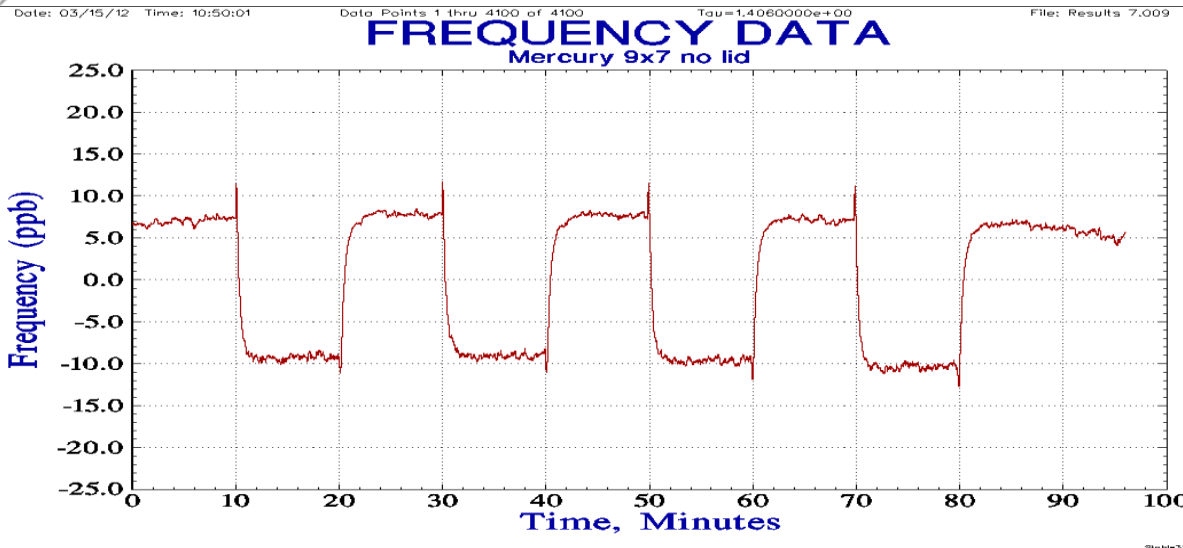


Change in frequency 1.7ppb

Change in current 70mA
Equivalent to ambient
temperature change of

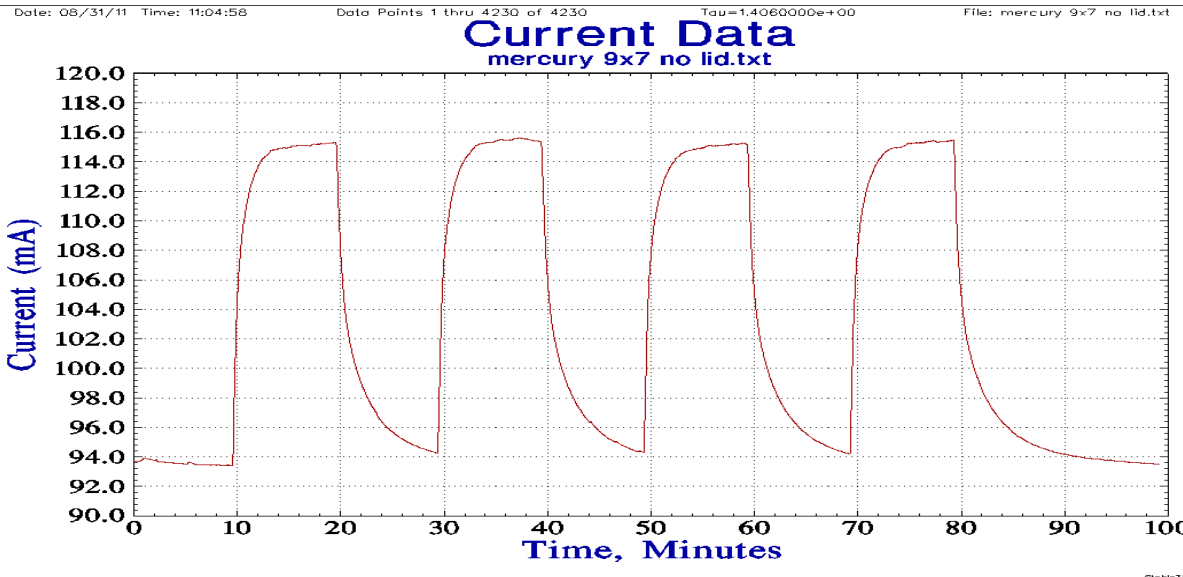
~30°C!

Airflow Miniature TCOCXO, 9x7



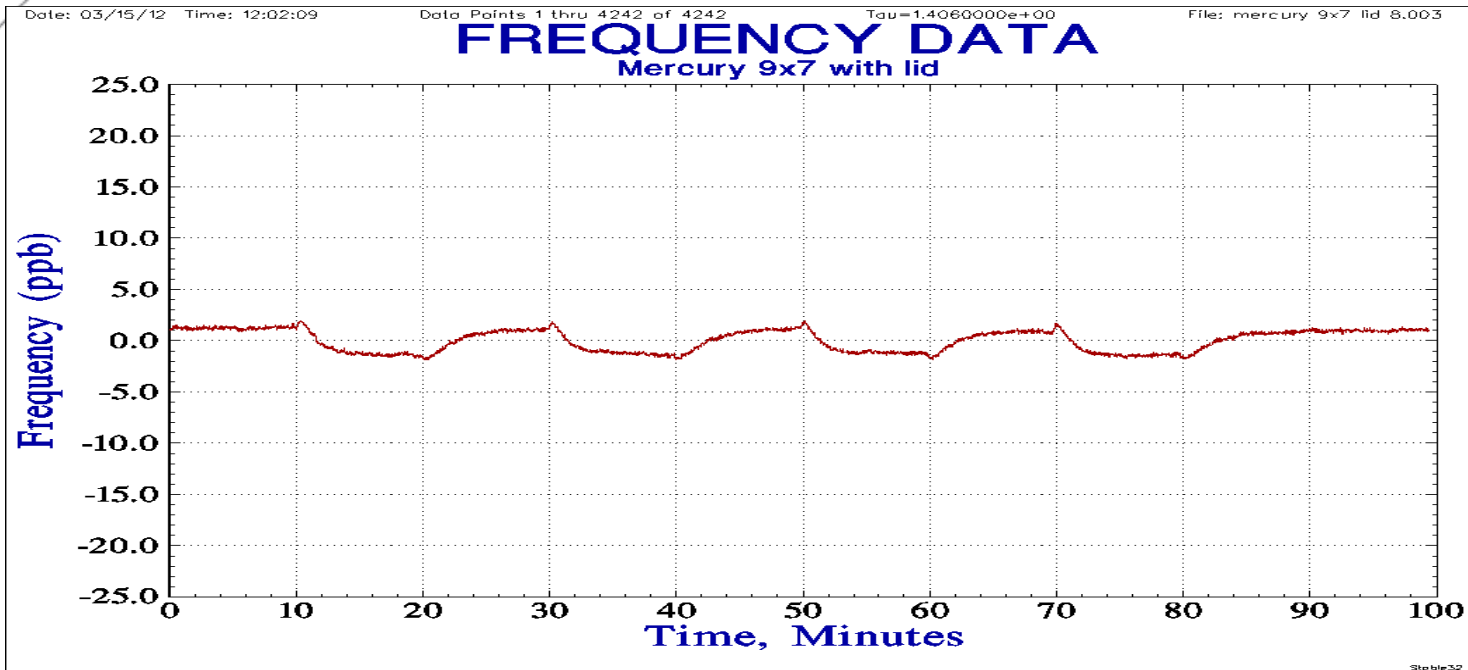
SMD: 9.5*7.5*4.5 mm
Volume: 0.32 cm³
Miniature TCOCXO
+/-25ppb -40/85C
Crystal: AT-Cut Fundamental

Airflow varied from 0 to 1m/s, 10 minutes off followed by 10 minutes on.



Change in frequency 17ppb
Change in current 22mA
Equivalent to ambient temperature change of **~17°C!**

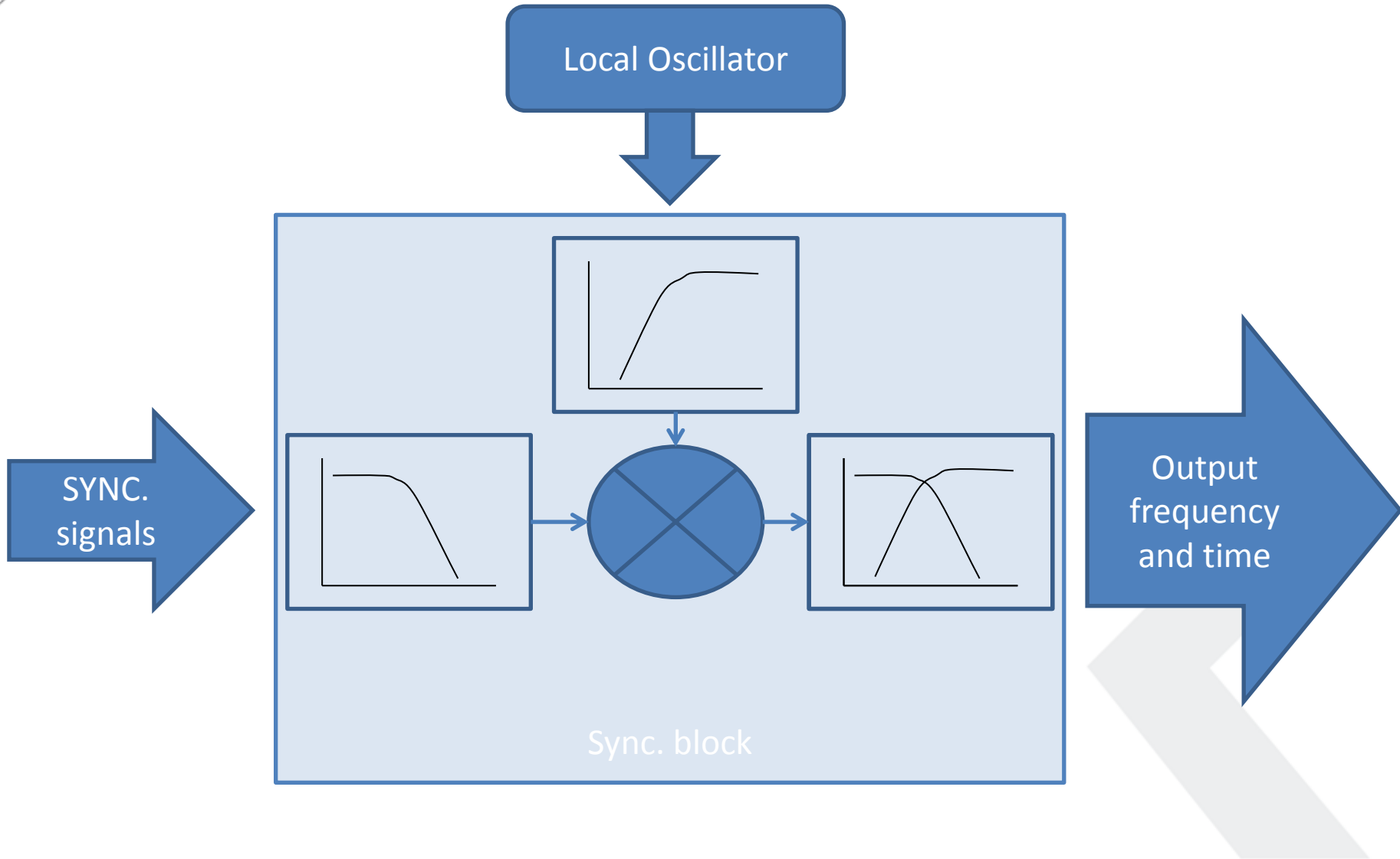
Miniature 9x7 with Lid



- › Smaller the volume the greater the effect.
 - Less insulation and less thermal mass
- › Miniature OCXO + Lid then \sim same magnitude as OCXO



Simplified Sync. System Schematic





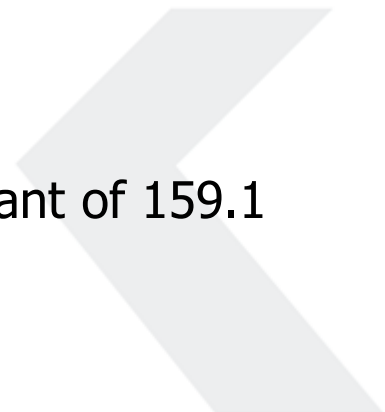
Loop Analysis

- › Loop type
 - Sonet/SDH or SyncE, Phase lock loop.
 - IEEE1588 or NTP, Clock recovery algorithm(servo)
 - SyncE assisted 1588, combination of Phase lock loop and Clock recovery algorithm.
- › But still has to follow some basic characteristics
 - Combines the Contribution from local oscillator and reference signal
 - Follows sync signal in the long term and local oscillator in the short term.
 - Presents Low pass filter to sync. Signal
 - Therefore imposes the equivalent High pass filter on local oscillator

- › Relationship between Loop bandwidth and loop time constant:-

$$\tau = \frac{1}{2\pi f}$$

- › 1 mHz loop bandwidth is equivalent to a loop time constant of 159.1 seconds



Filter function characteristics

- › One Traditional low pass filter model is defined in G.8251 section VIII.2.2
 - Second-order, low-pass filter with gain peaking and 20dB/decade roll-off. Eq VIII.2-6

ω_n – Is the undamped natural frequency

ζ – Is the damping ratio

$$H_L(s) = \frac{2\zeta\omega_n s + \omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

- › Therefore equivalent high pass filter

$$H_H(s) = 1 - H_L(s) = \frac{s^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

Simplified Approximation

› 20dB/decade is characteristic of first order filter: $H(s) = \frac{s}{s + \omega_n}$

› First order filter is easy to implement on series of samples: (e.g. high-pass filter – Wikipedia)

- // Return RC high-pass filter output samples, given input samples,
- // time interval dt , and time constant RC
- **function** highpass(*real*[0..n] x, *real* dt, *real* RC)
- **var** *real*[0..n] y
- **var** *real* a := RC / (RC + dt)
- y[0] := x[0]
- **for** i **from** 1 **to** n
- y[i] := a * y[i-1] + a * (x[i] - x[i-1])
- **return** y

› Create second order by concatenating two first order filters

$$H(s) = H_1(s) \cdot H_2(s) = \frac{s}{s + \omega_{n1}} \cdot \frac{s}{s + \omega_{n2}}$$

Filter function comparison

$$H(s) := \frac{s^2}{(s^2 + 2 \cdot \zeta \cdot \omega_n \cdot s + \omega_n^2)}$$

$$\zeta := 2.95845$$

$$f_{3dB} := 0.001$$

$$Hf2(s) := H1(s) \cdot H2(s)$$

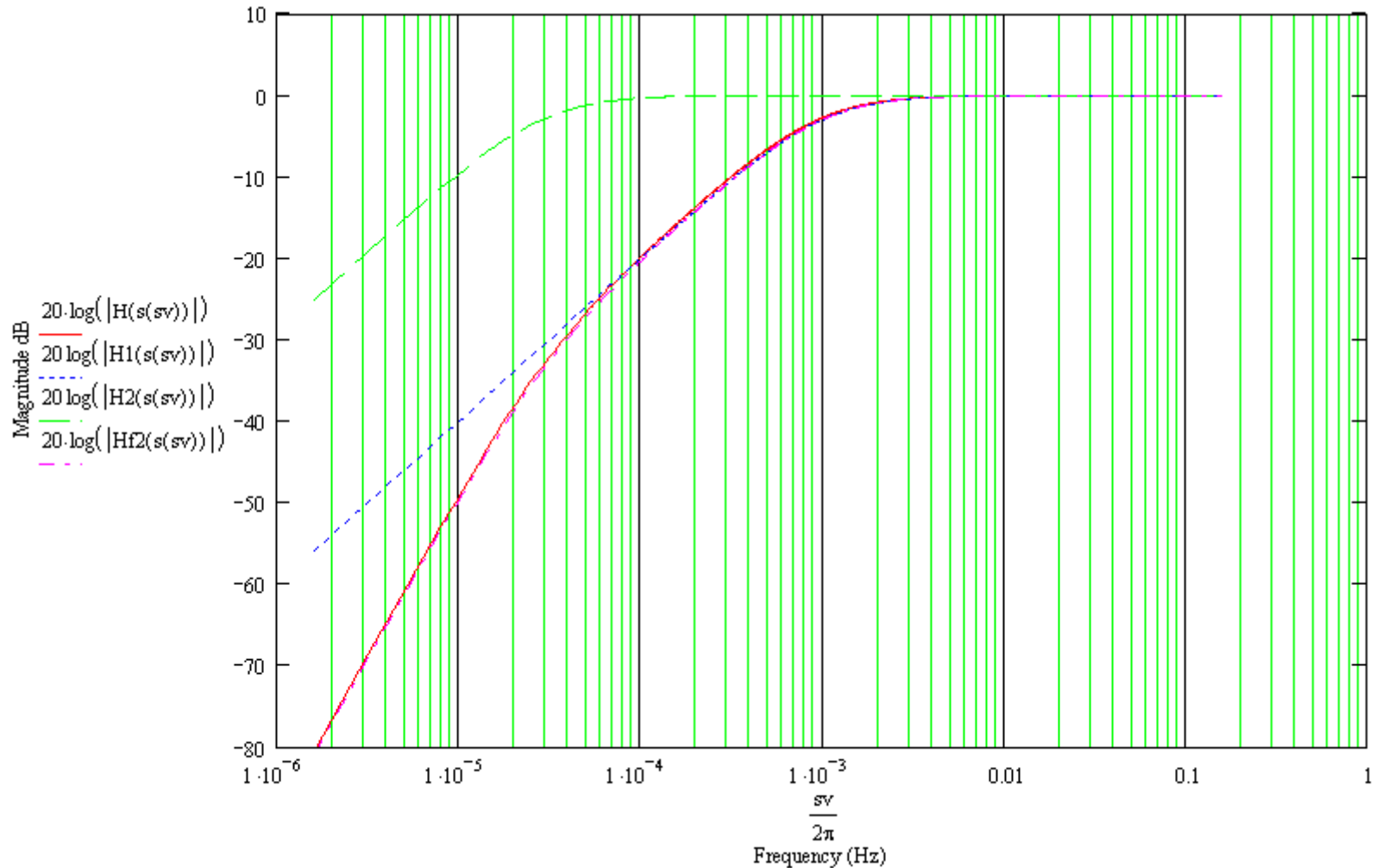
$$H1(s) := \frac{s}{s + \omega_1}$$

$$H2(s) := \frac{s}{s + \omega_2}$$

$$f_1 := 0.001$$

$$f_2 := \frac{f_1}{\text{mult}}$$

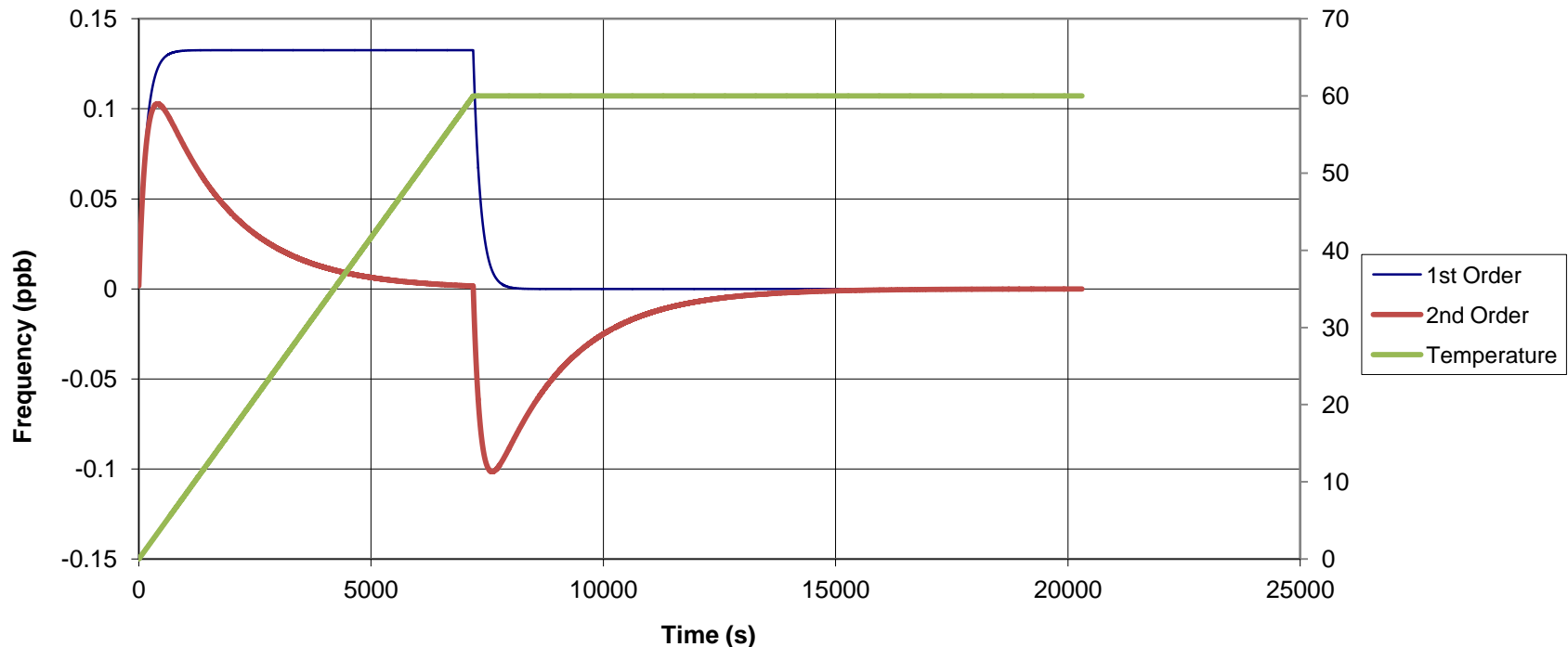
$$\text{mult} := 35$$



Linear frequency Drift

- Linear frequency drift either from aging or linear temperature change and linear frequency vs. temperature response.
 - i.e. 0.1 ppb/C frequency change with temperature, 0.5C/min temperature change, 60C limited excursion. 1MHz bandwidth, 159s first order time constant, 1591s second order time constant (6ppb total frequency movement)

Frequency: Locked 1st and 2nd order filter



Linear frequency drift

- › First order frequency error ~ 0.13 ppb
- › Second order phase error ~ 206 ns



First Order Loop response

› Response to frequency drift

- Results in constant frequency error and hence linearly increasing time error
- First order frequency error (lag) equal to

$$\Delta f = \tau \times \frac{df}{dt}$$

- Where τ is the loop time constant and df/dt is the rate of change of frequency with time.
- E.g. 1mHz loop with loop time constant of 159.1 seconds and a rate of change of frequency with time of 8.33×10^{-4} ppb/s ($0.1\{\text{ppb/C}\} \times 0.5\{\text{C/min}\} / 60$) frequency error of **0.13 ppb**

› **First order corrects for frequency error, does not correct for frequency drift.**

› **Linear increasing phase error when the frequency is moving and leaves a constant phase error when the frequency is stable**

2nd Order loop response

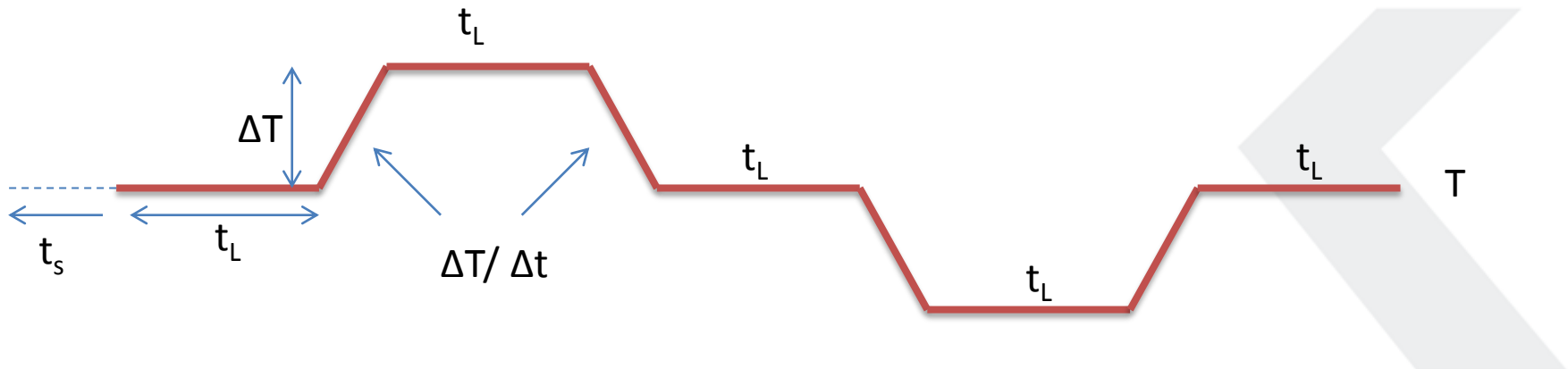
- › Response to frequency drift.
 - Zero frequency error, but constant phase error
 - Phase error

$$\Delta t \approx \Delta f \times \tau_2$$

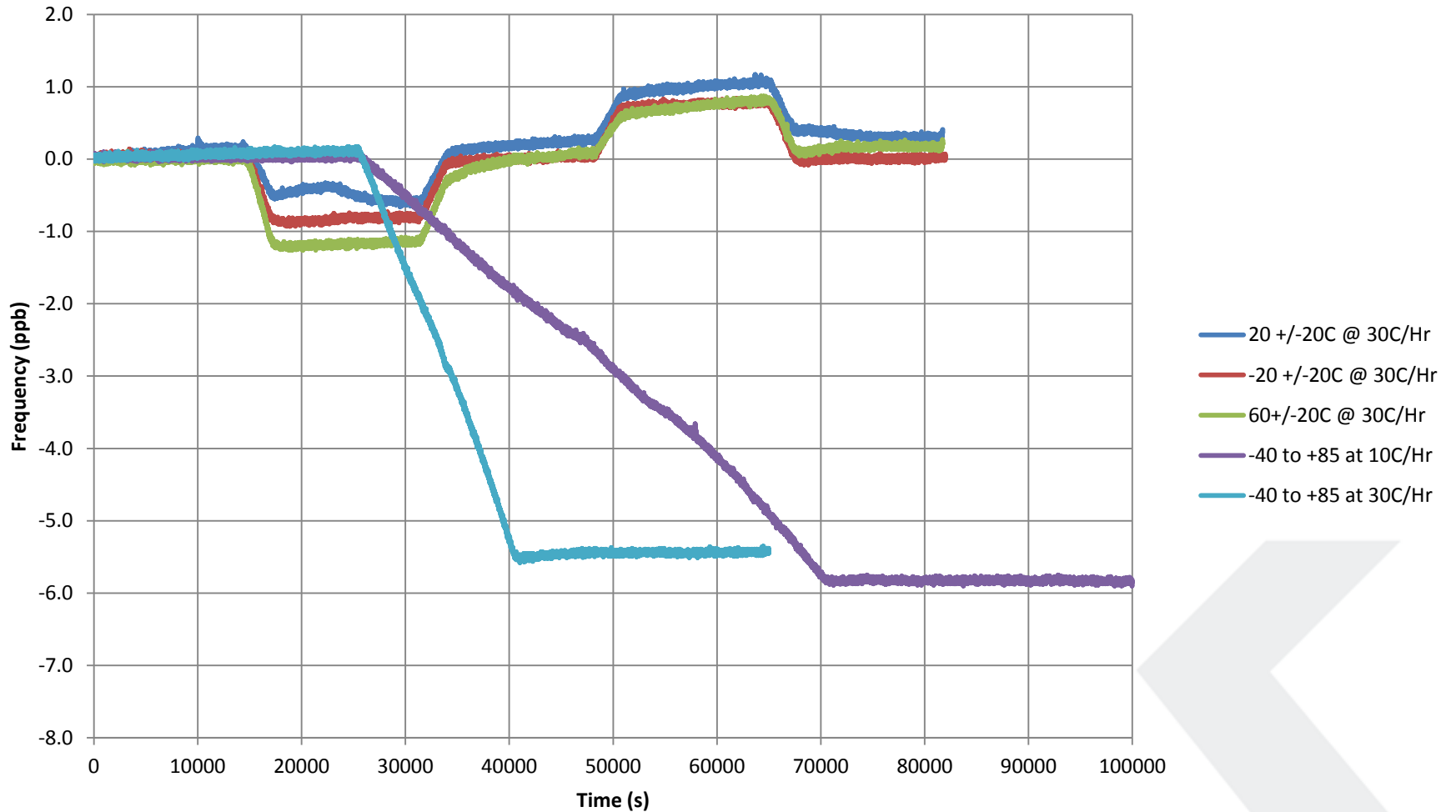
- 0.13 ppb first order error and 1591 second order time constant gives ~ 207 ns error.
- › **Second order corrects for frequency drift**
- › **Constant phase error when frequency is moving, reduces phase error to zero when frequency stable, but has to create frequency error to do this.**

Example Results

- › Stratum 3E OCXO, $\sim \pm 3\text{ppb}$ (6ppb peak to peak) over -40 to 85C
- › Measured with 5 temperature profiles:
 - -40 to 85 @ 30C/Hr, (7Hr -40C, ramp to 85C @ 30C/Hr, 7Hr 85C)
 - -40 to 85 @ 10C/Hr, (7Hr -40C, ramp to 85C @ 10C/Hr, 7Hr 85C)
 - -20 +/-20C @ 30C/Hr, ($T=-20\text{C}, t_L=4\text{Hrs}, \Delta T=20\text{C}, \Delta T/\Delta t=30\text{C/Hr}$)
 - 20 +/-20C @ 30C/Hr, ($T=20\text{C}, t_L=4\text{Hrs}, \Delta T=20\text{C}, \Delta T/\Delta t=30\text{C/Hr}$)
 - 60 +/-20C @ 30C/Hr, ($T=60\text{C}, t_L=4\text{Hrs}, \Delta T=20\text{C}, \Delta T/\Delta t=30\text{C/Hr}$)
- › Analysed with 0.3mHz first order and 0.03mHz second order.

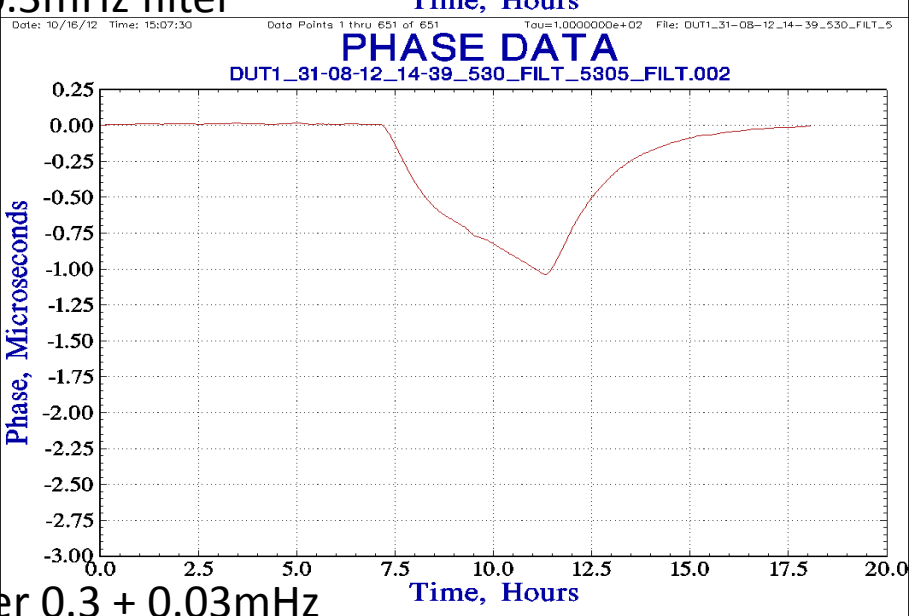
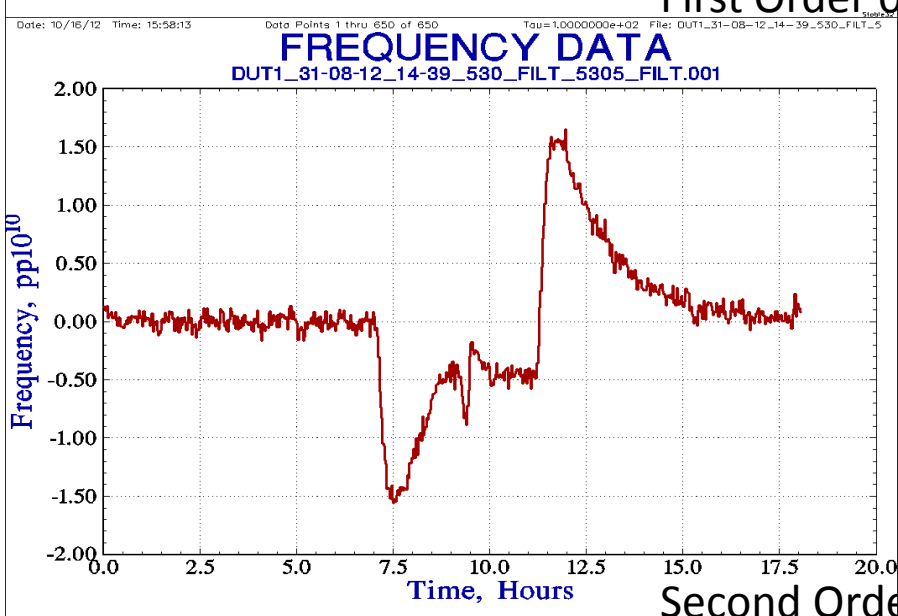
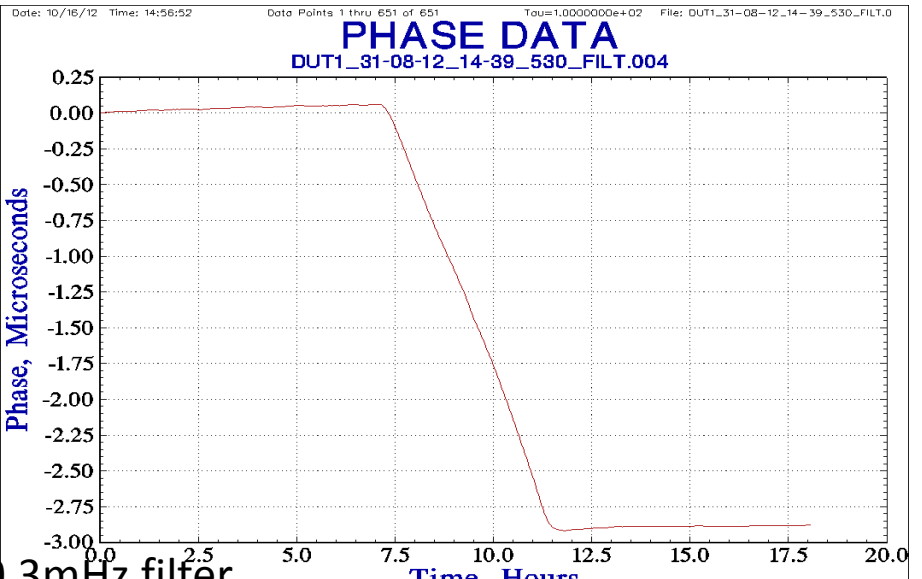
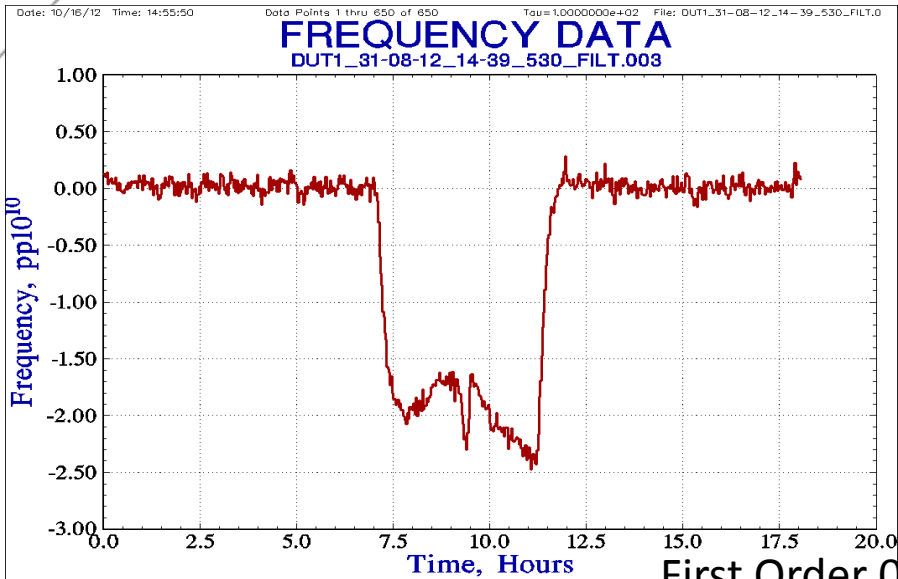


Stratum 3E OCXO raw data



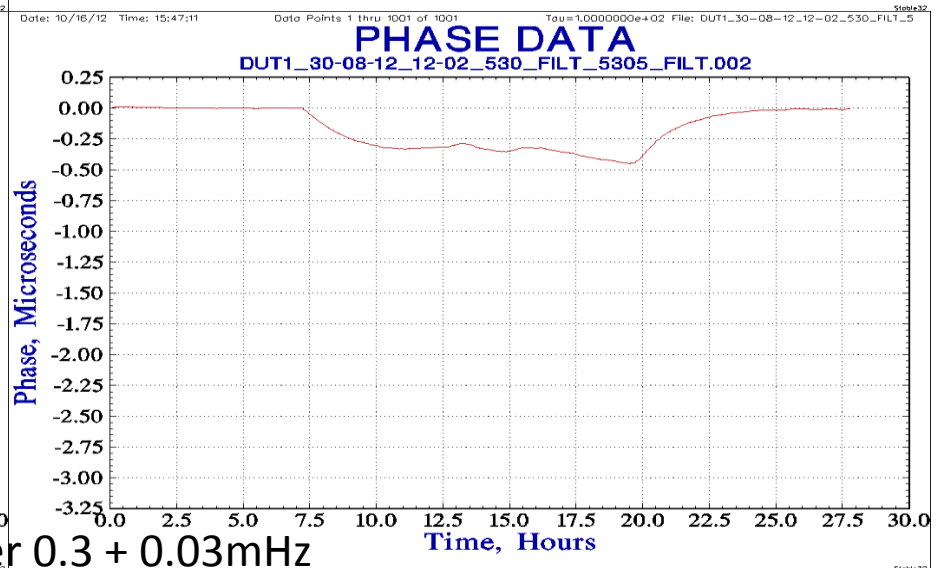
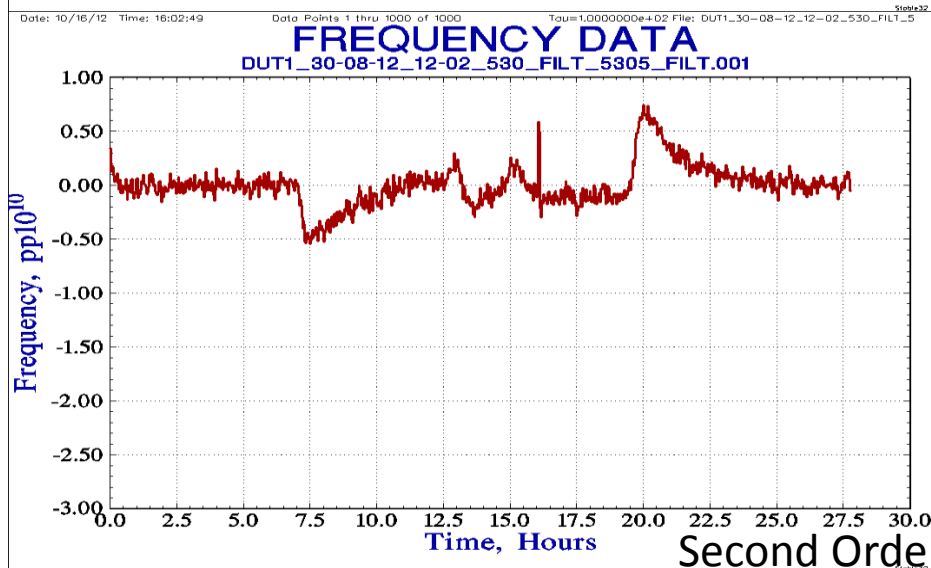
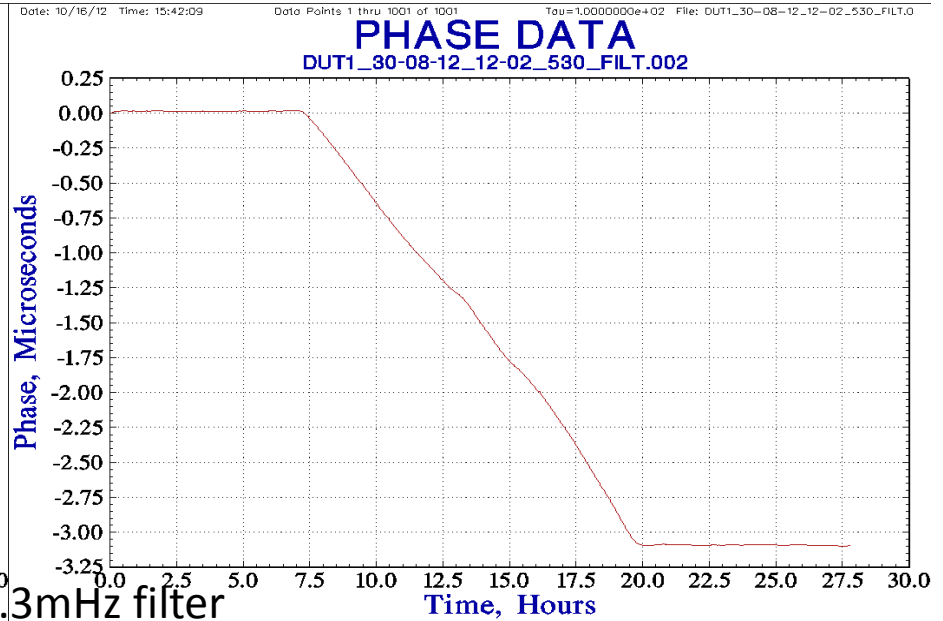
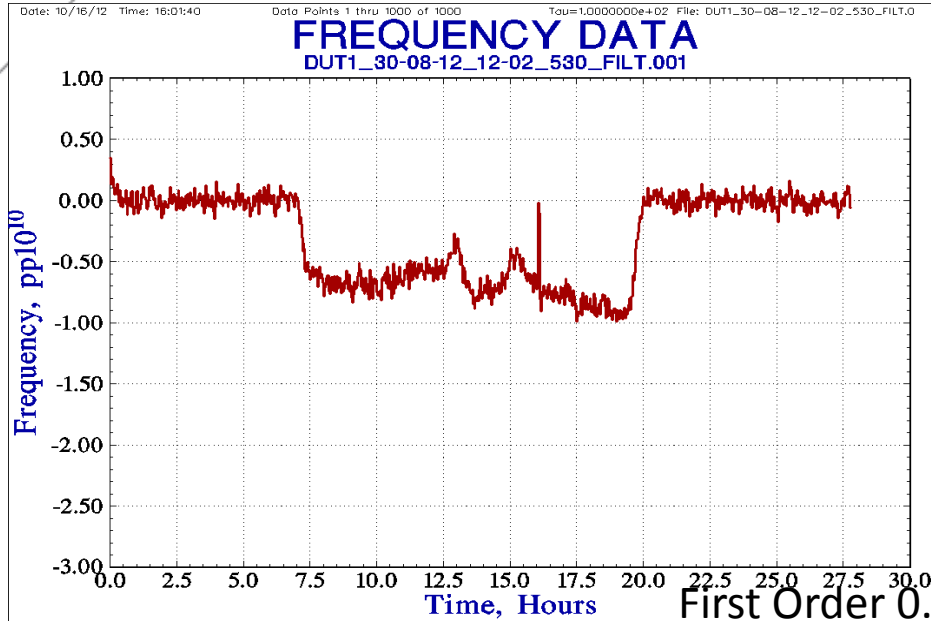


-40 to 85 @ 30C/Hr

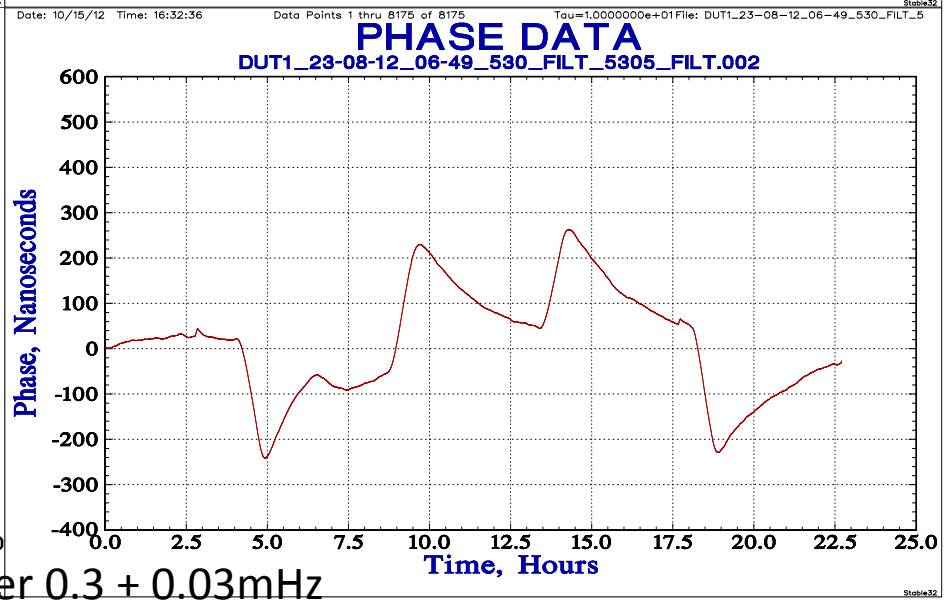
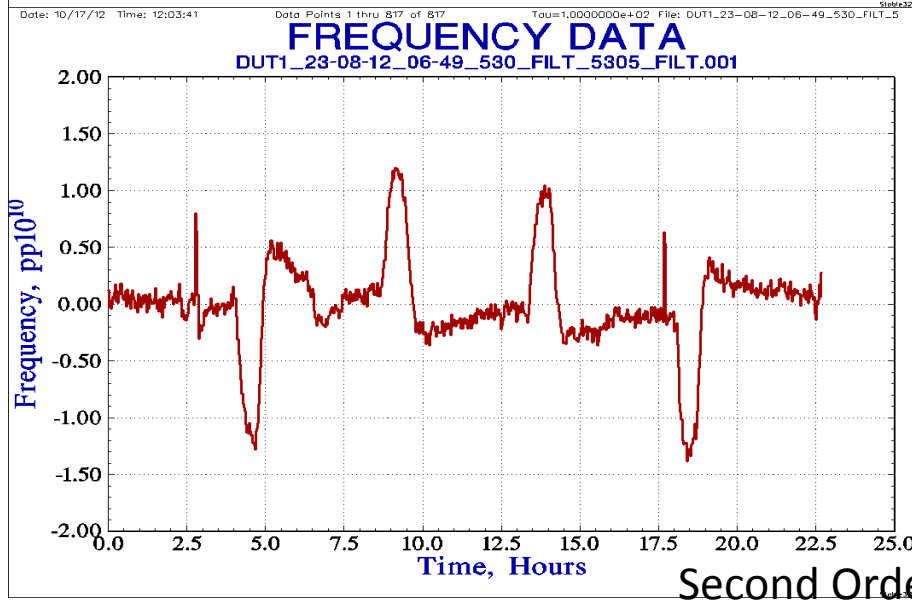
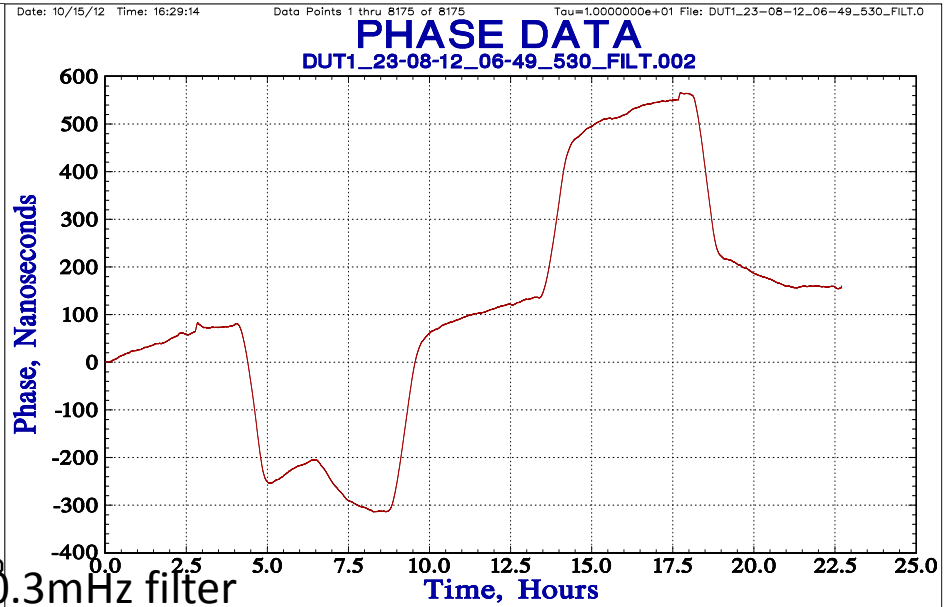
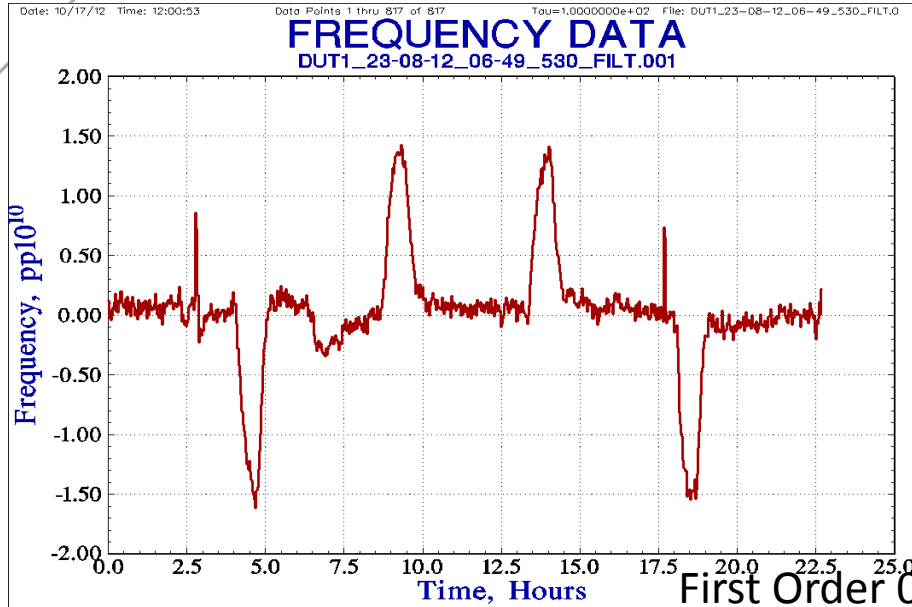




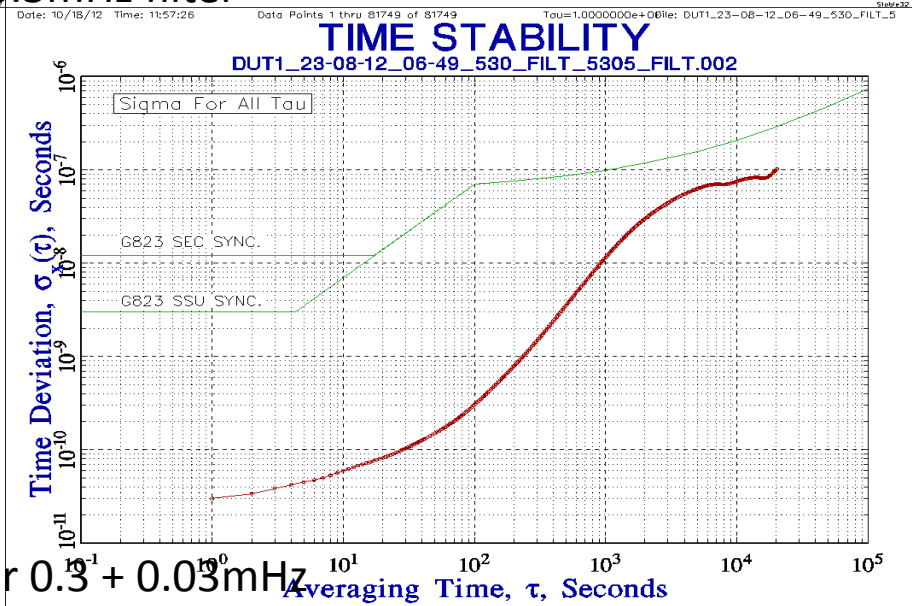
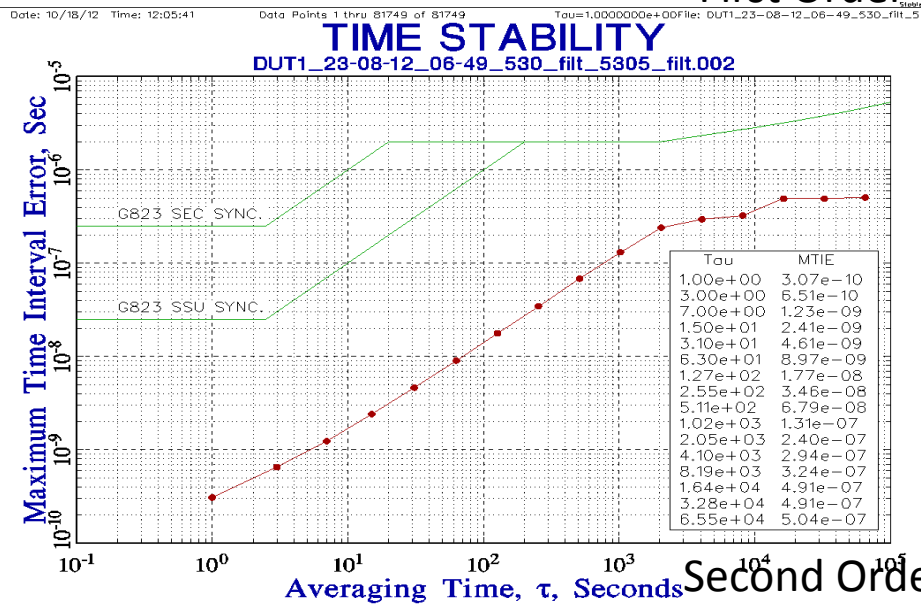
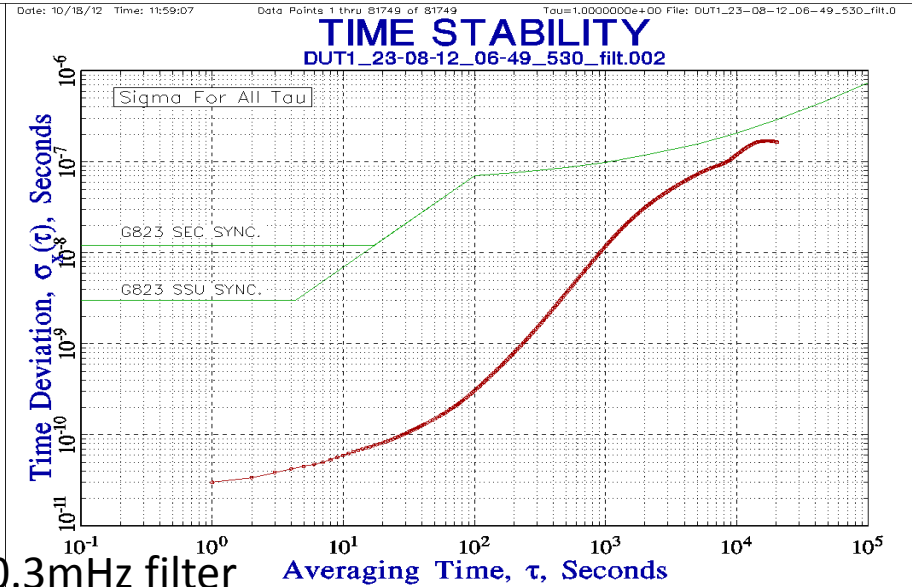
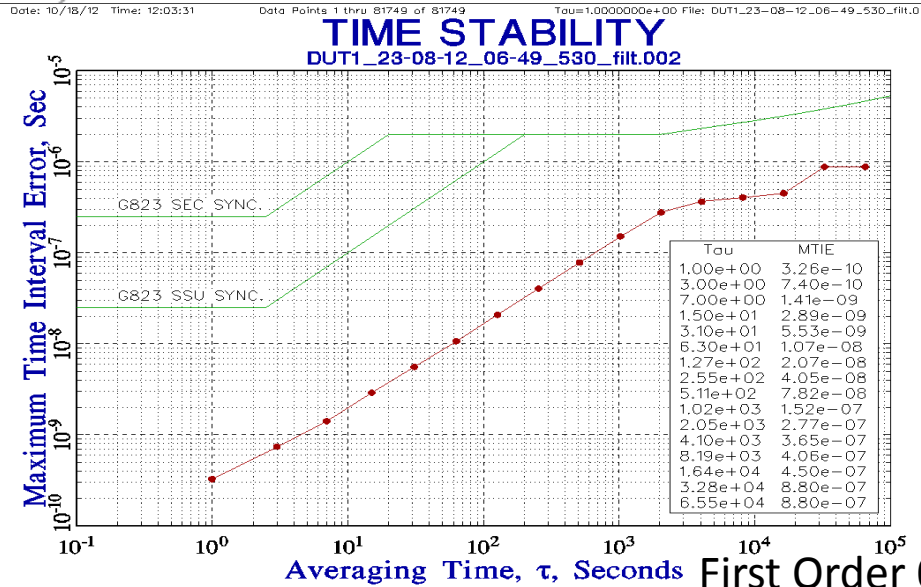
-40 to 85 @ 10C/Hr



20C+/-20C @ 30C/Hr



20C+/-20C @20C/Hr. MTIE & TDEV



← Requirements frequency and time sync.

- › For frequency synchronisation over longer loop time constants and more importantly for time sync., requires better oscillators:-
 - with lower frequency vs. temperature variation over the time period of interest. Determined by the loop time constants (1st and 2nd order).
- › May be required to move up the stability ladder.
 - OCXO to double oven OCXO or *TC-OCXO*
 - Mini-OCXO to OCXO or *double oven mini-OCXO*
 - TCXO to Mini-OCXO or *Ultra-Mini OCXO*





TC-OCXO (ROX-3827-T3)

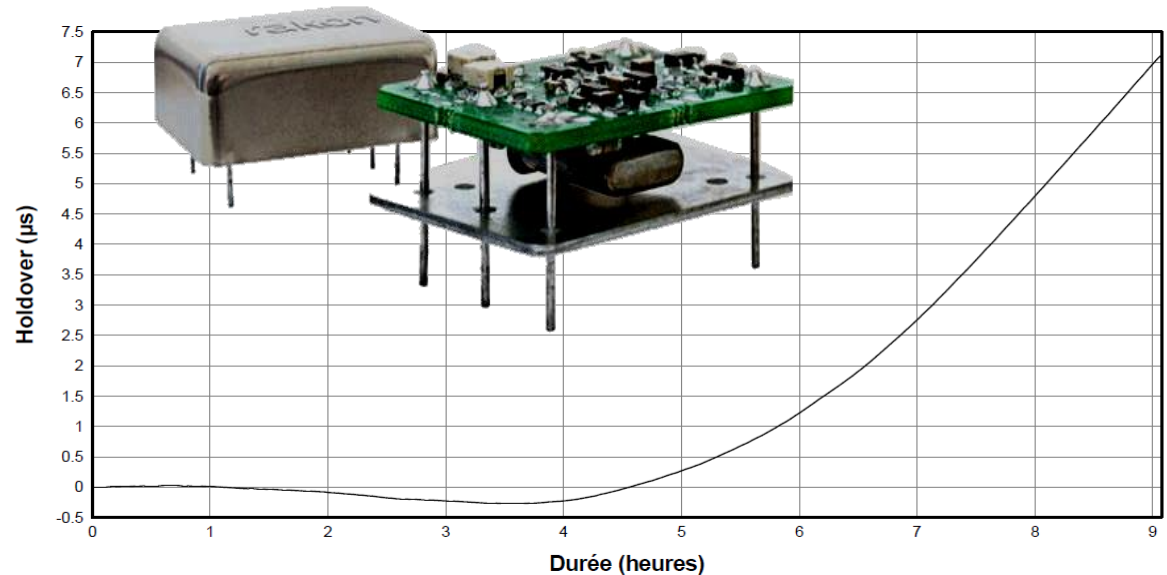
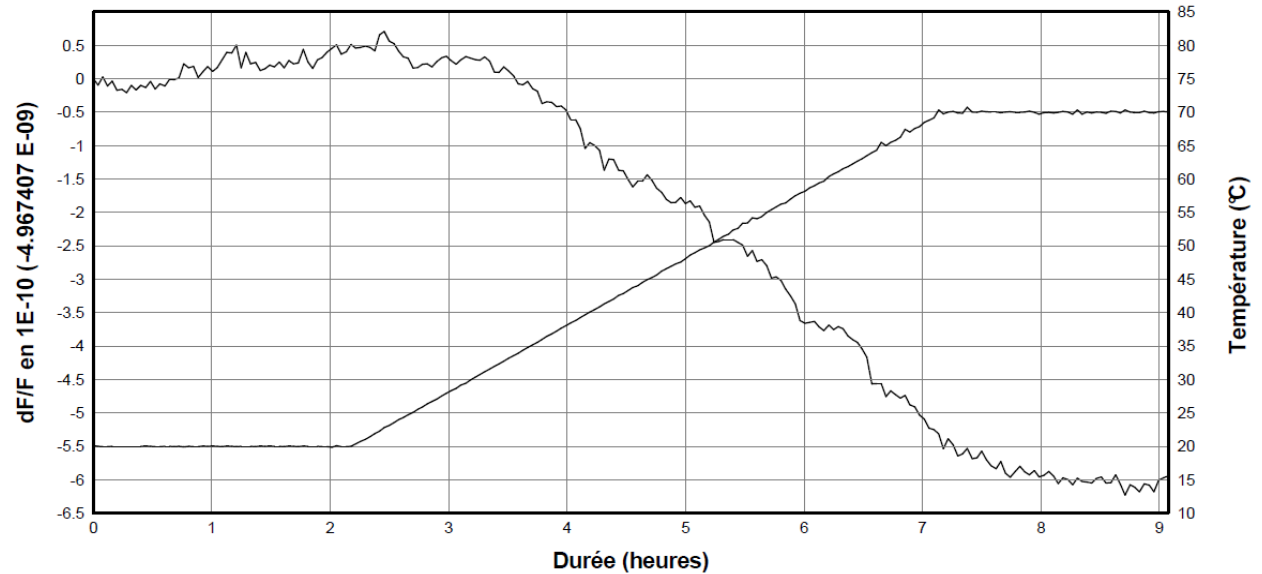
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Traditional SC-cut OCXO, with addition of ambient temperature frequency correction. TC-OCXO

Increases frequency stability: +/-5ppb to +/-1ppb.

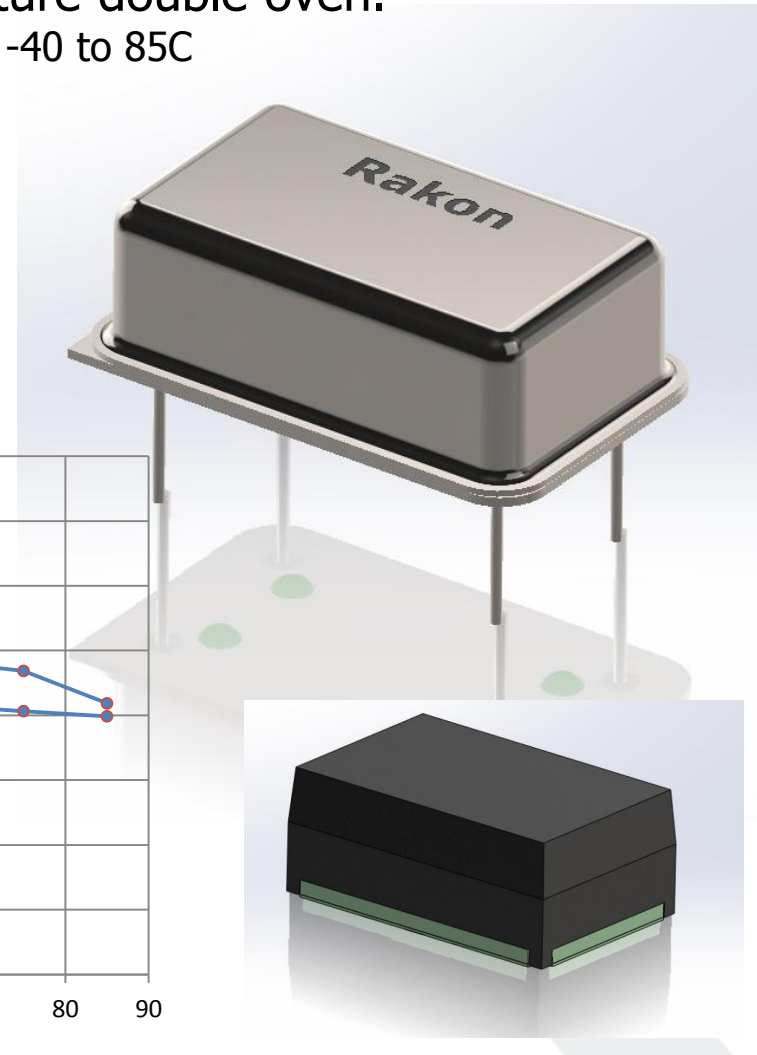
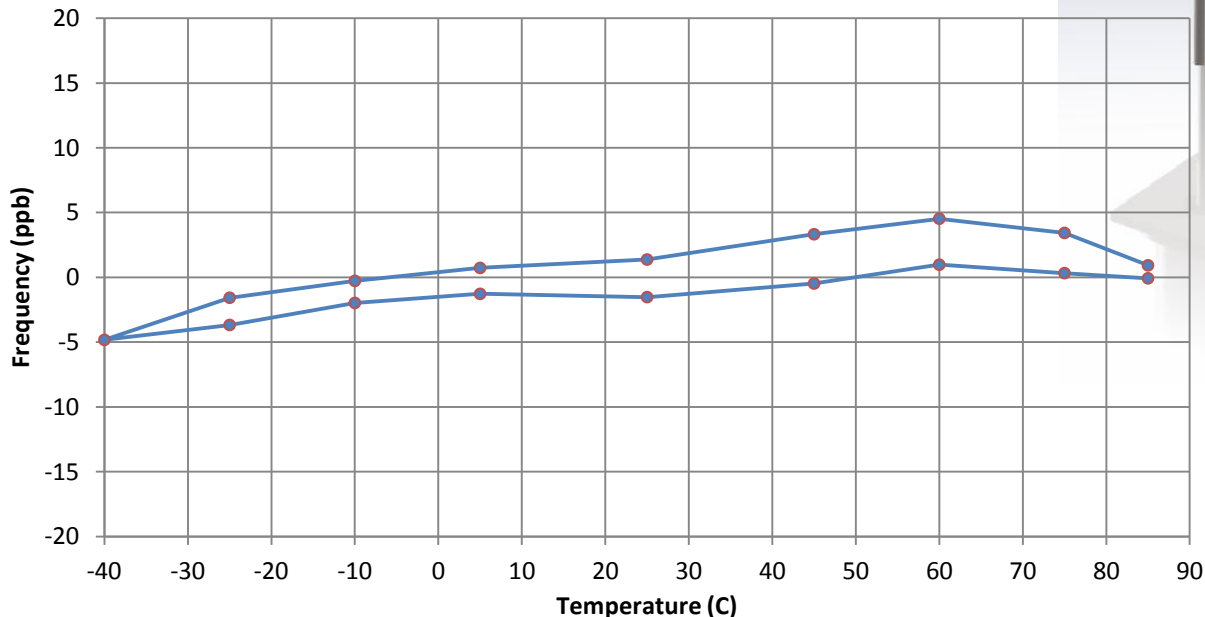
Decreases frequency temperature slope from 0.3ppb/C to 0.1ppb/C.

Allows time holdover of 8us for 8 Hrs, with 50C movement at 10C/Hr.



Miniature Double Oven

- › Integration of the TC-OCXO Oscillator functionality into single ASIC 'Mercury' allows the realisation of a miniature double oven.
 - +/-20ppb standard to +/-5ppb for double oven, -40 to 85C
 - 1ppb/C standard to 0.3 ppb/C for double oven.
 - More tolerant of airflow.
- › In Development
 - Leaded DIL 20*12*9, in trials
 - 14x9x6 SMD in development



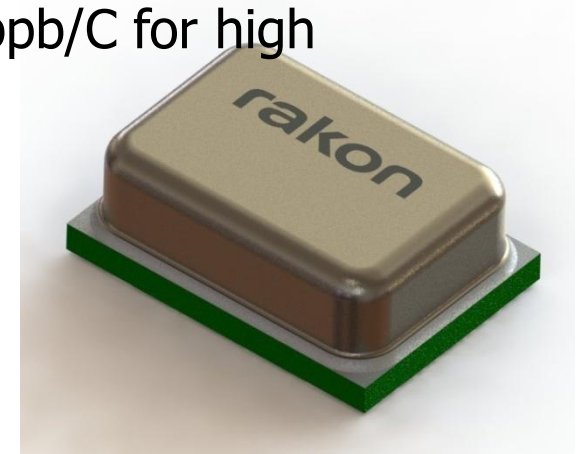
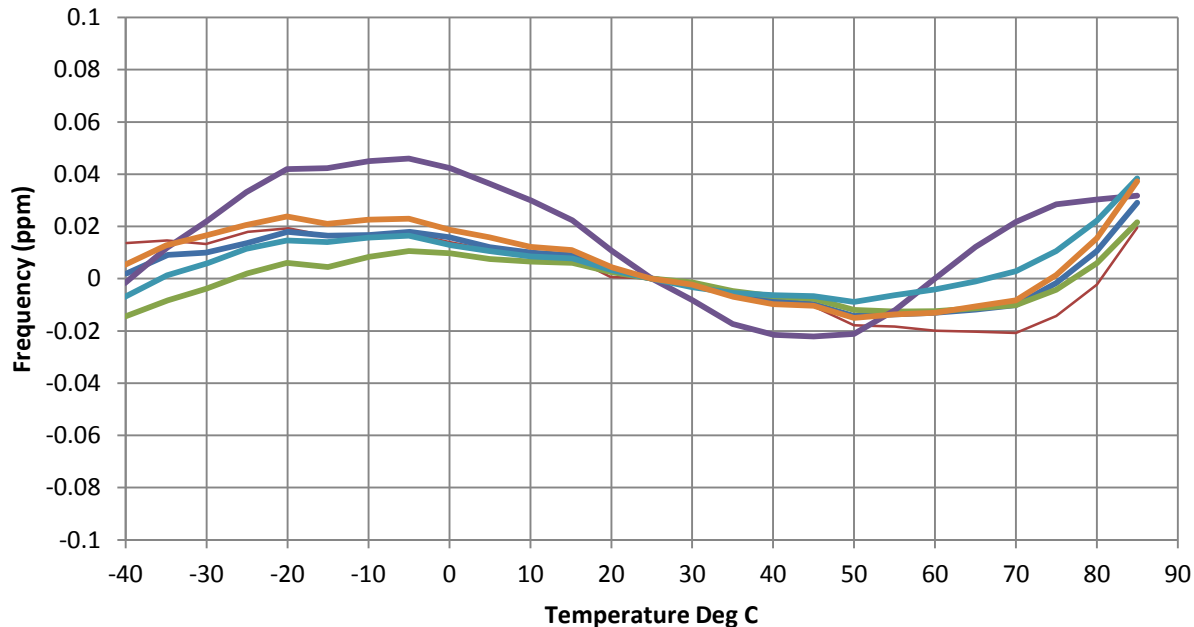
Ultra Mini TC-OCXO

rakon

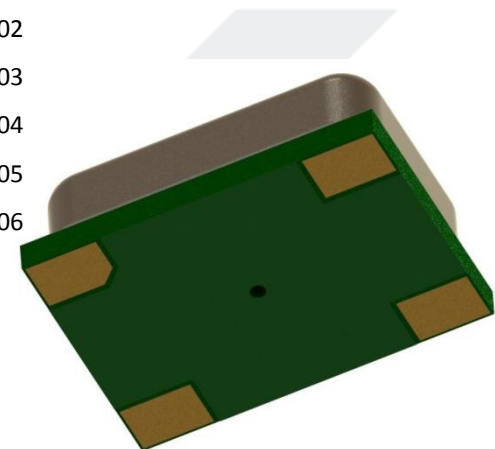
› In Development:

- Size 7x5x2.5mm equivalent to TCXO, with compatible footprint
- Slope 2 to 5 ppb/C as compared to 10 to 20 ppb/C for high stability TCXO
- Stability +/-50 to 100ppb, -40/85C

Mercury 7x5, 49.152MHz



- 01:01
- 01:02
- 01:03
- 01:04
- 01:05
- 01:06



Oscillator specification summary

- › Create Oscillators and Specifications targeted at requirements.
 - Most important parameter is rate of change of frequency with temperature over the period of the loop, loop time constant
 - 1st order for frequency and 2nd order for time.
 - Specification in terms of ppb/C averaged over a temperature range.
 - i.e. 0.5 ppb/C averaged over 5C
 - Traditional specifications do not address this e.g. Stratum 3E oscillator specification not ideal.
 - Designed for frequency synchronisation, wander filter \sim 1MHz bandwidth but
 - no slope spec in terms of ppb/C, assumes linear frequency vs. temperature curve, so underspecified.
 - Aging specified at 1ppb/day for holdover, not required when in loop, so over specified.

- › Testing, do not over-test.
 - Have an agreed Test regime,
 - thermal profile, range, ramp rates and maximum excursions
 - Determine the filter characteristics to allow estimation of oscillator performance in the system.
 - First and second order characteristic time-constant
 - Be aware of airflow effects!

› Thank You

- Be kind to your oscillators, do wrap them in cotton wool!!

