Crystal Oscillators Basics

APPLICATION NOTES QTAN-104

Q-Tech Oscillator Overview

Crystal Oscillator Basics

Oscillator 101

1

Information sources

Everything you could want to know about crystal oscillator design is available for free at

http://www.ieee-uffc.org/frequency_control/teaching.asp

The industry standard primer on frequency control is

"Quartz Crystal Resonators and Oscillators For Frequency Control and Timing Applications - A Tutorial"

Author: Dr. John R. Vig, formerly of Army Research Lab

2

Hybrid Crystal Oscillators and MIL-PRF-55310

Hybrid crystal oscillator =>

- *multiple chip components in a single package*
- *open crystal inside package requires:*
  - *package hermeticity*
  - *low out gassing materials*

What is MIL-PRF-55310?

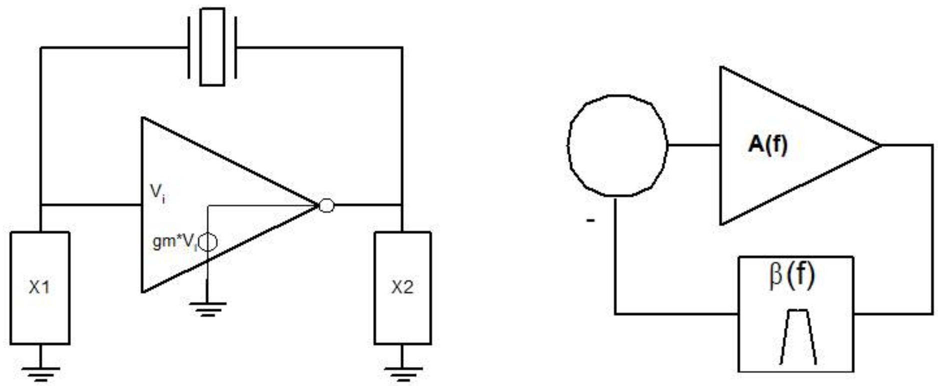
- *US government military specification for crystal oscillators (DLA Land and Maritime)*
- *Highest quality assurance provisions in the industry and forms the model for all Q-Tech hybrid oscillators*
- *Operating temperature range is -55 to +125 °C*
- *Mandates tight manufacturing process controls (ESD, SPC)*
- *Control and selection of materials and components ("element evaluation / qualification")*
- *QPL – Qualified Parts List – status awarded by DLA*
  - *Qualifying samples must be submitted every two years or upon any change in design or materials*
  - *There are few suppliers listed as QPL for '55310 products*

Hybrid Crystal Oscillators: MIL-PRF-38534 vs MIL-PRF-55310

- *Q-Tech heritage Space clocks follow custom Quality Assurance / Screening /QCI requirements based on MIL-PRF-38534*
- *Similar requirements for component quality testing but more stringent screening/QCI requirement*
- *Screening: Extended burn-in, 100% Aging Test, 100% frequency-temperature characterization, more extensive visual inspections*
- *QCI: Life Test, RGA*
- *Omission of tests not generally relevant to Space environment (e.g. salt atmosphere)*

4

What is a crystal oscillator?

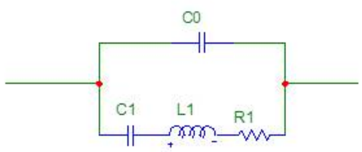


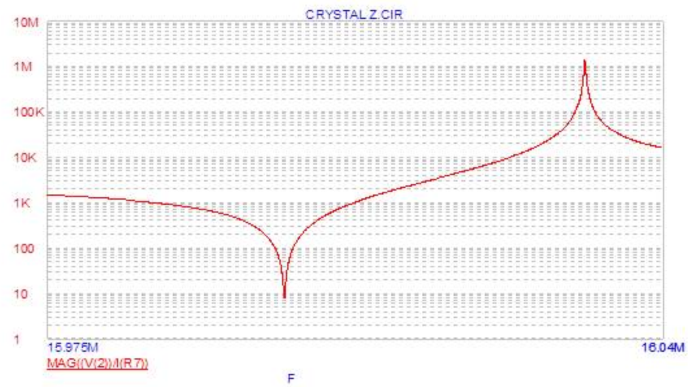
- *Extremely narrowband feedback amplifier with* $|A^*\beta| = 1$ *and* $\theta_{A\beta} = 2n\pi$
- *No net attenuation or phase shift in round trip through the loop*
- *High Q (f0/BW) provides extreme frequency stability – typically 10^-8 frequency variation for 1 second averaging time*

5

Why quartz crystal?

Crystal resonator is an extremely stable high-Q tuned circuit:

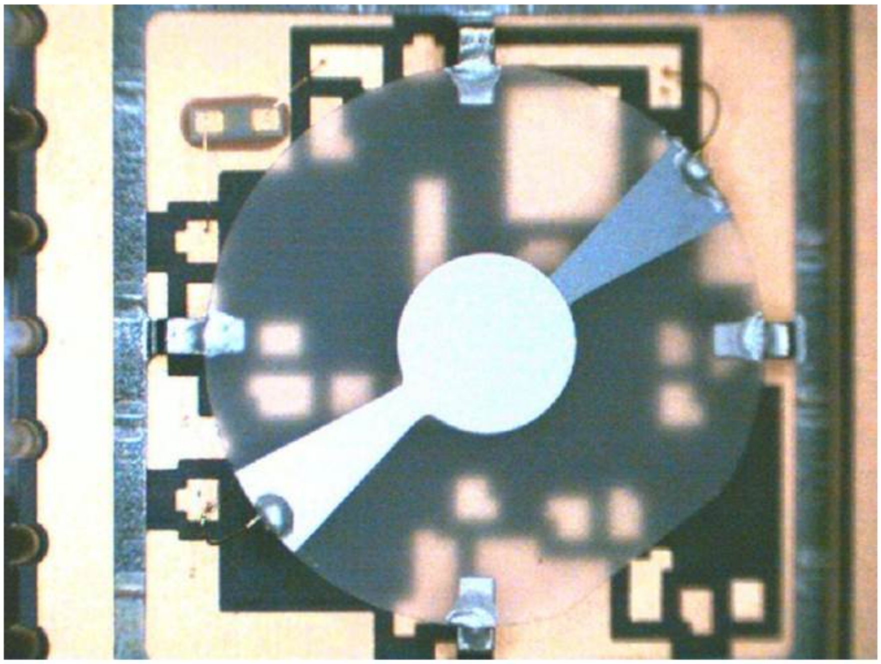




	Typical values - 16 MHZ xtal
C0: electrode capacitance	***C0 = 3 pf***
C1: motional capacitance (stiffness)	***C1 = .012 pf***
L: equivalent inductance (mass)	***L = 8.3 mH***
R: loss, resistance (damping)	***R = 8 ohms***
	Q = 104,000

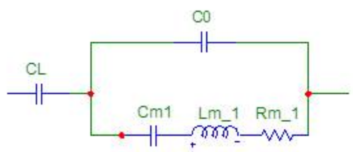
6

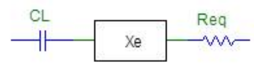
Typical fundamental mode crystal



7

Resonator actual operating frequency – "load capacitance"



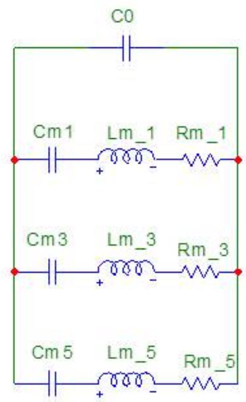


$$F_R = F_S * (1 + \frac{Cm}{2*(C0 + CL)})$$

crystal has inductive reactance $X_L = \frac{1}{\omega * C_L}$

8

Resonator overtone modes



$L \approx$ same for all modes

$$CmN = \frac{Cm_1}{N^2}$$

$$F1 = \frac{1}{2\pi\sqrt{LCm1}}$$

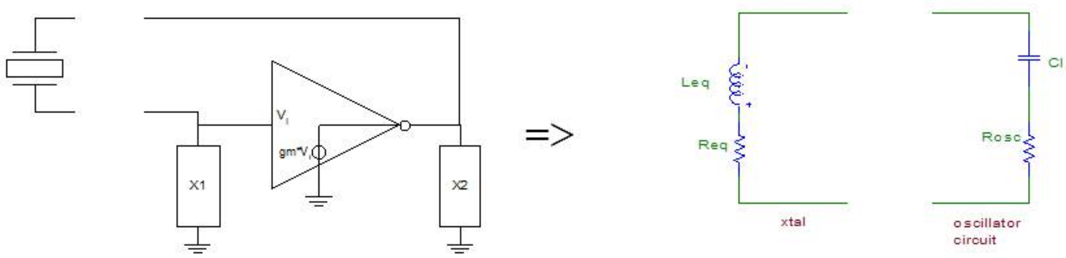
$$F3 = \frac{1}{2\pi\sqrt{LCm3}}$$

Typical values, 32 MHZ 3rd OT unit:

L =	***22 mH***		
Cm1 =	***.010 pF***	***Rm1 =***	***8***
Cm3 =	***1.1 fF***	***Rm3 =***	***25***
Cm5 =	***0.4 fF***	***Rm5 =***	***55***

9

Oscillator Analysis: negative resistance



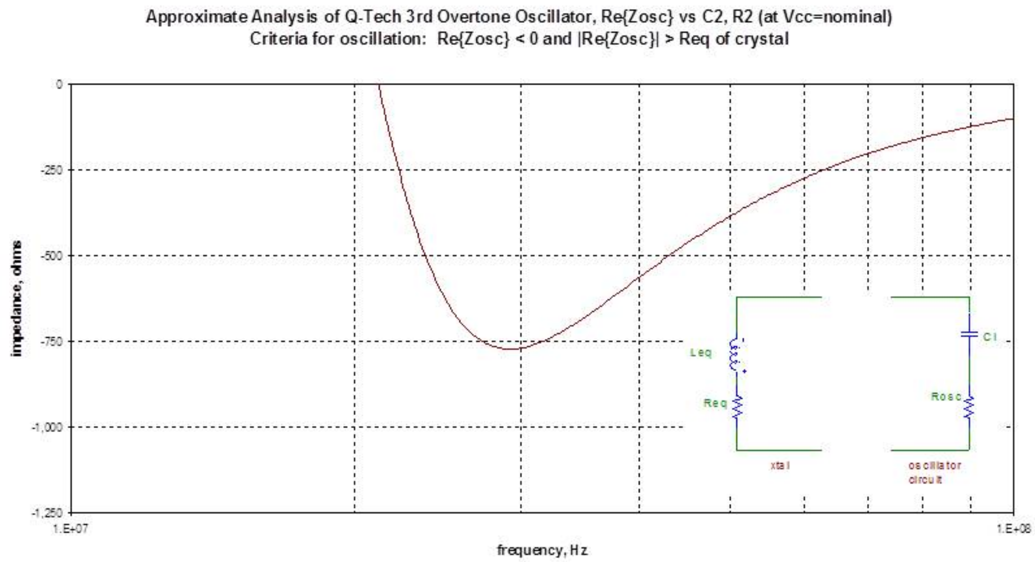
Oscillation will start if |Rosc| > |Req| and Rosc < 0

Steady state => |Rosc| = |Req| averaged over cycle

CL of oscillator determines operating frequency

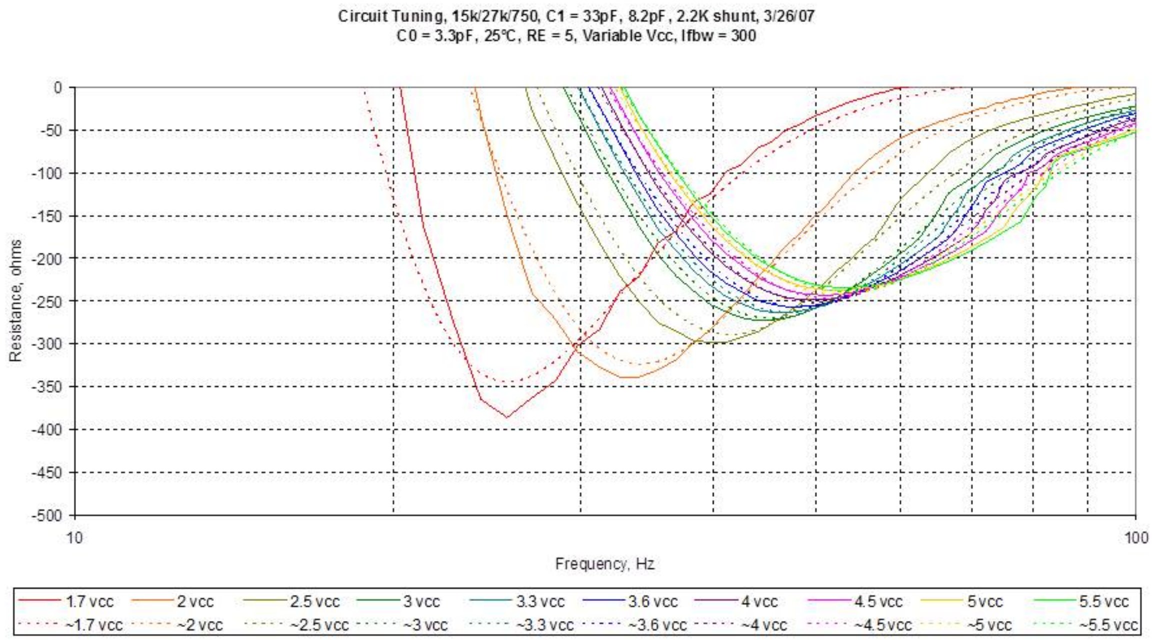
10

Negative resistance, frequency selectivity



11

Negative resistance model: direct measurement



12

Oscillator Frequency Stability

Long term stability – frequency drift

- ***temperature induced frequency change***
- ***Aging***
  - ***drift in average frequency over time caused by other deterministic processes (electrode annealing, package leaking, mounting stress relief)***

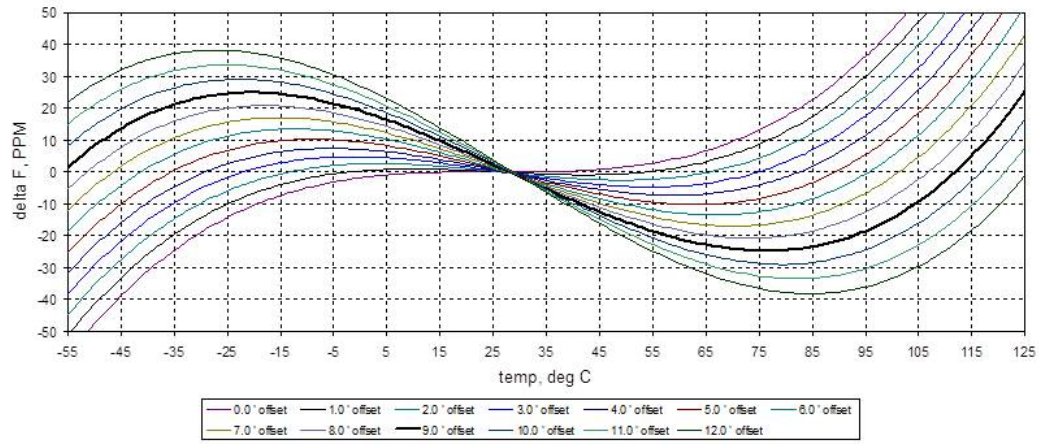
Short term – phase noise / jitter (period to period variation)

- ***caused by random processes***
  - ***thermally induced noise in resistive elements***
  - ***1/f noise (flicker) noise in components***
- ***mechanical inputs (vibration, shock)***
- ***power supply ripple***

13

Crystal Oscillator Stability - Temperature

Beckman Curves for AT cut
"zero temperature coefficient angle" is 12.5' for fundamental mode, 20' for overtone



By far the greatest influence on crystal's resonant frequency is TEMPERATURE

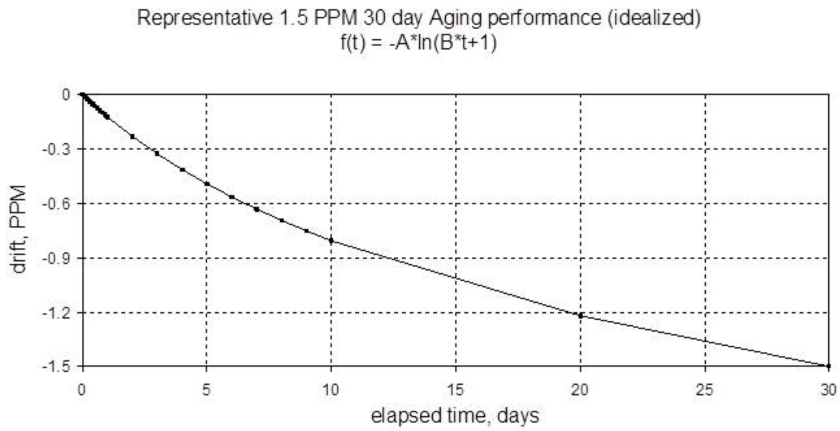
14

Various Grades of Crystal Oscillator Stability

	type	typical output frequency (MHZ)	typical accuracy (long term)	temperature range, °C	typical power consumption (@ 5 V)
XO	uncompensated	1 HZ - 250	20-100 PPM	-55 to >200	10 to 150 mW
VCXO	voltage tuned	1 HZ - 250	100 PPM	-55 to >200	10 to 150 mW
TCXO	temperature compensated	5 - 40	10 PPM	- 45 to +85	25 to 150 mW
OCXO	ovenized (temperature controlled)	10 - 40	.02 PPM	20 to 70	.25 - 1 W
MCXO	digitally compensated	10 MHZ	.06 PPM	-50 to 95	95 mW

15

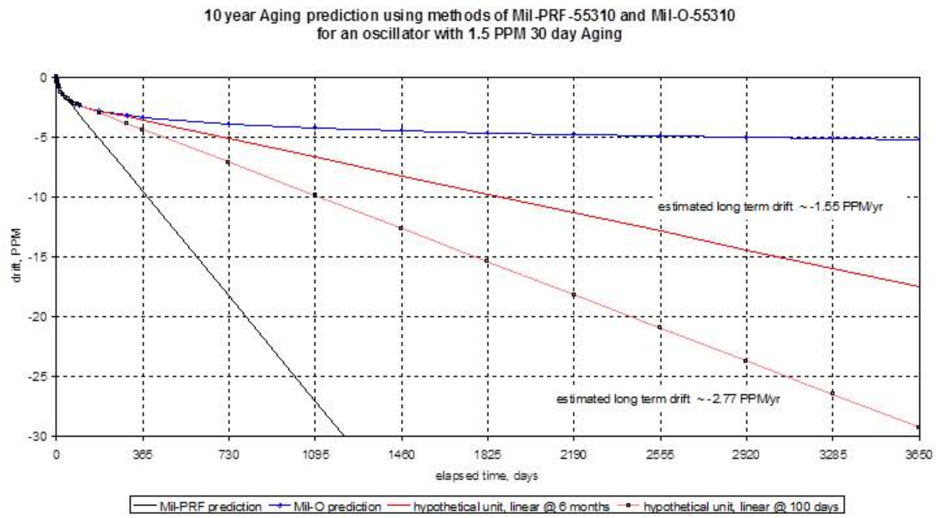
Oscillator Aging



30 day test screening test is standard for basic XO; longer term testing for precision oscillators (OCXO, MCXO).

16

Oscillator Aging Prediction Methods



Long term Aging, typical values are

XO: 4 PPM first year, 1.5 PPM/yr thereafter

TCXO: 0.5 PPM per year or less

17

Oscillator Short Term stability: What is phase noise?

Random variable, AM	Linear phase term	Random variable, PM

$$V(t) = (A + \varepsilon(t))\cos(2\pi f_0 t + \phi(t))$$

$$S_\phi(f) = \left|\mathcal{F}(\phi(t))\right|^2 = \text{PSD, rad}^2/\text{Hz}$$

$$\mathcal{L}(f) = \text{Single sideband - to - carrier PSD, rad}^2/\text{Hz}$$

$$\mathcal{L}(f_m) = \frac{\phi_{rms}^2}{2},\ \text{rad}^2/\text{Hz}$$

18

Phase Noise

- Crystal oscillators produce a small fraction of undesirable energy (phase noise) near the output frequency.
- Phase noise is measured in the frequency domain, and is expressed as a ratio of signal power to noise power measured in a 1Hz bandwidrh at a given offset from the desired signal.
- **A:** Noise relatively close to the carrier (Flicker Noise) primarily depending on quality of the crystal.
- **B:** Noise "1/F" caused by the semiconductor used in circuit.
- **C:** White Noise or Broadband Noise.
- Frequency Multiplying by "n" worsen the phase noise by a magnitude of 20logn, i.e. 6dBc for doubling the frequency.

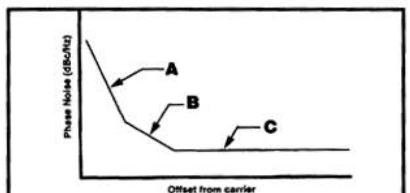
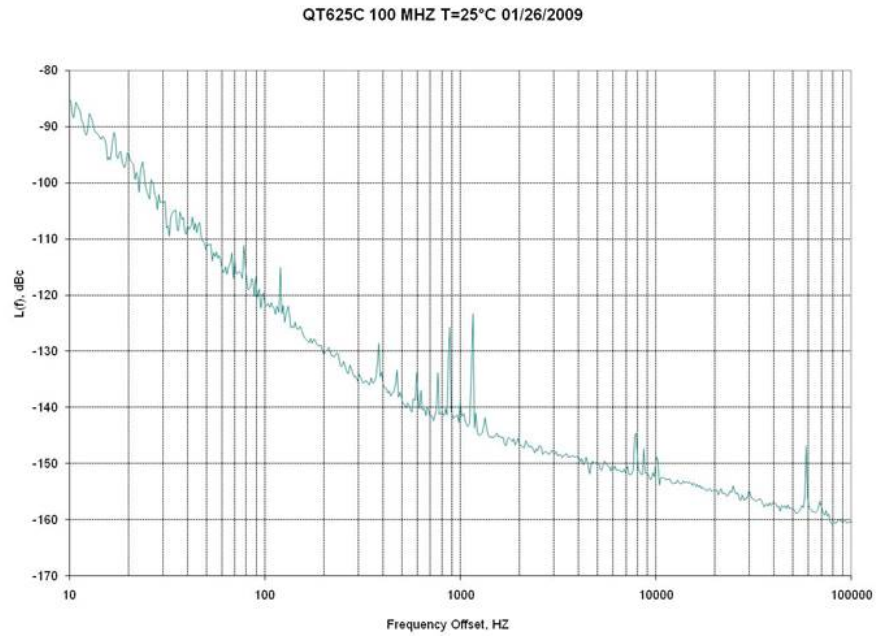


Figure 1

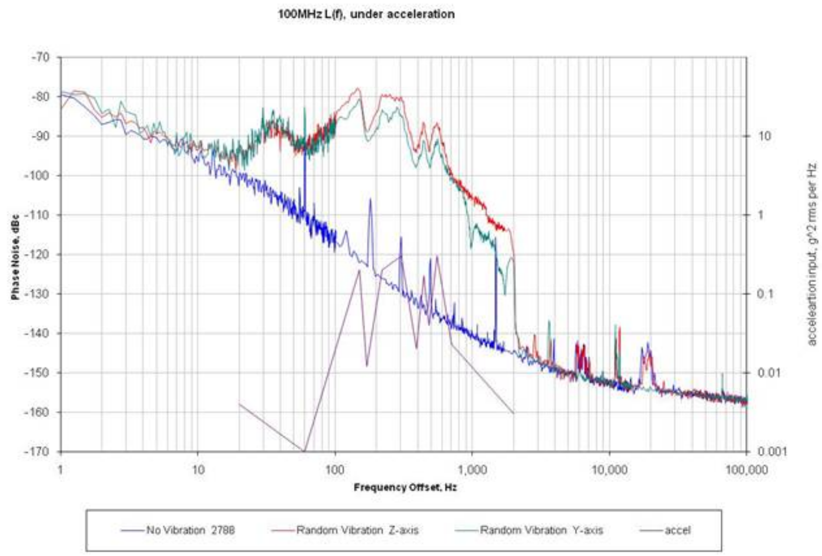
19

Typical XO phase noise



20

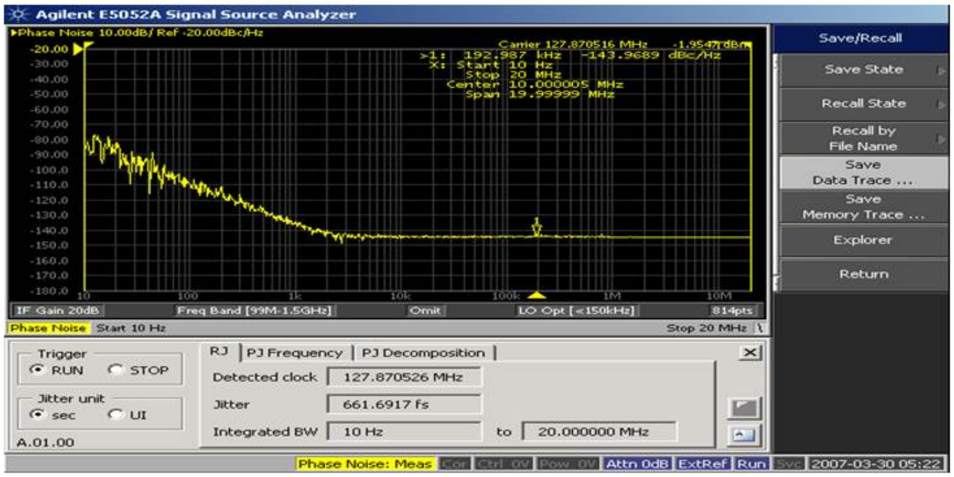
Acceleration sensitivity – frequency modulation



G sensitivity depends on resonator design including thickness/diameter ratio & orientation of mounting structure (referenced to the quartz atomic lattice). Unit shown has ~ 1E-9 per g sensitivity.

21

Integrated Phase Noise



- *The phase noise plot provides the noise at certain offset frequencies from carrier, e.g. 10Hz, 100Hz, 1kHz, 10kHz, 100kHz, etc. In order to determine the total noise power over a certain frequency range (bandwidth), the time domain must be analyzed in the frequency domain, and then reconstructed in the time domain into an RMS value with the unwanted frequencies excluded. This may be done by converting L(f) back to Sφ(f) over the bandwidth of interest, integrating and performing some calculations.*

22

Measuring
Time domain jitter

Equipment:

Agilent DSO80604B, 6GHz bandwidth at maximum sampling rate of 40Gs/s.

EZJit Software

Power supply

Method:

Measure cycle to cycle jitter with 10,000 samples and determine Deterministic Jitter (DJ) and Random Jitter (RJ).

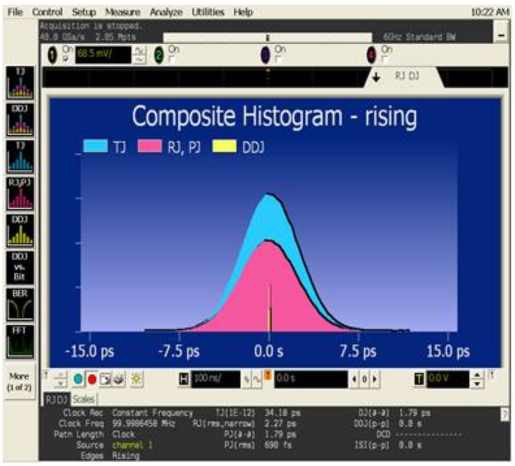
Calculate Total Jitter (TJ)

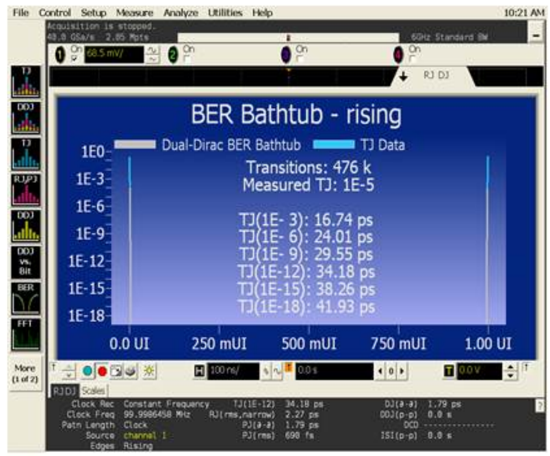
$$RJ = \text{Random Jitter} = \alpha * RJrms$$

$$TJ = RJ + DJ(pk\text{-}pk)$$

23

Typical Jitter plots





Deterministic jitter is clock timing jitter or data signal jitter that is predictable and reproducible. The peak-to-peak value of this jitter is bounded, and the bounds can easily be observed and predicted.

Deterministic Jitter includes different categories such as periodic jitter, data dependent jitter, and duty-cycle dependent jitter.

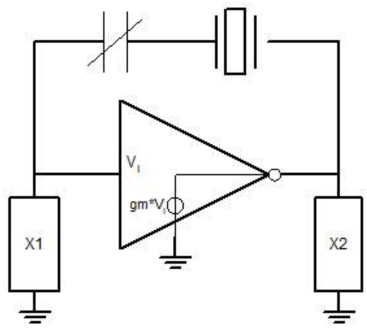
24

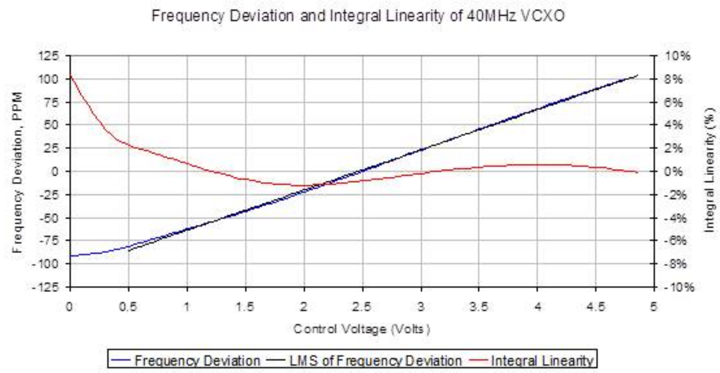
Sources of Jitter

- ***Sources of DJ:***
  - ***Electromagnetic Interference EMI***
  - ***Crosstalk***
  - ***Reflections***

- ***Sources of RJ:***
  - ***Shot noise (white noise in semiconductor)***
  - ***Flicker noise (proportional to 1/f, most dominant at low frequencies)***
  - ***Thermal noise (broadband "white" noise)***

VCXO - varactor tuned XO



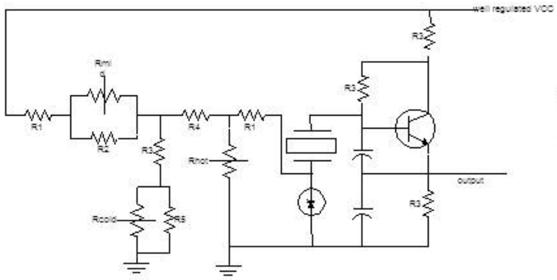


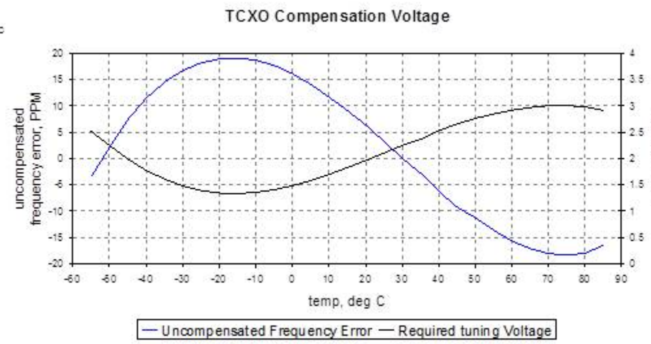
Cload = varactor capacitance in series with Cosc

Must specify tuning range or sensitivity, modulation bandwidth

10% integral non-linearity is standard

Temperature Compensated Crystal Oscillator – TCXO (indirect compensation)





Indirectly compensated TCXO is a

Precision, repeatable VCXO

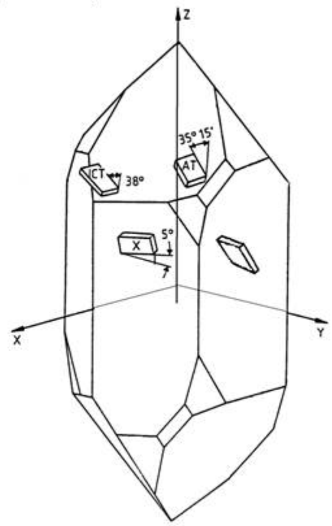
+ temperature dependent voltage generator

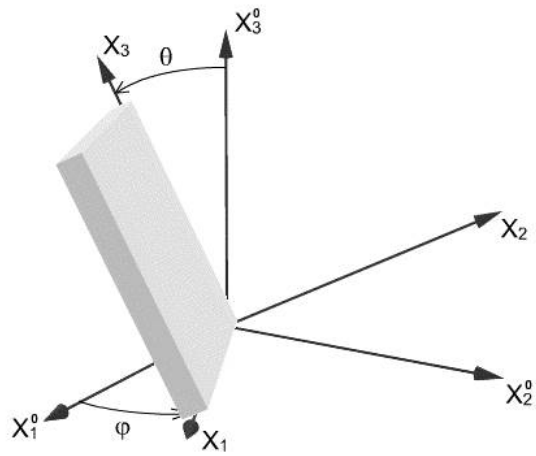
27

High Temperature Oscillators (up to +225°C)

- ***Q-Tech produced High Temperature Oscillators in all packages meeting demands for Oil Drilling services.***
- ***Supply voltages +3.3Vdc and +5Vdc.***
- ***Frequency up to 100MHz.***
- ***Proprietary assembly techniques to assure Long Life Reliability.***
- ***Low current for battery operation (0.3µA at +3.3Vdc for RTC 32.768kHz)***
- ***Wide operating temperature -55°C to +225°C.***
- ***Special use of AT, IT, or SC cut crystals.***
- ***Hybrid modules assembly.***

28





29

Quartz crystals (cont'd)

- ***Different quartz crystal cuts can be made possessing different properties.***
- ***Cuts are defined by two rotation angles phi and theta around the crystallographic axes.***
- ***Most common cuts are the single rotation AT- cut (phi = 0°) and the double rotation SC-cut (phi = 22°) . The theta angle in both cases is around 34°.***

30

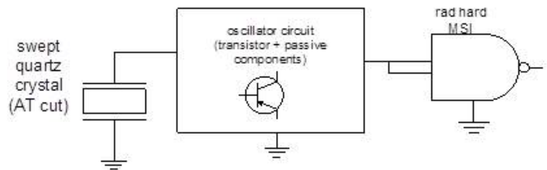
- ***ADVANTAGES OF QUARTZ***
  - *Piezoelectric effect*
  - *Low temperature coefficient*
  - *Low loss (High Q)*
  - *Pullability*
  - *Abundant in nature*
  - *Can be reproduced in autoclave*
  - *Excellent shock and vibration resistant*
  - *Can be swept suitable for Space use*

SWEPT QUARTZ USED IN RADIATION ENVIRONMENTS

- *Radiation environments can affect parameters of a quartz crystal, such as frequency, Equivalent Series Resistance, and Quality factor. The use of "swept quartz" crystals in Radiation environments is needed.*
- *Swept quartz has better characteristics than standard natural synthetic quartz because it is grown in a highly degree of purity. This helps to minimize the changes in electrical parameters of a crystal when it is exposed to Radiation.*

Q-Tech Space Oscillator Characteristics

Basic Class S XO design



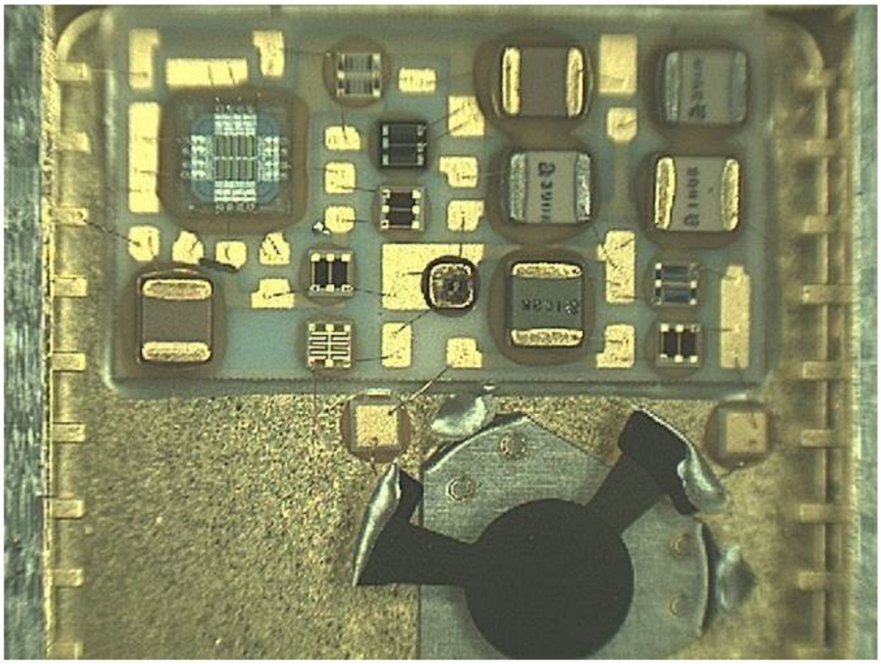
UHF transistor oscillator + swept quartz crystal + Class V microcircuit (radiation hardened)

Design approach has a 20+ year track record

- ***Very few design changes have been required***
- ***Heritage => reliability, radiation tolerance***
- ***All Class S design configurations are "frozen" => no changes without customer notification and concurrence***

32

Q-Tech Space clock photo



33

Q-Tech Space Oscillators: Reliability

Quality/Screening/QCI per Q-Tech General Specification 401-0298-001 follows MIL-PRF-38534 Class K, more stringent than MIL-PRF-55310 'Class S'

Use of QPL components or alternatively, elements meeting MIL-PRF-38534 'Element Evaluation' or Aerospace TOR enhanced EE requirements

Microcircuits are Class V qualified with Radiation Lot Acceptance Tests. QT625: 54AC logic (ST Micro)

Design are micro-power with extremely low component stress levels

34

Q-Tech Space Oscillators Radiation Hardness - TID

All Space clocks possessed Radiation Hardness Assurance by:

- ***QML V die, with RHA Level F (300kRad(Si)) Total Dose***
- ***QML V die, with SEE characterization (No Latch-Up, and SEU/SET)***
- ***Components Level RAD testing (Low Dose TID, Displacement Damage Neutrons and Protons, Dose Rate)***
- ***Oscillator level RAD testing by Q-Tech as well as by customers.***

Table II. Frequency shift through TID

Device Under Test	Delta f, PPM 100 kRad (Si)	Delta f, PPM 300 kRad (Si)
16 MHZ, 3.3 V units	+4	+8.5
66 MHZ, 3.3 V units	-1.5	-2
24 MHZ 5.0 V units	+3	+4
98 MHZ 5.0 V units	-2	-5

Table III. Duty cycle change through TID

Device Under Test	Duty cycle change, % of period 100 kRad (Si)	Duty cycle change, % of period 300 kRad (Si)
16 MHZ, 3.3 V units	-1.7 %	-2%
66 MHZ, 3.3 V units	-1.3%	-3.4%
24 MHZ 5.0 V units	-1.5%	-2%
98 MHZ 5.0 V units	-1.7%	-3.5%

Q-Tech Space Oscillator (QT625) Radiation Hardness - SEE

SEE has been characterized by our customers – data is mostly proprietary. General tolerance levels for the basic design:

Heavy ion	***limiting cross section***	***~ 5E-6 cm^2***
	no latchup	***> 120 MeV–cm^2/mg***
	no outage/glitches	***> 85 MeV–cm^2/mg***

Dose Rate (Flash x-ray test)

	no outage	***> 1.5E9 rad/S***
	damage	***> 1E12 rad/S***

Pending tests (RAD, inc):

Neutron displacement damage	***{1E13 N/cm^2}***
Dose Rate upset/damage	***{1E11rad/S}***
Heavy ion SEU/SEL	***to 120 MeV–cm^2/mg***

Q-Tech Space Level TCXO

Qualification testing includes

- ***1000 hour life @ 125 °C***
- ***1500 g shock and 44 g rms random vibration***
  - ***Post shock freq shift < .15 PPM***
- ***Long term Aging characterization***
- ***TID test (Q1 2009)***

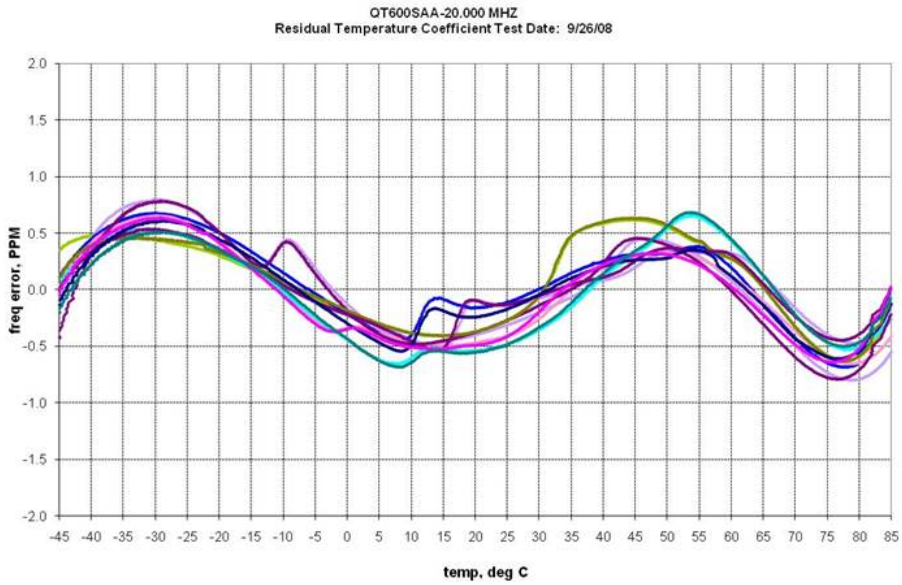
Aging rate typically 0.5 PPM/year

Low phase noise, e.g. 16 MHz unit:

- ***-100 dBc @ 10 Hz***
- ***-125 dBc @ 100 Hz***
- ***-140 dBc @ 1000 Hz***
- ***-155 dBc white noise region***

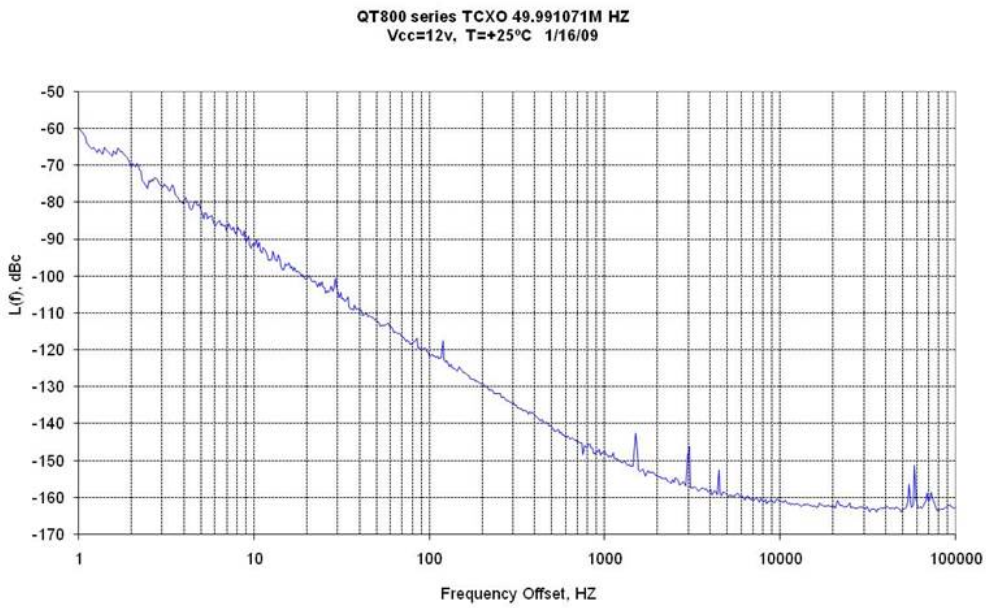
37

Q-Tech TCXO temperature stability



38

Q-Tech TCXO phase noise



39