Power Matters.™

Microsemi Space Time and Frequency Products

Microsemi Space Forum 2015

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Agenda

- Introduction
- Acknowledgements
- Oscillators for Satellites
- Why Quartz? About quartz Resonators
- Quartz Oscillators
- Frequency Accuracy
- Phase Noise and Allan Deviation
- Oscillator Comparisons: XO, VCXO, TCXO, and OCXOs
- Microsemi's SDA Group and Legacy
- Microsemi's Oscillator Product Overviews
- Core Capabilities
- SDA Product and Quick Turn (QT) Summary
- Space Qualified Cesium
- Conclusion

Introduction

- Frequency and timing sources are an integral part of satellites
- Presentation will provide an overview of Quartz oscillator technology
- Description of Microsemi's capabilities in space craft timing and frequency generation.
- Overview of Microsemi's frequency and timing devices, and capabilities

Acknowledgement

- Crystal and Crystal Oscillator theory is a broad topic with a great deal of information
- An excellent resource is John Vig's tutorial, a public document available through the IEEE or a Google search on "John Vig Tutorial"
- Dr. Vig's tutorial is referenced throughout this "tutorial segment" of this presentation

Dr. John Vig

Oscillators for Satellites

- Oscillators are required an numerous applications in space including communication, navigation, frequency synthesis, metrology
- Several key technologies are utilized depending upon the accuracy and stability of the frequency required
  - LC, Quartz Crystal, SAW, CRO, DRO, micro-strip and stripline
- The most common precision oscillators use quartz crystals
- In rare cases, such as GNSS satellites atomic clocks are used.

Temperature Compensated Crystal Oscillator TCXO

Ovenized Crystal Oscillator OCXO

GPS IIF Cesium Clock

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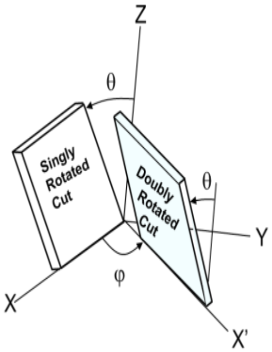
Why Quartz

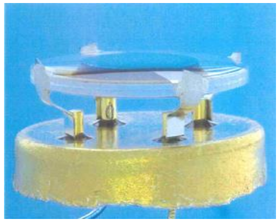
- Quartz has unique properties suited to precision frequency generation
  - Piezoelectric material (pressure-electric)
  - Zero temperature and stress compensated cuts have been developed
  - Low loss, easily processed and durable
  - Capable of extremely high Q
- Crystals used in the first half of the 20th century used naturally occurring material
- Synthetic quartz, grown in high temperature and pressure autoclaves, provides all of modern crystals

Natural Quartz

Quartz Bar

Rotated Cuts





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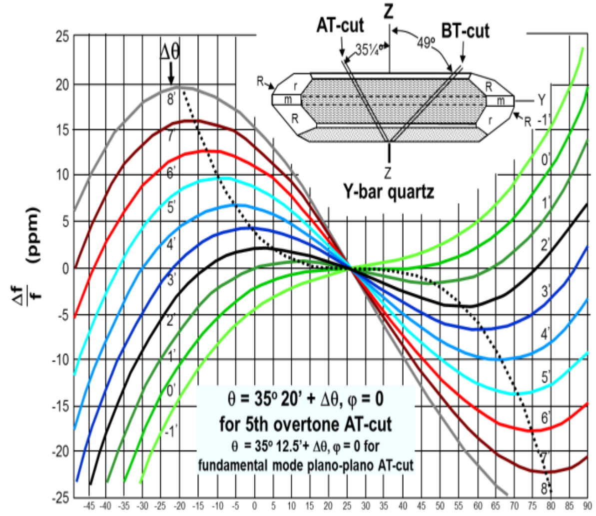
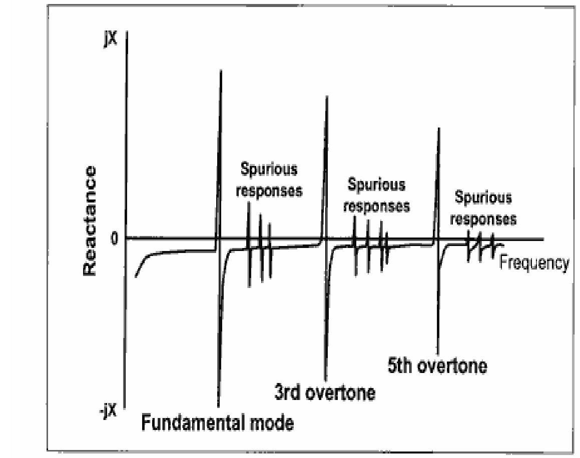
Quartz Resonators

- Many combinations of angle cuts for crystals to optimize performance, two most common are
  - AT Cut – Wide tuning range ideal for frequency synthesis and temperature compensation
  - SC Cut – Operated at a fixed temperature, used for high stability applications
- Piezo electric effect is very complex and often crystals are optimized for particular modes of operation that operate optimally for certain parameters.
  - Common modes are fundamental, 3rd and 5th overtone
  - Fundamental mode devices are used for lower performance requirement that require a wide tuning range
  - 3rd and 5th overtone devices are used for precision applications



Overtone Response of a Quartz Crystal



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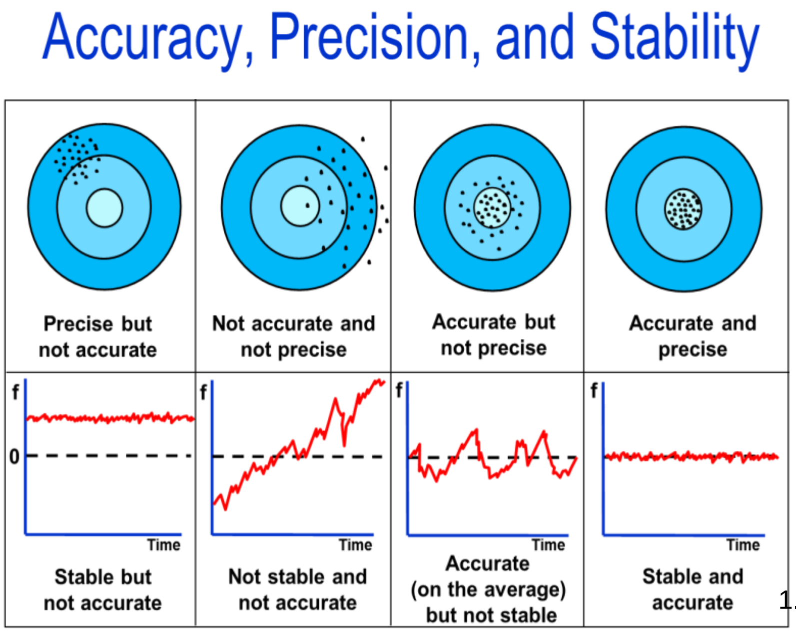
Oscillator Characteristics

- Accuracy
- Power Consumption (Watt or mW)
- Output signal type
  - Sine Wave: RF in dBm
  - CMOS, PECL, ECL
- Temperature Stability
  - Frequency Change over a temperature range
- Phase Noise
  - Power Spectral Density
- Allan Deviation
  - Statistical measure of oscillator noise
- Aging or Drift
  - Accuracy over long periods of time (days, months, years)



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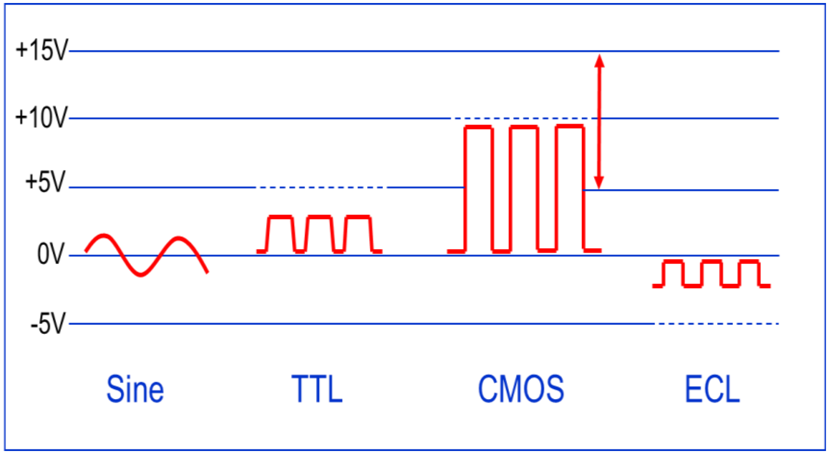

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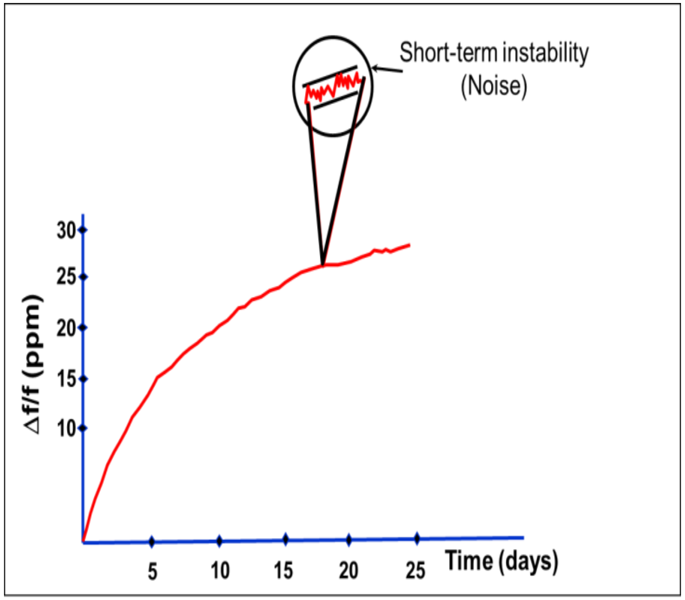
Frequency Accuracy

- Many applications will define the overall accuracy of the system that is dependent on the mission life
- Composed of initial accuracy, environmental sensitivities and long term effects
  - Aging (Drift)
  - Initial accuracy
  - Retrace
  - Acceleration Sensitivity
  - Temperature stability
  - Supply voltage
  - Radiation
- **Fractional Frequency expressed as the frequency divided by the nominal frequency**
  - 10 MHz Oscillator – 10 Hz offset frequency is equal to 1 ppm

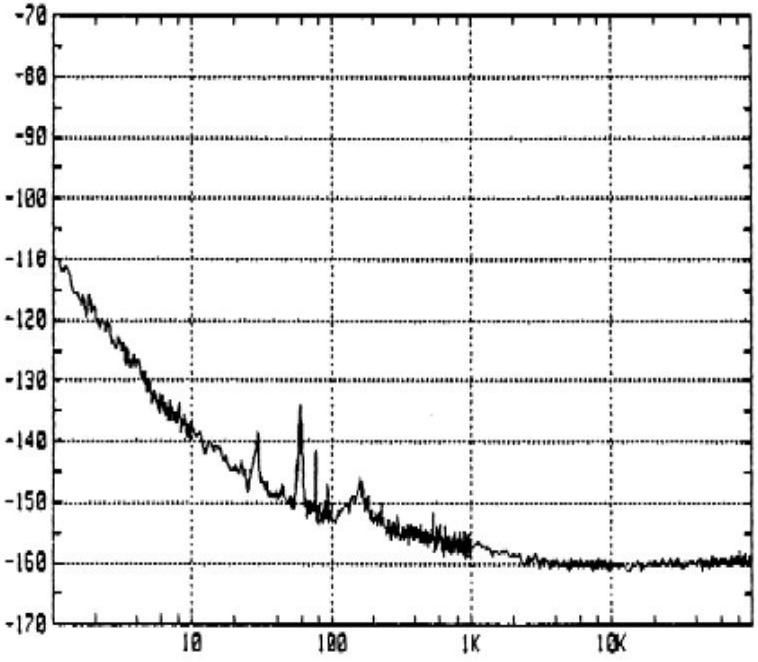
Long Term Drift and Noise$_1$



Phase Noise

- Measures the spectral purity of the oscillators output
- Phase noise is an important measure of performance for communications systems, radar and frequency synthesis
- PSD, power spectral density close the carrier drives stability for communications and timing
- PSD farther away from the carrier is critical for radar and frequency synthesis

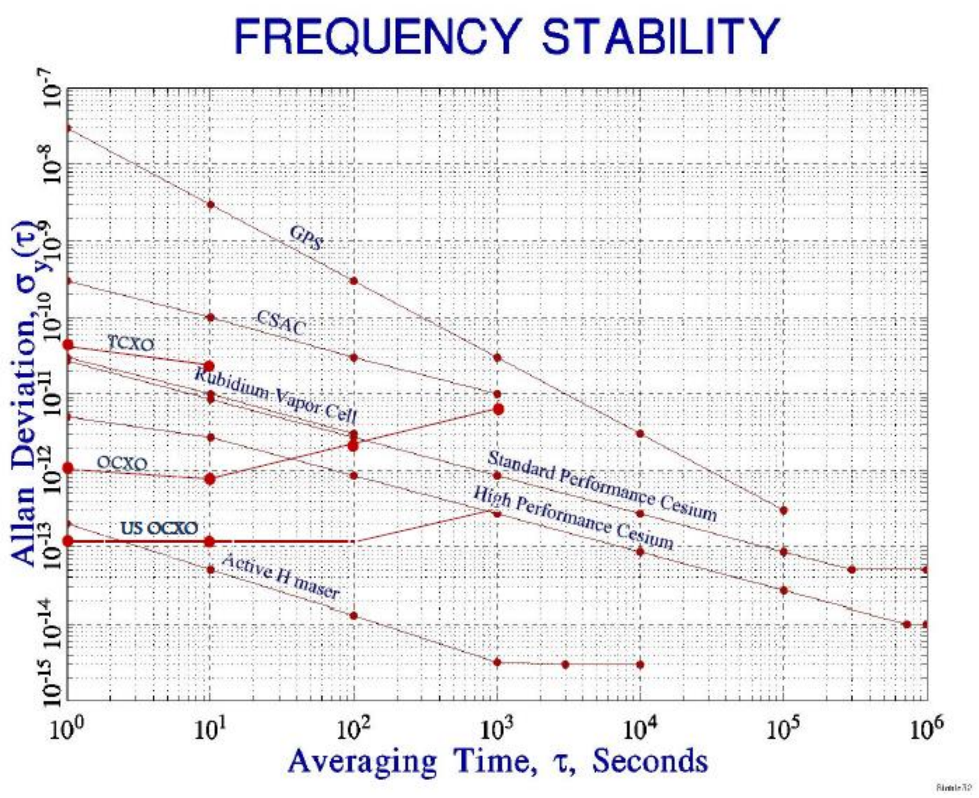
Phase Noise of 10 MHz OCXO



Typical test results for the 10MHz oscillator

Allan Deviation

- Alan deviation is a statistical means of measuring the frequency and time performance of many types of oscillators
- Allan deviation (or two sample deviation) takes into account systematic changes in the environment or duration of a test.
- Allan deviation allows a comparison of various crystal oscillators and atomic clocks



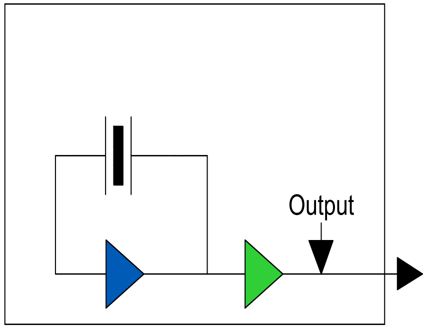
Oscillator Comparison

Technology	Accuracy	Phase Noise	Alan Deviation (1s)	Aging per day	Power Consumption
Crystal Oscillator (XO)	30 ppm	N/A	N/A		100 mW
Temperature Compensated Crystal Oscillator – TCXO	2 ppm	-80 dBc/Hz at 1 Hz	$\sim 10^{-11}$	10^{-8} to 10^{-9}	200 mW to 300 mW
Voltage Controlled Crystal Oscillator	2 ppm		$\sim 10^{-10}$	10^{-8} to 10^{-9}	200 mW to 300 mW
Oven Controlled Crystal Oscillator OCXO	20 ppb	-100 dBc @ 1 Hz	$\sim 10^{-12}$	10^{-10} to 10^{-11}	700 mW to 2 W
Ultra Stable Oscillator USO	20 ppb	-120 dBc @ 1 Hz	$\sim 10^{-13}$	10^{-11} to 10^{-12}	3 W to 5W
Rb Oscillator	1ppb	-100 dBc @ 1 Hz	$\sim 10^{-11}$	10^{-11} to 10^{-13}	20W to 30 W

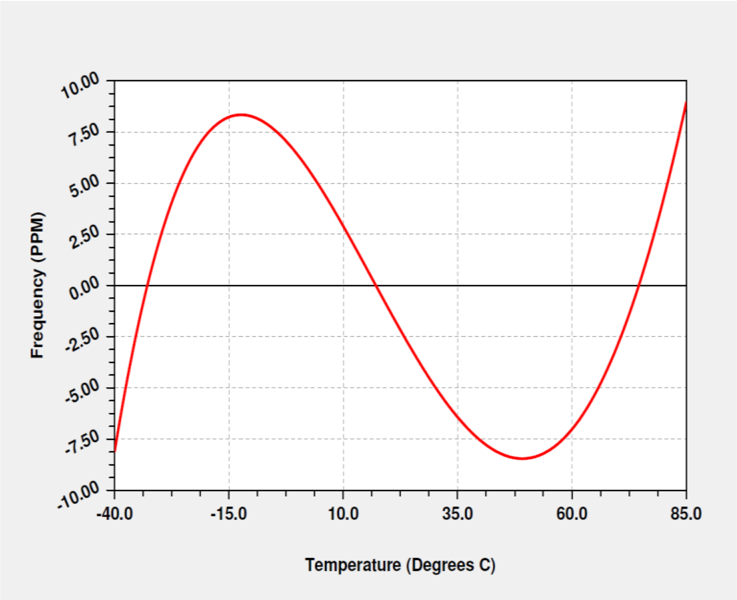
Crystal Oscillator XO

- XO are the least stable crystal oscillators and most commonly used
- Used in conventional digital subsystems when frequency or timing is non critical
- Circuitry is simple because the performance requirements are modest.
  - A simple logic gate is sufficient
- Space applications can utilize a crystal mounted on the pcb or a hybrid circuit.

Crystal Oscillator (XO)

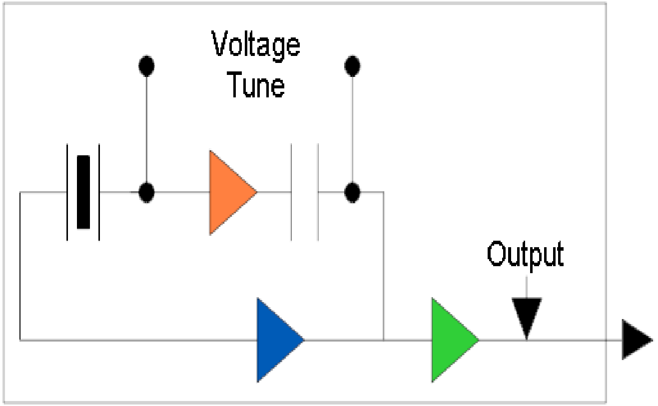


Frequency vs Temperature

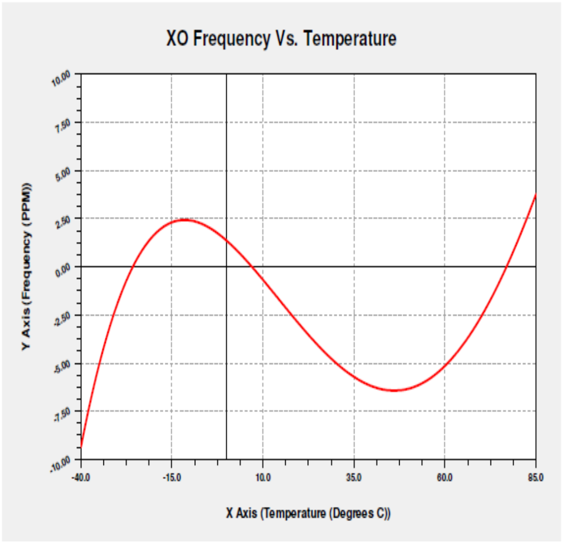


Voltage Controlled Crystal Oscillator (VCXO)

- External adjustment of the frequency using a device in the oscillator loop (usually a varactor diode.)
- Frequency adjustment range is needed to perform function within the system
  - Phase Locked Loops and Frequency synthesis are
- Phase Noise Performance is very important

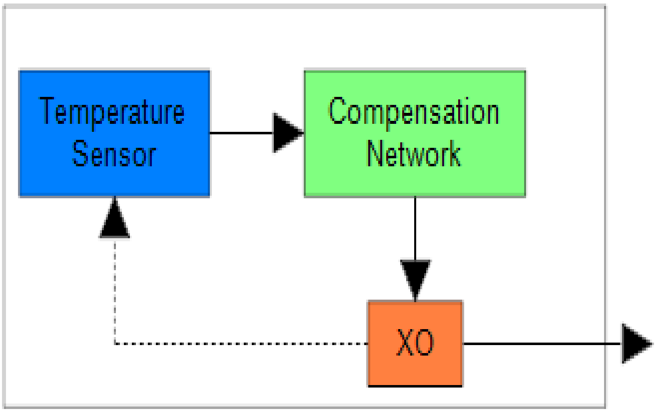


- Crystal Oscillator (XO)

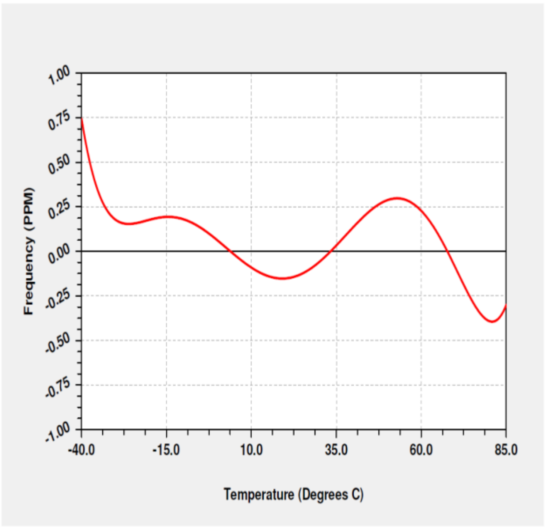


Temperature Compensated Crystal Oscillator (TCXO)

- TCXOs use a temperature sensor to adjust a crystal frequency
  - AT cut crystal is common because of the tuning range
- Commercial and Military TCXOs use ASICs for performance, size and cost improvements
- Radiation considerations for space TCXO typically exclude ASICs
- Space TCXOs use thermistor bridges and resistive networks.
- TCXOs can be fixed frequency or voltage controlled.

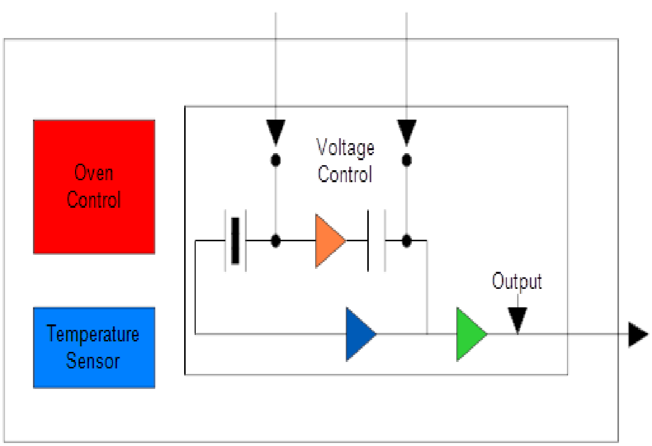


Frequency vs Temperature

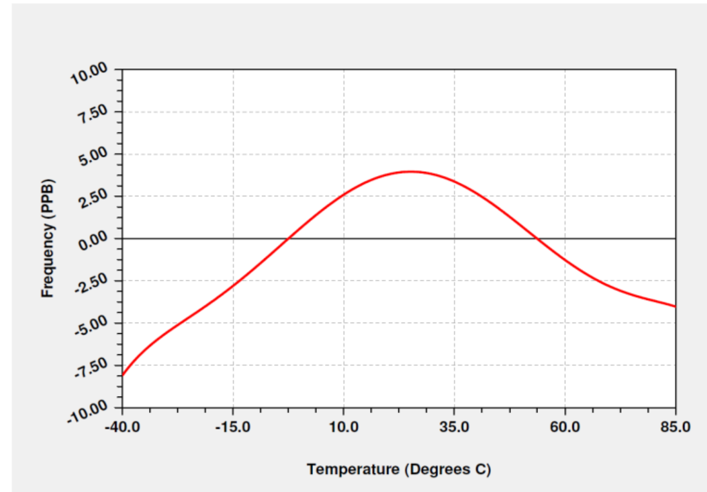


Oven Controlled Crystal Oscillator (OCXO)

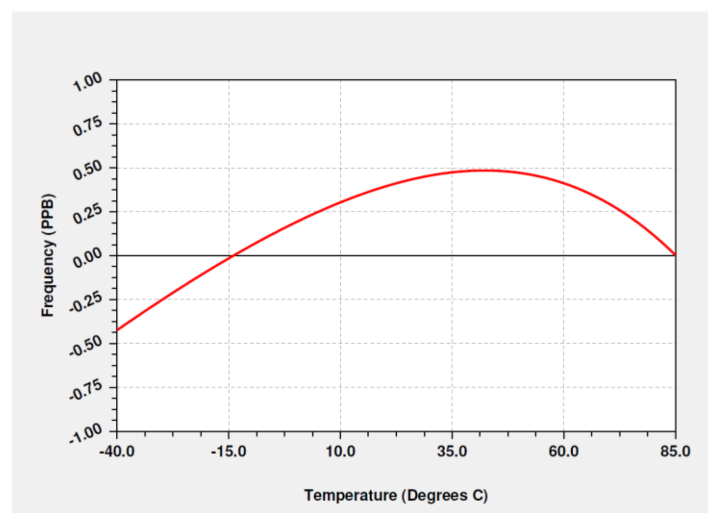
- Uses an 3rd overtone Stress Compensate (SC) maintained at a constant temperature
  - SC Crystal has a parabolic frequency vs temperature characteristic at a temperature between 80°
- Higher performing OCXO will thermally stabilize all electronics that influence thermal stability
- Thermal stability, along with the Quality factor, or “Q”, an electronic noise directly effect Allan Deviation, Phase Noise.



OCXO Temperature Coefficient

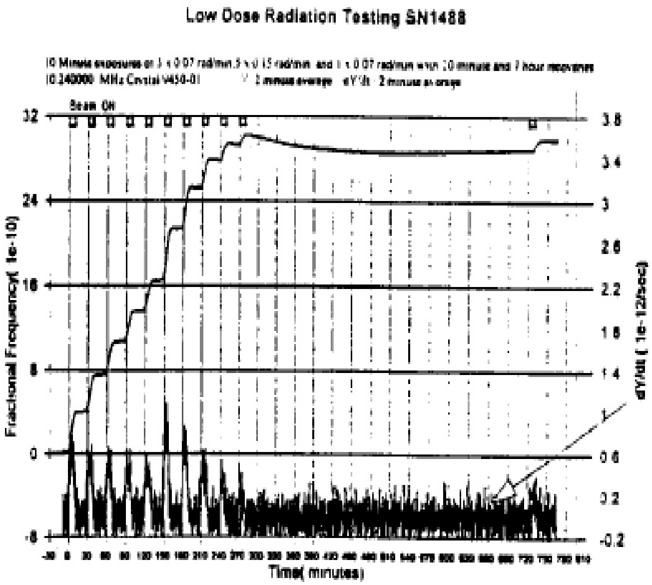


Ultra-Stable OCXO



Oscillator Characteristics in Space

- Mechanical robustness for launch
  - Random Vibration
  - Shock
- Radiation Sensitivity
  - Total Ionizing Dose (TID) and ELDRS
  - Single Event Effect (SEE)
  - Sub-atomic Particles (Protons, Neutron electrons)
  - Man-made environments for Defense Applications
- Reliability for Long Term Operation
  - Operational scenarios exist for up to 30 years
  - Analyses
    - Worst Case Circuit
    - Stress, Derating and Reliability
    - Radiation
    - Structural
    - Thermal
    - FMECA



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Space, Defense, and Avionics (SDA)

- SDA group located in Beverly, MA and focuses on providing precision frequency references for military and space applications
  - Group formed in 2003 to serve unique requirements of space and military oscillators and atomic clocks
  - Based on > 44 years of heritage
  - More than 800 oscillators delivered into Space
  - 70 Space Qualified Cesium Atomic Clocks for the GPS constellatoin
- Separate manufacturing capability focused on additional environmental controls, hi-reliability materials control and enhanced process tolerances
- Strong technical skills in quartz oscillators, ruggedized atomic clocks, low noise synthesizers, frequency and time sub-systems

44 Years of Heritage on more than 100 programs with greater than 800 oscillators delivered

Spaceborne GPS Receiver	SkyFox	JPSS-1	WorldView I-III
QuickBird QuickBird II	MUOS	SBIRS GEO 1-4	SASSA
GPS I, II, IIA, IIF, III	NPP	SAOCOM	CHIRP
Loral FM	IRIS	PAN	INTELISAT
COSMO IV	KOMPSAT	LRO	NEXTVIEW
STEREO	MESSENGER	CLOUDSAT	CLIO

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SDA Core Capabilities

- Extensive experience in precision quartz oscillators for space and military applications
- Provides the lowest noise and most stable quartz oscillators in the world
- Low noise circuit design and frequency synthesis
- Advanced timing capabilities
- Atomic Clock development for space
- Expertise in radiation characterization, analysis and testing for natural and man-made applications.

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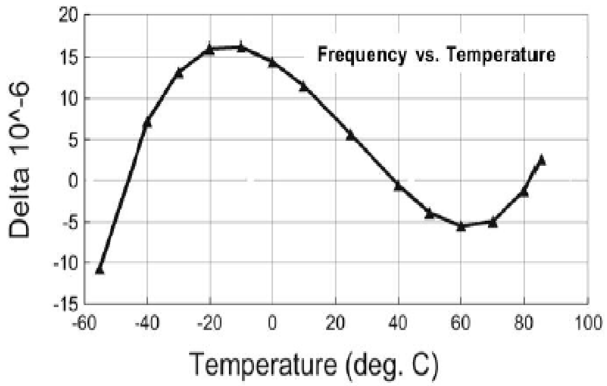
SDA Infrastructure

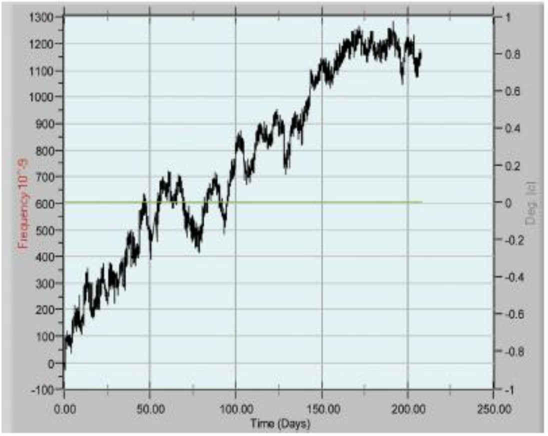
- Dedicated facilities and staff to support unique aspects of Space and Military Hardware
- Stock of standard class S and class B electronic components
- Well established source of supplies for critical components such as hybrids and crystals
- In house, 100% sampling of all parts for prohibited materials (pure tin, etc.)
- Certified J-STD Space Addendum Soldering Instructors on staff
- 6 Thermal Vacuum Chambers
- 6 Thermal Chambers
- 2 Vibration tables and Shock system

Voltage Controlled Crystal Oscillator (VCXO)

- Space Qualified VCXO are usually hybrid construction for reduced size and durability
- Microsemi has developed and delivered oscillators from 10 MHz to 544 MHz
- Assembly and test performed at Mil-prf-38534 class K facility



Aging Projection

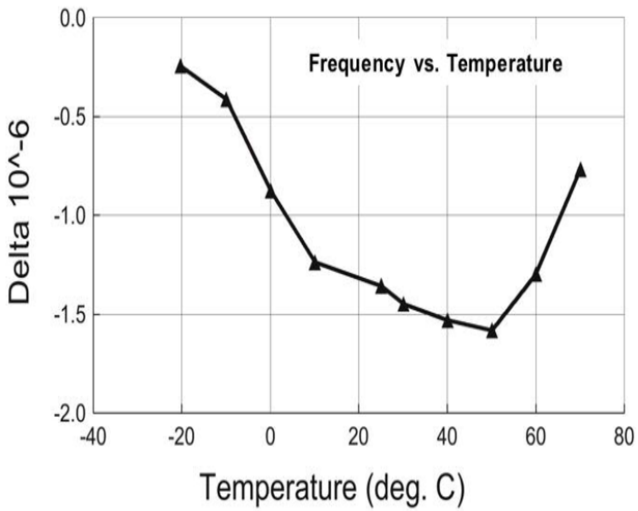


Mil-0-55310 Projection 3ppm for 15 Years

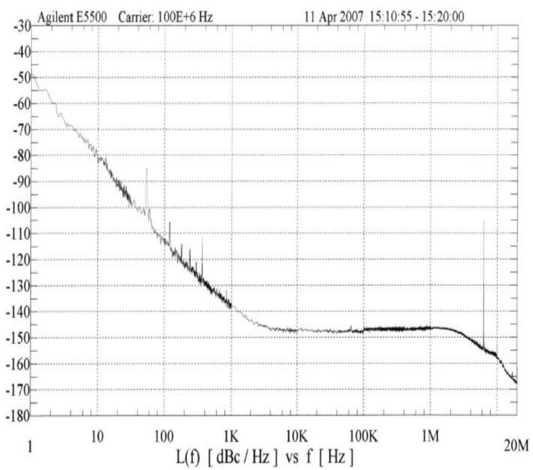
9940 VCXO

VCXO and TCXO

- Space Qualified TCXOs are usually hybrid construction for reduced size
- Microsemi has developed and delivered oscillators from 10 MHz to 100 MHz
- Vacuum sealed crystals result in low aging and excellent phase noise
- Assembly and test performed at Mil-prf-38534 class K facility



Phase Noise



9960 TCXO

9600 and 9700 Ovenized Crystal Oscillators

- High Stability and Low Phase Noise
- Allan Deviation of < 1 x 10^{-12} 1-10 seconds
- Phase Noise < -110 dBc/Hz
- 1.3 W @ 25°C in thermal vacuum
- Frequency Range of 1 MHz to 25
- Grade 1 or 2 EEE Parts
- MTBF of six million hours
- 300+ oscillators delivered for space missions
- Volume of 2.25 in^2
- 300 krad (Si) hard and SEL immune

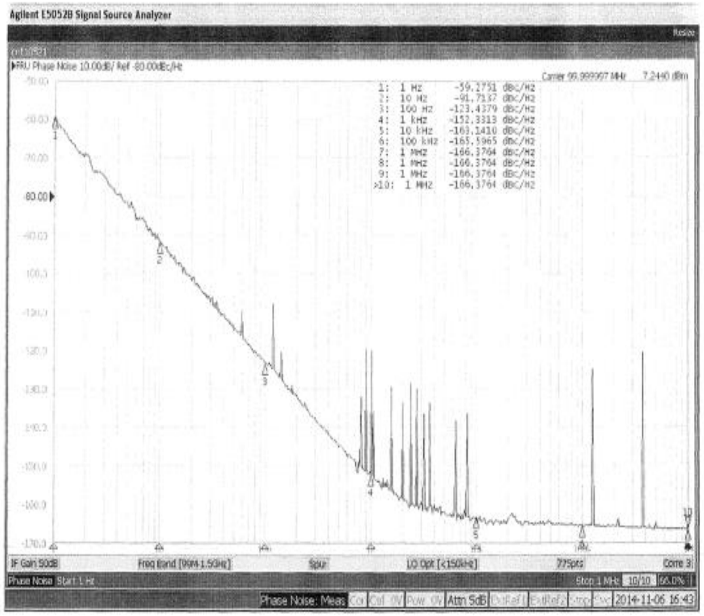
PCB Mount Package

Connectorized Package

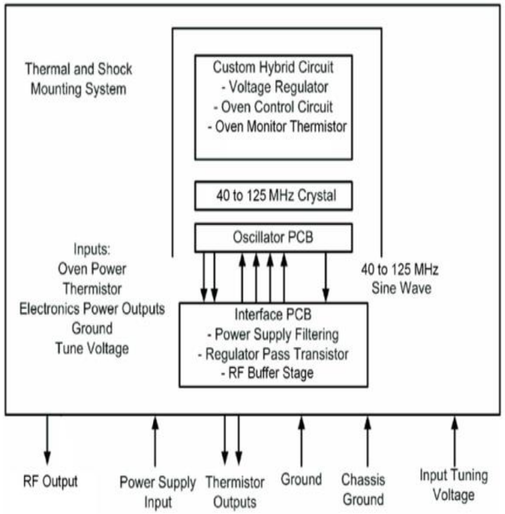
9800 Ovenized Crystal Oscillators (OCXO)

- 40-200 MHz output frequency
- Low power consumption < 1.3 W at 25°C in thermal vacuum
- Low phase noise: < -105 dBc / Hz at 10 Hz for 50 MHz
- Superior ADEV: < $5e^{-12}$ at 1 second for 50 MHz
- Aging of less than 1 ppm over 20 years
- MTBF of six million hours
- 300 krad (Si) hard and SEL immune

9800 100 MHz Phase Noise

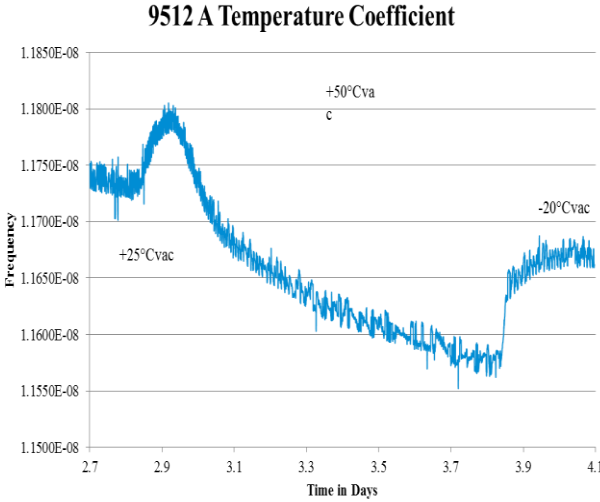


9800 Block Diagram



Microsemi 9500 Ultra Stable Oscillator

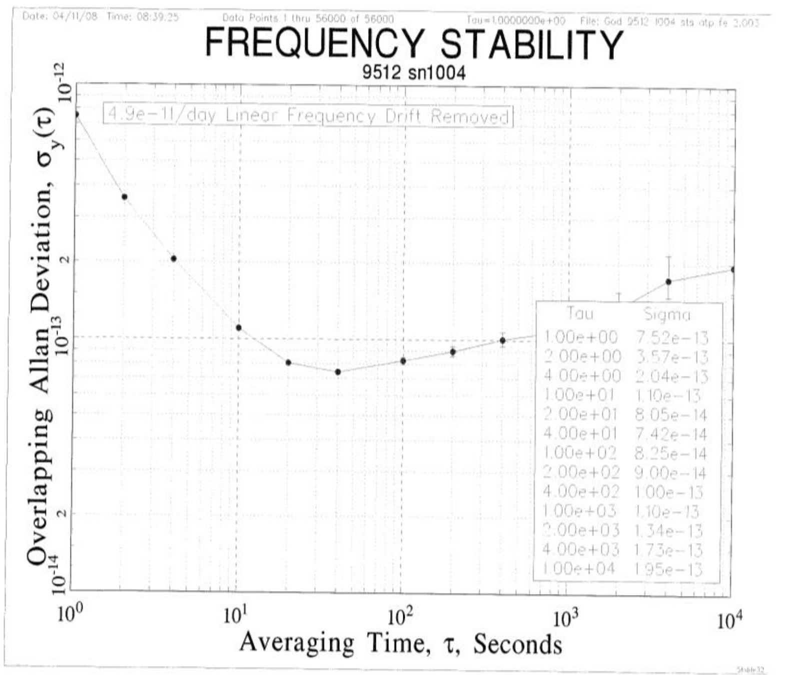
- **Highest Performance Commercially available oscillator**
  - Temperature Stability < 3 x 10^{-12}/ °C
  - Frequency Stabilities < 1 x 10^{-13} for τ=1-100 seconds
- **Key Programs**
  - GPS III – Navigation Payload Master Reference Oscillator
  - SBIRS High – Master Reference Oscillator
  - Lunar Reconnaissance Orbiter
  - EOS – AM
  - SkyFox Platform Timing Module



Microsemi 9500 Ultra Stable Oscillator

- Performance is achieved by using complex isothermal oven design
- Capability for digital frequency control using FPGA
- Multiple output frequency
- Internal vibration and shock isolation system

9500B Measure Allan Deviation

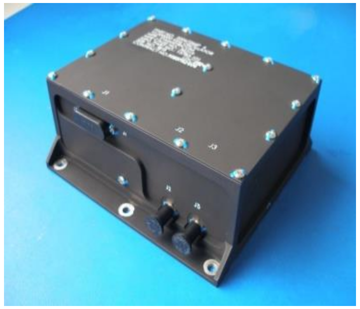


9500B Measure Allan Deviation

	Adev - Typical Performance
T=1 second	1.1×10^{-13}
T=10 seconds	1.3×10^{-13}
T=100 seconds	1.5×10^{-13}

Oscillator Subsystems

- Sub-systems have been delivered that include:
  - Multiple and/or redundant Oscillators
  - Power Supplies
  - Frequency multipliers and synthesizers
  - Integrated thermal baseplate controllers for improved performance
- Mechanical Survivability
  - 3000 g’s pyroshock
  - Greater than 20 grms



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Space Qualified Crystal Oscillators

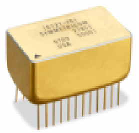
Model	Characteristics
9500B	• **5-600MHz (OCXO)** • World-class Phase Noise and Allan Deviation performance < 1e-13 • High resolution Frequency Control • Integrated mechanical shock isolation
9600 **9700**	• **5-25 MHz (OCXO)** • Compact form-factor with ruggedized construction • Exceptional low-noise/high stability
9800	• **50-200 MHz OCXO**
9960/ **9940**	•**10-600 MHz (TCXO/VCXO)** • Through hole or surface mount options • Hybrid space qualified oscillators

* These Oscillators are available in various frequencies ranges and can be customized to meet customer specific requirements.

9500B

9600/9700

9960



9800

SDA "Quick Turn"(QT) Products Key Features

Model	Key Features
9800QT (50MHz), 9801QT (100MHz)	• 50MHz & 100MHz (OCXO) • Excellent STS (5E-12 @1 sec) • Smallest Package size 1.33"x 1.33"x 1.33" • Short lead times • **< 4weeks (Engr. Model), <12weeks (Flight Model)**
9600QT (5MHZ), 9601QT (10MHz)	• 5MHz and 10 MHz OCXO (STD) • Compact form-factor •Exceptional low-noise/high stability •Strong Space Flight Heritage • Short lead times • **< 4weeks (Engr. Model), <12weeks (Flight Model)**
9635QT	•10MHz (OCXO) •Low Cost •Smallest Package size 1.33"x 1.33"x 1.33" •Excellent STS (4E-12 @1 sec) •**<4weeks "Off-The-Shelf Delivery"**

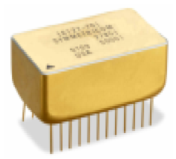
**9960QT (10MHz),
99601QT (50MHz)**
	•10MHz & 50MHz (TCXO)
	•Low- SWaP
	    • Size 24-pin ddip, 0.5" profile
	    • Weight <.03kg
	    •Power 220mW (Steady-state)
	• Hybrid space qualified oscillators
	• **<4weeks "Off-The-Shelf Delivery"**

9800QT

9600QT

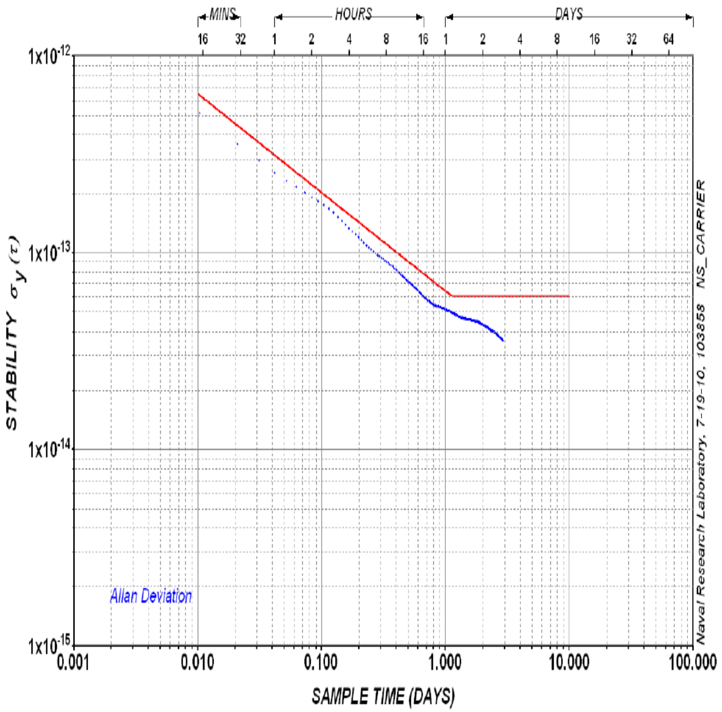
9635QT

9960QT



Model 4410 CAFS – Cesium Atomic Clock - GPS Block IIF

Parameter	Value
Output Frequency	10.23 MHz (nominal in-orbit)
Output Power	+18 dBm ±1.5 dB
Adjustment Range	$\pm 1 \times 10^{-9}$
Adjustment Resolution	1×10^{-15}
Accuracy	$\pm 1 \times 10^{-11}$
Reproducibility	$\pm 2 \times 10^{-12}$
Stability	$2 \times 10^{-11} \tau^{-1/2}$
Temperature Sensitivity	$< 5 \times 10^{-14}$/°C
Voltage Sensitivity	$< 1.3 \times 10^{-13}$/Volt
Magnetic Field Sensitivity	$< 1 \times 10^{-12}$/Gauss
Operating Temperature Range	0° to 50°C
Functional Temperature Range	-29° to 66°C
Size	6.25” x 7.70” x 16.50”
Weight	30 lbs
Power	29Watts



Conclusions

- Timing is a critical element to all satellites
- Space has been the foundation of Microsemi's timing technology from the Space borne Cesium clocks in the 1970’s to the next generation Satellite Timing modules of the future
- Microsemi designs, develops and delivers industry leading frequency and timing products with unsurpassed reliability

Model 4401 GPS Cesium Standard
NTS-2 and GPS I, II and IIA

9500B Ultra Stable Oscillator

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Thank You

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