Precision Oscillator Overview

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Discussion Outline

- Quartz Crystal Oscillators
- Atomic Oscillators
- Atomic Oscillator Size History & Future
- Performance Characteristics
Main Categories of Precision Quartz Oscillators

Temperature Compensated (TCXO)

Oven Controlled (OCXO)

Double Oven Controlled (DOCXO)

Quartz Crystal Oscillators have no wear out mechanism. If manufactured properly, should last 25 years or more.
Precision Crystal Oscillators from raw materials

- Dynamic Cleaning
- Crystal Cutting i.e. SC, AT, FC, etc
- Rounding
- Polishing
- Plating
- Mounting
- Tuning
- Sealing
- Testing

Typically 0.75” x 1.5” x 1.5”

Piezoelectric properties of quartz
Typical Resonator Package Examples

- 500 MHz, SAW Resonator
- FE-103A - CRYSTAL OSCILLATOR
  - Double Oven Design
  - With Excellent Stability: 1x10^-11/SEC
- 10 MHz, 3rd Overtone
  - SC (Stress-Free) Cut Crystal
- 5 MHz, 5th Overtone
  - SC (Stress-Free) Cut Crystal
The piezoelectric effect provides a coupling between the mechanical properties of a piezoelectric crystal and an electrical circuit.

Courtesy, John Vig (Ft. Monmouth NJ)
**Modes of Piezoelectric Motion**

<table>
<thead>
<tr>
<th>Flexure Mode</th>
<th>Extensional Mode</th>
<th>Face Shear Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness Shear Mode</td>
<td>Fundamental Mode Thickness Shear</td>
<td>Third Overtone Thickness Shear</td>
</tr>
</tbody>
</table>

Courtesy, John Vig (Ft. Monmouth NJ)
The AT, FC, IT, SC, BT, and SBTC-cuts are some of the cuts on the locus of zero temp. coefficient cuts.

Courtesy, John Vig (Ft. Monmouth NJ)
**Oven Effect on Temperature Coefficient**

Typical f vs. T characteristic for AT and SC-cut resonators

- **Oven Set Point**
- **Turnover Point**
- **Oven Offset**
- **Oven Cycling Range**

2Δ To

Courtesy, John Vig (Ft. Monmouth NJ)
Aging Mechanisms

- **Mass transfer due to contamination**
  Since $f \propto 1/t$, $\Delta f/f = -\Delta t/t$; e.g., $f_{5\text{MHz}} \approx 10^6$ molecular layers, therefore, 1 quartz-equivalent monolayer $\Rightarrow \Delta f/f \approx 1$ ppm

- **Stress relief** in the resonator's: mounting and bonding structure, electrodes, and in the quartz (?)

- **Other effects**
  - Quartz outgassing
  - Diffusion effects
  - Chemical reaction effects
  - Pressure changes in resonator enclosure (leaks and outgassing)
  - Oscillator circuit aging (load reactance and drive level changes)
  - Electric field changes (doubly rotated crystals only)
  - Oven-control circuitry aging
**Summary - Most Significant Effects**

**Temperature**
Control temperature deltas with ovens

**Frequency Aging**
Control aging with superior manufacturing technology

**Dynamic Environments (vibration, shock, acceleration)**
Control sensitivity with:
- Superior manufacturing technology
- Shock mounts
- Electronic g-compensation technology
**g-Compensation Technology**

The actual product encloses the disk with a cap.

The Quartz Disk responds to vibration applied to the Oscillator.

Sensing devices mounted in each axis respond.

Electronic Compensation

Oscillator Output
- Acceleration sensitivities better than 2E-12/g
- Improvements of greater than 30dB
- Optimized compensation from DC to 200 Hz
- Broadband compensation from DC to 2 KHz is possible
- Economies in manufacturability
- Small package < 5in³
Discussion Outline

- Quartz Crystal Oscillators
- **Atomic Oscillators**
- Atomic Oscillator Size History & Future
- Performance Characteristics
**Stand-alone Precision Oscillator Technologies**

- **Rubidium Vapor Atomic Oscillator**
  - Rb Vapor Phy Pkg
  - Qz Osc. (Out)
  - Qz oscillator frequency-locked to Hyperfine Rb frequency of ~6.8 GHz

- **Cesium Beam Atomic Standard**
  - Cs Beam Phy Pkg
  - Qz Osc. (Out)
  - Qz oscillator frequency-locked to Hyperfine Cs frequency of ~9.2 GHz

- **Hydrogen Maser Atomic Oscillator**
  - Hm Fountain Phy Pkg
  - Qz Osc. (Out)
  - Qz oscillator frequency-locked to Hyperfine Hm frequency of ~1.4 GHz (Passive Hm) or Phase-locked to ~1.4 GHz (Active Hm)
**Atomic Energy Levels**

**Electron Energy Levels** - Electrostatic interaction between Proton and Electron (+ and - charges)

- Collapsing the orbit releases energy
- Expanding orbit requires energy

**Fine Structure** - Interaction between electron spin dipole moment and the magnetic field due to the electron’s orbital motion. ~1/50 of the first energy level.

- (Energy out or in is generally in the infrared-visible-UV frequencies)

**Hyperfine Structure** - Magnetic dipole interaction between the electron spin dipole moment with the nucleus. ~1/1000 of fine structure interaction.

- (Energy out or in is generally in the microwave frequency area)

- \( f \approx 1.4 \text{ GHz for Hydrogen} \)
- \( f \approx 6.8 \text{ GHz for Rubidium} \)
- \( f \approx 9.2 \text{ GHz for Cesium} \)

**Zeeman Effect** - Magnetic interaction between external magnetic field and electron and proton spin dipoles.

- (Energy out or in is generally in the audio frequency area and above)

(Courtesy: Ed Mattison, Smithsonian from his tutorial 12-92 (a H. Fruehauf modification of his chart)
### Periodic Table of the Elements

<table>
<thead>
<tr>
<th>Group</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>IIA</td>
<td>Na, Mg</td>
</tr>
<tr>
<td>IIIA</td>
<td>Al, Si, P, S, Cl, Ar</td>
</tr>
<tr>
<td>IVA</td>
<td>C, N, O, F</td>
</tr>
<tr>
<td>VA</td>
<td>F, Ne</td>
</tr>
<tr>
<td>VIA</td>
<td>Ne, Ar</td>
</tr>
<tr>
<td>VIIA</td>
<td>K, Rb, Cs</td>
</tr>
<tr>
<td>VIIIB</td>
<td>Fe, Co, Ni</td>
</tr>
<tr>
<td>VIIIB</td>
<td>Zn, Cd, Hg</td>
</tr>
<tr>
<td>VIIIB</td>
<td>Sn, Sb, Te</td>
</tr>
<tr>
<td>VIIIB</td>
<td>Pb, Bi, Po</td>
</tr>
</tbody>
</table>

**Table of Radioactive Isotopes**

<table>
<thead>
<tr>
<th>Element</th>
<th>Isotopes</th>
<th>Decay Mode</th>
</tr>
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<tbody>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
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</tbody>
</table>

Naturally occurring radioactive isotopes are indicated by a blue mass number. Half-lives are in parentheses when it is known; only elements with half-lives of more than one year are listed. Elements with a mass number of 1 are not radioactive.

**Notes:**
- Periodic table data is based on the work of the International Union of Pure and Applied Chemistry (IUPAC) and the International Union of Pure and Applied Chemistry (IUPAC).
- The table includes information on atomic number, atomic weight, electron configuration, oxidation states, and common compounds.
- The periodic table is organized by increasing atomic number, with elements grouped by similar chemical properties.

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Atomic Vapor Oscillators have no wear out mechanism. If manufactured properly, should last 25 years or more.

Atomic Vapor Oscillator

87Rb  85Rb
Glass Cells (3)
Heaters (2)
Lamp (4)
Rubidium (1)
(could also be a Laser Diode)

Servo (8)
Synth (8a)
Qz Osc (9)

Photo Cell (7)
DC+Mod Freq
~6.8 GHz
10 MHz

(1) Active Element of Choice
(2) Controlled Environment
(3) Element Container
(4) Atomic Pump
(5) Resonator
(6) Irradiation Source
(7) State Detector(s)
(8) Control Electronics
(9) Frequency Source

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Optical Pumping Process

Dip Due to Rb Resonance

Microwave Frequency: $f_c < f_{Rb}$, $f_c = f_{Rb}$, $f_c > f_{Rb}$

Modulated Photo Current Output

Cavity (6.834, 682, 613 GHz)

Frequency Modulation

6.8 GHz from Osc.

Resonance Cell

Spectral Line Filtered

Spectral Line Excited

87Rb Lamp

87Rb

Filter Cell

Photo Detector

(20 to 50 ns)

(≈0.15 ns)

N

S

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Modulation Scheme

Dip Due to Rb Resonance

Photo Current

Modulated Photo Current Output

Frequency Modulation

Microwave Frequency

$fc < f_{Rb}$

$fc = f_{Rb}$

$fc > f_{Rb}$

$fm$

$f$

~500 Hz

$fc = f_{Rb}$

$2fm$
Rubidium Vapor Atomic Oscillator

Physics Package

Size: ~1.5” x ~3” x ~3”
Cesium Beam Atomic Frequency Standard

Cesium Beam Atomic Frequency Standard

Cesium Oscillators have a wear out mechanism, mainly due to the detector getting noisy from un-gettered ions. It begins to show up in 7 to 10 years.
Passive Hydrogen Maser Atomic Oscillator

Passive H-Maser Oscillators have a wear out mechanism, mainly from Hydrogen depletion and Ion Pump failures, which begin to show up in 5 to 7 years.
Active Hydrogen Maser Atomic Oscillator

Active Hydrogen Maser Atomic Oscillator have a wear out mechanism, mainly from Hydrogen depletion and Ion Pump failures, which begin to show up in 3 to 5 years.

1. Active Element of Choice
2. Controlled Environment
3. Element Container
4. Atomic Pump
5. Resonator
6. Irradiation Source
7. State Detector(s)
8. Control Electronics
9. Frequency Source
10. Ion Pumps and Getters

(6) No Irradiation Source; the Cavity Oscillates and thus is the Frequency Source, not the Qz Oscillator as in previous configurations.
Discussion Outline

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• Atomic Oscillator Size History & Future
• Performance Characteristics
Volume History of Rubidium and Cesium Osc.

Volume History of Rubidium and Cesium Osc.

~2400 in³ (HP, TRACOR, GENRAD)

~64 in³ (Efratom)

~350 in³ (FTS)

~6.4 in³ (AccuBeat)

~13 in³ (FEI, TNT)

~7.35 in³ (Symmetricom)

~5500 in³ (Lab)

~180 in³

~1 in³?

(DARPA Man-Pac Spec, Low Pwr)

~1.0 cm³ (my guess, HF)

~1 in³ = 16.4 cm³
Discussion Outline

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- Performance Characteristics
# Accuracy, Precision, and Stability

<table>
<thead>
<tr>
<th></th>
<th>Time</th>
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<th>Time</th>
<th></th>
<th>Time</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Precise but</td>
<td></td>
<td>Not accurate</td>
<td></td>
<td>Accurate but</td>
<td></td>
<td>Accurate and</td>
</tr>
<tr>
<td>not accurate</td>
<td></td>
<td>not precise</td>
<td></td>
<td>not precise</td>
<td></td>
<td>precise</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Stable but</td>
<td></td>
<td>Not stable</td>
<td></td>
<td>Accurate but</td>
<td></td>
<td>Stable and</td>
</tr>
<tr>
<td>not accurate</td>
<td></td>
<td>and not</td>
<td></td>
<td>not stable</td>
<td></td>
<td>accurate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>accurate</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

- **Precise but not accurate**: Precise timing is indicated by the center of the target being close to the target center, but the spread of the dots suggests variability. This implies that while close to the target, the variability is significant, indicating precision but not accuracy.

- **Not accurate and not precise**: The center of the target is far from the target center, and the spread of the dots is wide, indicating both inaccuracy and lack of precision.

- **Accurate but not precise**: The center of the target is close to the target center, indicating accuracy, but the spread of the dots is wide, indicating lack of precision.

- **Accurate and precise**: The center of the target is both close to the target center and the spread of the dots is narrow, indicating both accuracy and precision.

- **Stable but not accurate**: The red line (frequency) fluctuates around the target value (0 Hz), indicating stability but not being close to the target, indicating stability but lack of accuracy.

- **Not stable and not accurate**: The red line fluctuates significantly and is far from the target value, indicating both instability and lack of accuracy.

- **Accurate but not stable**: The red line fluctuates around the target value, indicating accuracy, but not being stable, indicating precision but lack of stability.

- **Stable and accurate**: The red line fluctuates slightly and is close to the target value, indicating both stability and accuracy.
Qz Osc Best-in-Class Frequency Domain Noise
(Phase Noise for a 10 MHz Carrier)
$\mathcal{L}(f)$ Phase Noise at 6.3 MHz (dBc/Hz)

FEI 6.3 MHz LN Osc. Test Plot, 03-09-2006

- Measurement problem; should be at -165 floor
- HP 10811 Qz
- FEI State of Art Equivalent for 10 MHz

Input 6.3 MHz 6 dBm

Reference 5.0 MHz 6 dBm

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**Qz Osc Best-in-Class Time Domain Noise**
*(Short-term Stability for 10 MHz)*

![Graph showing Qz Osc best-in-class time domain noise for 10 MHz](image)

- **HP 10811 Qz**
- **FEI-Zyfer 10 MHz- LN Module (- 4036)**
- **FEI State of Art**

**Legend:**
- **1 Day**
- **10 Hrs.**
- **1 Hr**

**Averaging Time, T(Sec.)**

**Allan Variance**, $\sigma_y(\tau)$

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Comparison of Qz, Rb, GPS, Cs, and Maser Time Domain Noise

(Allan Variance)\(^{1/2}\), \(\sigma_y\) vs. Averaging Time, T(Sec.)

- Sym 5061A, Cs
- Sym 5071A, Cs
- GPS-Disciplined Qz/Rb
- Good Qz Osc
- High Performance Rb
- VREM
- VCH-1006 Passive Maser
- Kvarz Passive Maser
- Kvarz Active Maser
- Sym 5071A Option 001 Cs

- 1 Hr
- 10 Hrs.
- 1 Day
- 1 Week
- 1 Mo.
Stability & Accuracy of Precision Oscillators

Short & Long Term Stability

Approx. Time Error at One Day (Lab Conditions)

Low Cost Rb
STD. Cs
GPS/Rb (Cs Substitute)
Space Qz & Super OCXO
Hi-Perf. Cs & Space Rb
Hi-Perf. Rb
Hi-Perf. Cs & Space Rb
Hi-Perf. Space Rb
Hi-Perf. Rb + Low Cost Space Rb
GPS/Rb (Cs Subst) & STD. Cs

Range

Accuracy

Averaging Time in Seconds

Elapsed Time

1-Day
1-Year

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500 MHz Osc Output; Best-in-Class Frequency Domain Noise (Qz and SAW combo)
# Typical Specs for Precision Quartz Oscillators

<table>
<thead>
<tr>
<th>Basic Parameters</th>
<th>TCXO (Temp. Comp. XO)</th>
<th>OCXO (0.5” High) (Oven Control XO)</th>
<th>OCXO (0.75” High) (Oven Control XO)</th>
<th>DOCXO (Double Oven XO)</th>
<th>For Reference Only Rubidium Osc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
<td>10 MHz, Sine 0.5Vrms, 50Ω</td>
<td>10 MHz, Sine 0.5 Vrms, 50 Ω</td>
<td>10 MHz, Sine 0.5 Vrms, 50 Ω</td>
<td>10 MHz, Sine 0.5 Vrms, 50 Ω</td>
<td>10 MHz, Sine 0.5 Vrms, 50 Ω</td>
</tr>
<tr>
<td>Short Term Stab.</td>
<td>1s 1E-9 5E-10</td>
<td>5E-12 1E-11</td>
<td>5E-12 1E-11</td>
<td>5E-12 1E-11</td>
<td>3E-11 7E-12 3E-12</td>
</tr>
<tr>
<td></td>
<td>10s 1E-10</td>
<td>1E-11</td>
<td>1E-11</td>
<td>1E-11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100s 5E-10</td>
<td>1E-10</td>
<td>1E-10</td>
<td>1E-10</td>
<td></td>
</tr>
<tr>
<td>Phase Noise,</td>
<td>1Hz - 55 dBC/Hz</td>
<td>- 80 dBC/Hz</td>
<td>- 90 dBC/Hz</td>
<td>- 90 dBC/Hz</td>
<td>-75 dBC/Hz</td>
</tr>
<tr>
<td></td>
<td>100Hz -115 dBC/Hz</td>
<td>-135 dBC/Hz</td>
<td>-135 dBC/Hz</td>
<td>-135 dBC/Hz</td>
<td>-125 dBC/Hz</td>
</tr>
<tr>
<td></td>
<td>1000Hz -130 dBC/Hz</td>
<td>-145 dBC/Hz</td>
<td>-145 dBC/Hz</td>
<td>-145 dBC/Hz</td>
<td>-145 dBC/Hz</td>
</tr>
<tr>
<td>Aging/Day/Month/Year</td>
<td>--- 5E-7/yr</td>
<td>5E-10/day 2E-7/yr</td>
<td>2E-10/day 2E-8/yr</td>
<td>2E-10/day 2E-8/yr</td>
<td>5E-11/day 5E-10/yr</td>
</tr>
<tr>
<td>Temp Range</td>
<td>0° to 75°C 5E-7</td>
<td>0° to 75°C 2E-8*</td>
<td>0° to 75°C 2E-9*</td>
<td>0° to 70°C 2E-10</td>
<td>0° to 60°C 3E-10</td>
</tr>
<tr>
<td>Frequency Stability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Consumption</td>
<td>50 miliwatts</td>
<td>2 watts</td>
<td>2.5 watts</td>
<td>3.5 watts</td>
<td>8 watts</td>
</tr>
<tr>
<td>Warm-up Time</td>
<td>50 milisecond</td>
<td>10 min, 1E-8</td>
<td>10 min, 1E-8</td>
<td>10 min, 1E-8</td>
<td>4 min, ~1E-9</td>
</tr>
<tr>
<td>Magnetic Field Sensitivity</td>
<td>--- 5 Vdc± 0.25%</td>
<td>--- 12 Vdc± 10%</td>
<td>--- 12 Vdc± 10%</td>
<td>--- 12 Vdc± 10%</td>
<td>2E-11/Gauss 15 to 28 Vdc</td>
</tr>
<tr>
<td>Input Volts Range</td>
<td>1E-8 for +/-10%</td>
<td>1E-9 for +/-10%</td>
<td>1E-9 for +/-10%</td>
<td>1E-9 for +/-10%</td>
<td>2E-11 for +/-10%</td>
</tr>
<tr>
<td>Supply Volts Sensitivity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>1.0&quot; x 0.7&quot; x 0.22&quot; H 0.154 in³ &lt; 0.1 lbs</td>
<td>1.5&quot; x 1.5&quot; x 0.5&quot; H 1.125 in³ &lt; 0.15 lbs</td>
<td>2.0&quot; x 2.0&quot; x 0.75&quot; H 3 in³ &lt; 0.22 lbs</td>
<td>2.0&quot; x 2.0&quot; x 1.0&quot; H 4 in³ &lt; 0.3 lbs</td>
<td>3.0&quot; x 3.0&quot; x 1.4&quot; H 13 in³</td>
</tr>
<tr>
<td>Volume</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Weight</td>
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* With GPS learning algorithm, X20 improvement