Frequency Electronics, Inc.

Tutorial
Precision Frequency Generation Utilizing OCXO and Rubidium Atomic Standards with Applications for Commercial, Space, Military, and Challenging Environments

IEEE Long Island Chapter
March 18, 2004

Olie Mancini
Vice President, New Business Development
Tel: +516-357-2464 *email: oliem@freqelec.com*

Acknowledgement:
Some of the following slides are provided courtesy of Dr. John R. Vig, U.S. Army Communications-Electronics Command

Agenda

- **Section 1: Quartz Oscillator Technology**
- **Section 2: Atomic Frequency Standards**
- **Section 3: Applications**
  - Commercial
  - Space
  - GPS
  - Radar
- **Section 4: Breakthrough in Vibration Effects on Clocks Stabilities and Side Bands--Vibration Insensitive Oscillators???**
- **Reference Charts**

Section 1

Quartz Technology

Hierarchy Of Oscillators

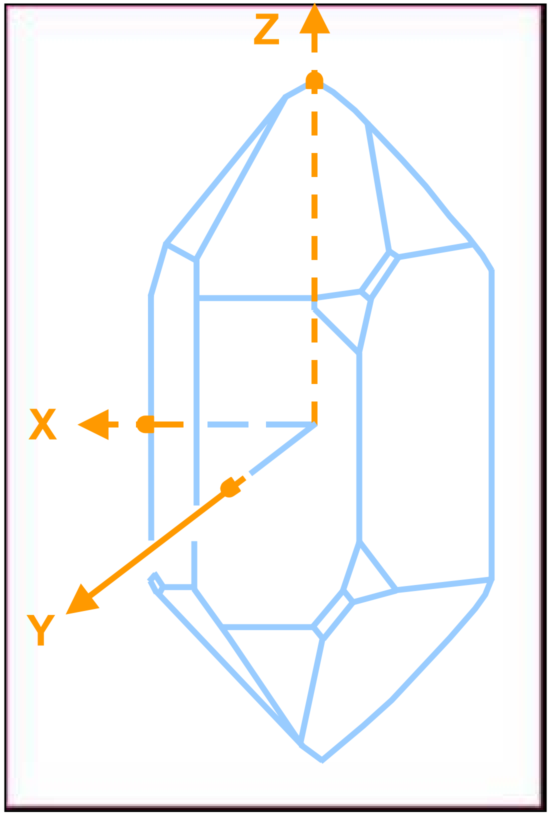
Oscillator Type *	Accuracy**	Aging/ 10 year	Radiation Per RAD	Power	Weight
Crystal oscillator (XO)	10^{-5} to 10^{-4}	10-20 PPM	-2×10^{-12}	20 µW	20 gram
Temperature compensated crystal oscillator (TCXO)	10^{-6}	2-5 PPM	-2×10^{-12}	100 µW	50 gram
Microcomputer compensated crystal oscillator (MCXO)	10^{-8} to 10^{-7}	1-3 PPM	-2×10^{-12}	200 µW	100 gram
Oven controlled crystal oscillator (OCXO) - 5 to 10MHz - 15 to 100MHz	 10^{-8} 5×10^{-7}	 2×10^{-8} to 2×10^{-7} 2×10^{-6} to 11×10^{-9}	-2×10^{-12}	1 – 3 W	200-500 gram
Small atomic frequency standard (Rb, RbXO)	10^{-9}	5×10^{-10} to 5×10^{-9}	2×10^{-13}	6 – 12 W	1500-2500 gram
High Performance atomic standard (Cs)	10^{-12} to 10^{-11}	10^{-12} to 10^{-11}	2×10^{-14}	25 – 40 W	10000-20000 gram

* Sizes range from <5 cm^3 for clock oscillators to >30 liters for Cs standards. Costs range from <$5 for clock oscillators to >$40,000 for Cs standards.

** Including the effects of military environments and one year of aging.

Raw Quartz to Resonator

- Dynamic Cleaning
- Crystal Cutting i.e. SC, AT, FC, etc
- Rounding
- Contouring
- Polishing
- Plating
- Mounting
- Aging
- Sealing
- Test
- Into Oscillator

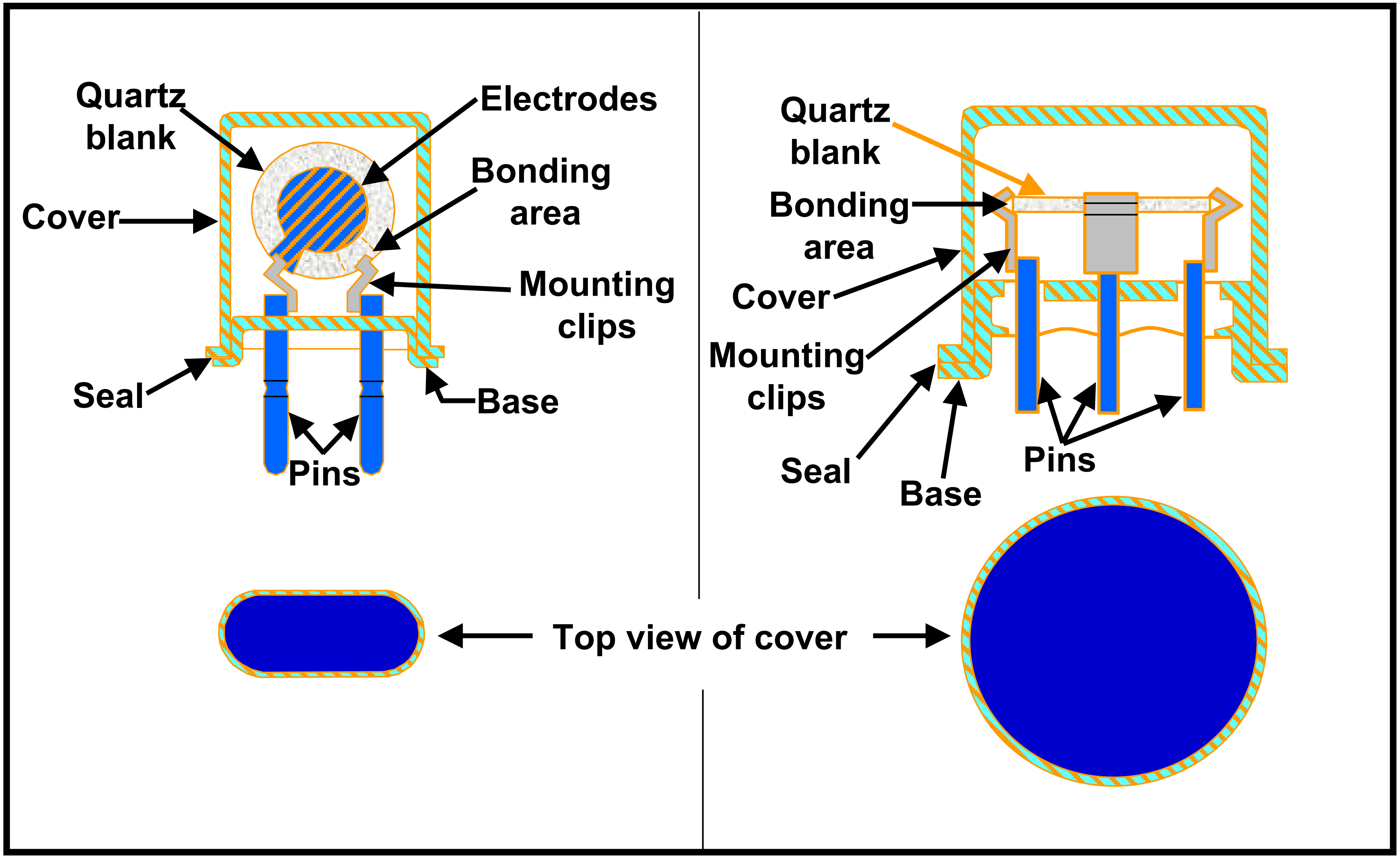


Piezoelectric properties of quartz

Resonator Packaging

Two-point Mount Package

Three- and Four-point Mount Package

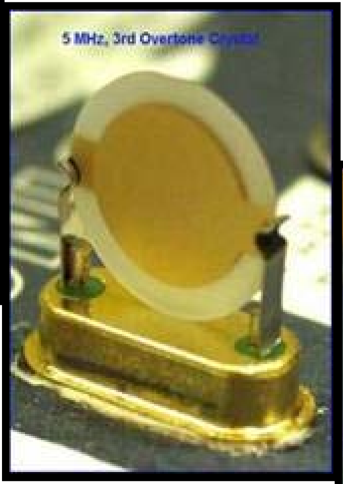


Crystal Technology Mounting Examples


500 MHz, SAW Resonator

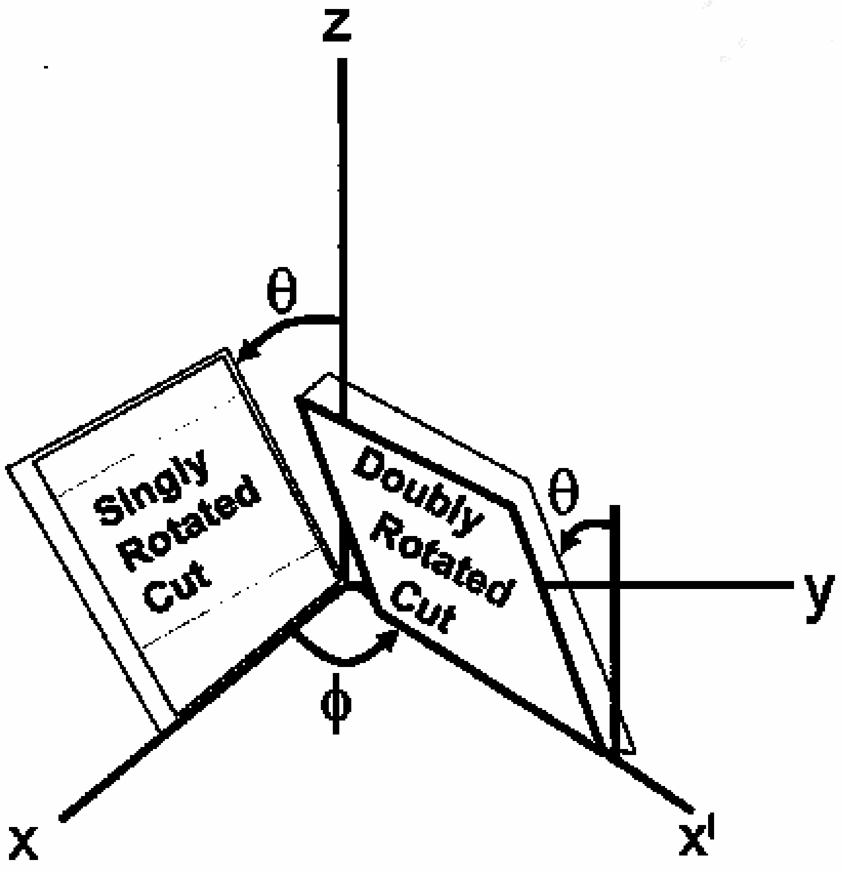

10 MHz, 3rd Overtone SC (Stress-Free) Cut Crystal


5 MHz, 5th Overtone SC (Stress-Free) Cut Crystal


5 MHz, 3rd Overtone Crystal


Split Ring Resonator

Crystallographic Axes

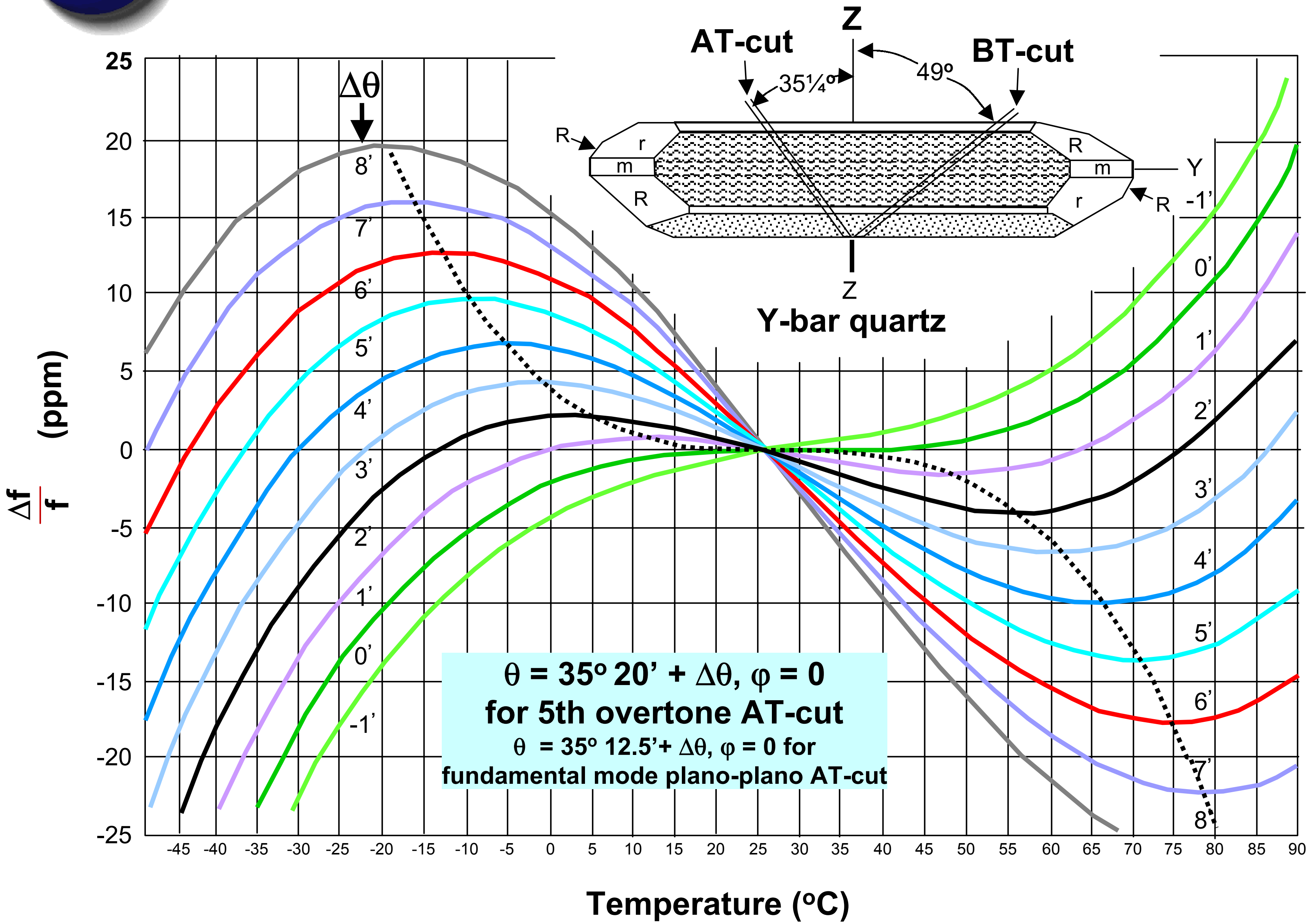


SC-Cut 21.93°

Frequency-Temperature vs. Angle-of-Cut

$\Delta\theta$

Frequency-Temperature vs. Angle-of-Cut, AT-cut

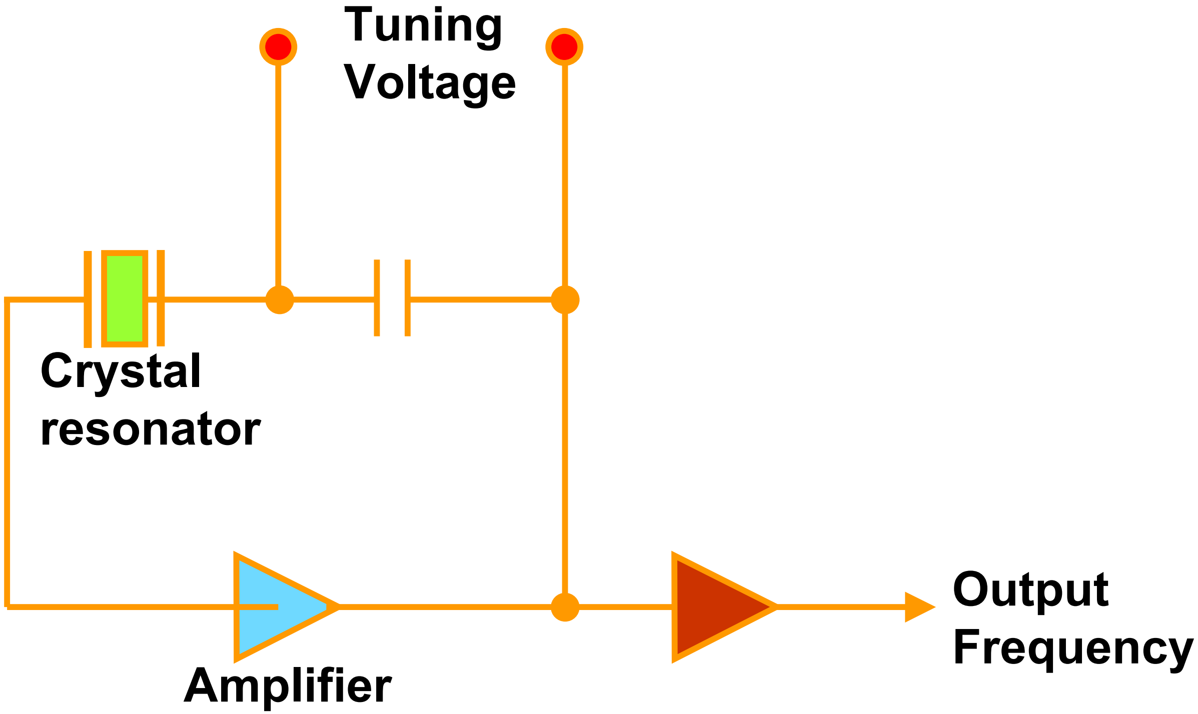


θ = 35° 20' + Δθ, φ = 0
for 5th overtone AT-cut
θ = 35° 12.5'+ Δθ, φ = 0 for
fundamental mode plano-plano AT-cut

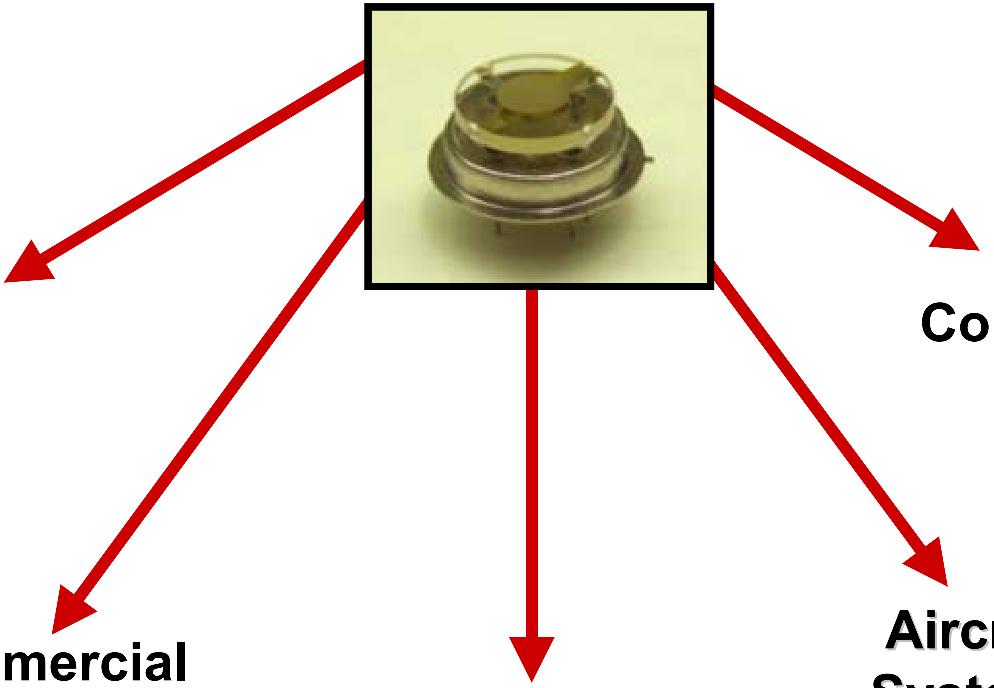
Sealing

- **Sealing**
  - **For precision oscillators cleanliness and purity is extremely important, and sealing takes place in atmospheric chambers down to 1E-9 Tor, and requires about 18 hours of pumping to achieve this atmospheric level**
- **Testing**

Typical Crystal Oscillator



Into Oscillators



Missile Systems

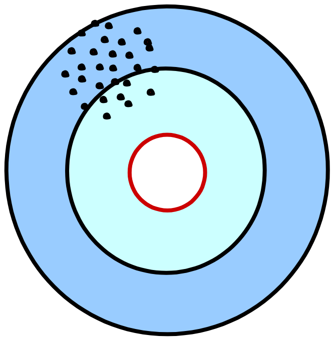
Secure Communications

Commercial Telecommunications

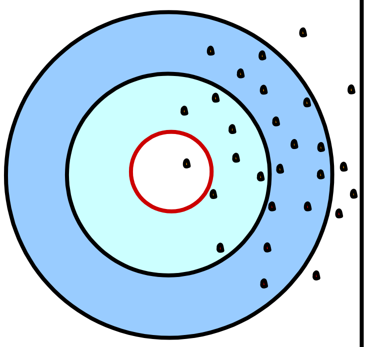
Space Applications

Aircraft Systems

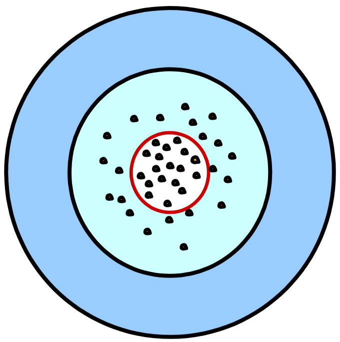
Accuracy, Precision, and Stability



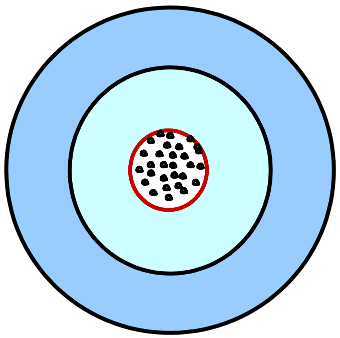
Precise but not accurate



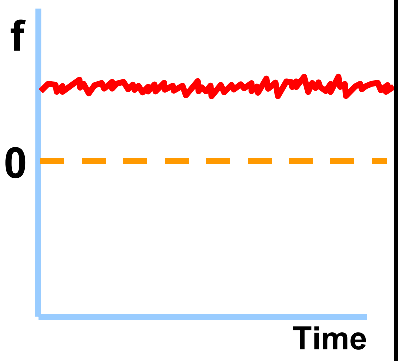
Not accurate and not precise



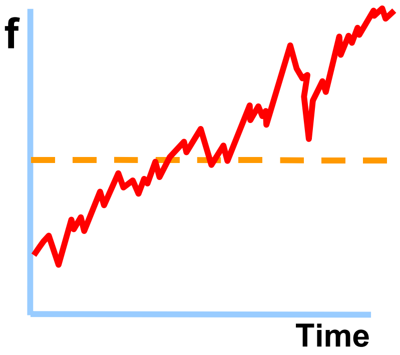
Accurate but not precise



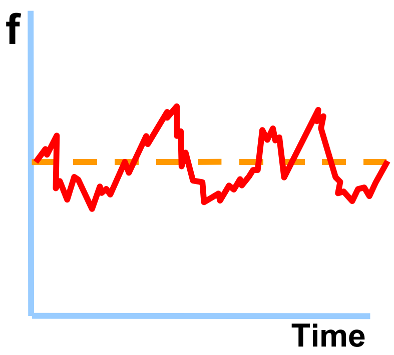
Accurate and precise



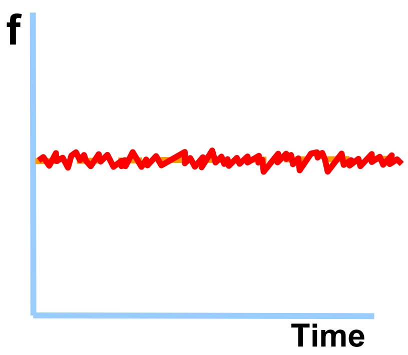
Stable but not accurate



Not stable and not accurate



Accurate but not stable



Stable and accurate

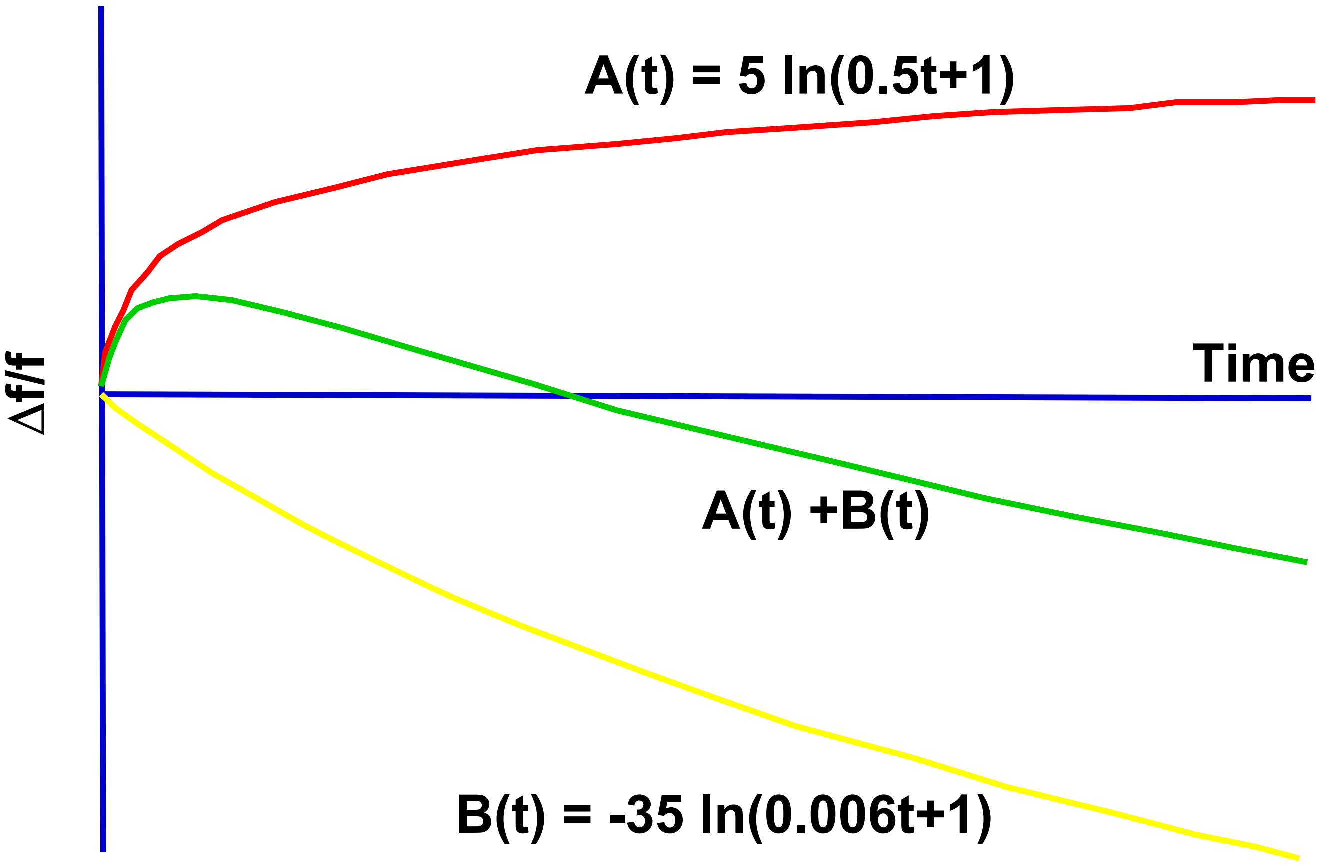
Oscillator Stability

- **Definitions:**
  - $1x10^{-10}$ = 1E-10 = $1e^{-10}$ = 1/10,000,000,000 = .000 000 000 1 or $0.1x10^{-9}$ = 0.1ppb.
  - Example: An Accuracy of $1x10^{-10}$ at 10MHz affects the frequency as shown on a sensitive freq meter

10,000,000.00$\underline{1}$ ← **Note that the milli-Hertz position is affected**

- **What Affects Oscillator Stability?**
  - Aging
  - Temperature
  - Radiation
  - Vibrations

Typical Aging Behaviors



Aging Mechanisms

- Mass transfer due to contamination
  Since f $\propto$ 1/t, $\Delta f/f = -\Delta t/t$; e.g., $f_{5MHz} \approx 10^6$ 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

QUARTZ CRYSTAL THICKNESS AS A FUNCTION OF CUT

$f = AK/t$

$t = AK/f$

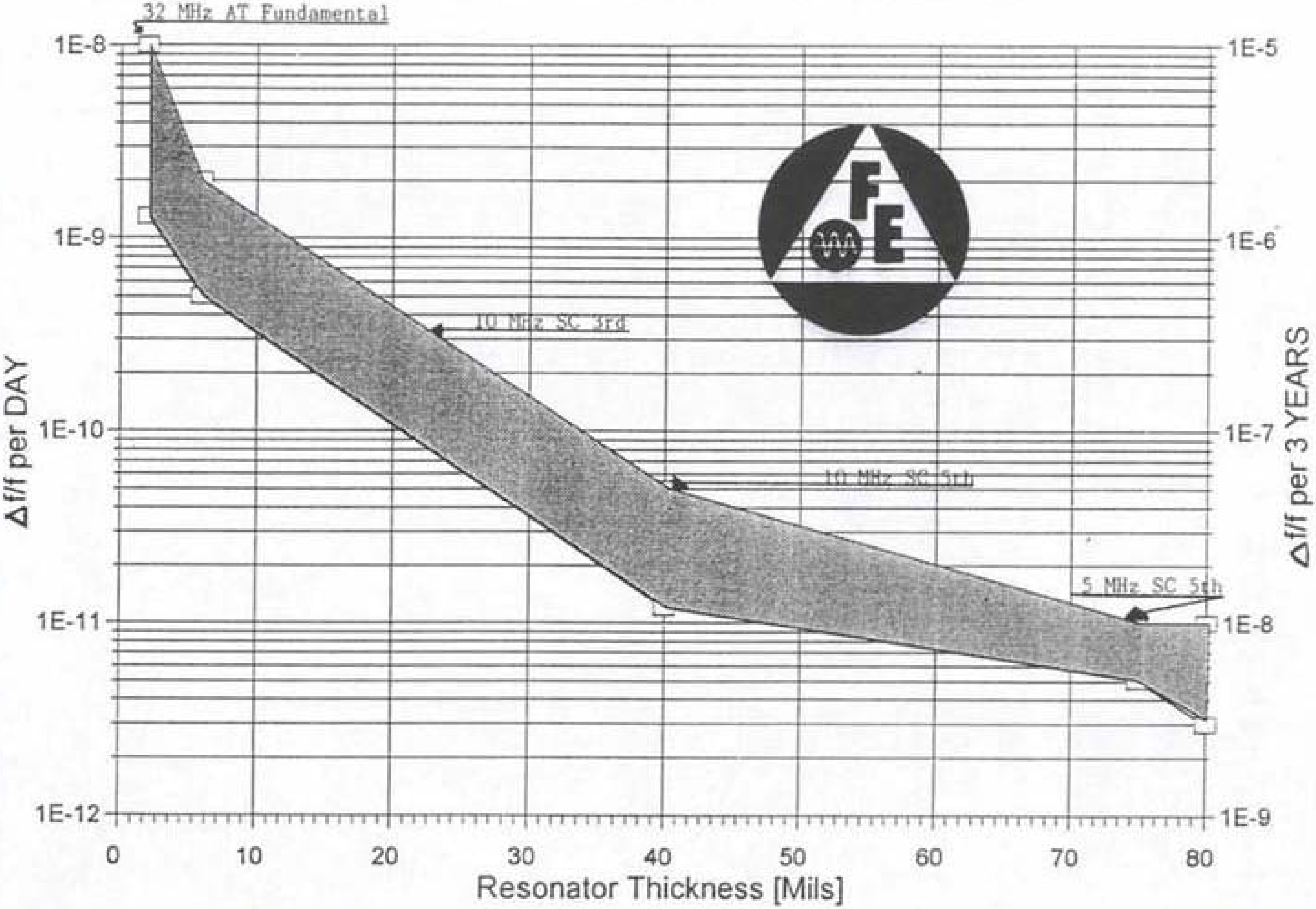
f = Frequency in MHz
A = Overtone (1, 3, 5, 7)
K = A constant (Mils)
t = Thickness in Mils

$K_{AT} = 65.5$ Mils
$K_{FC} = 68$ Mils
$K_{SC} = 72.3$ Mils

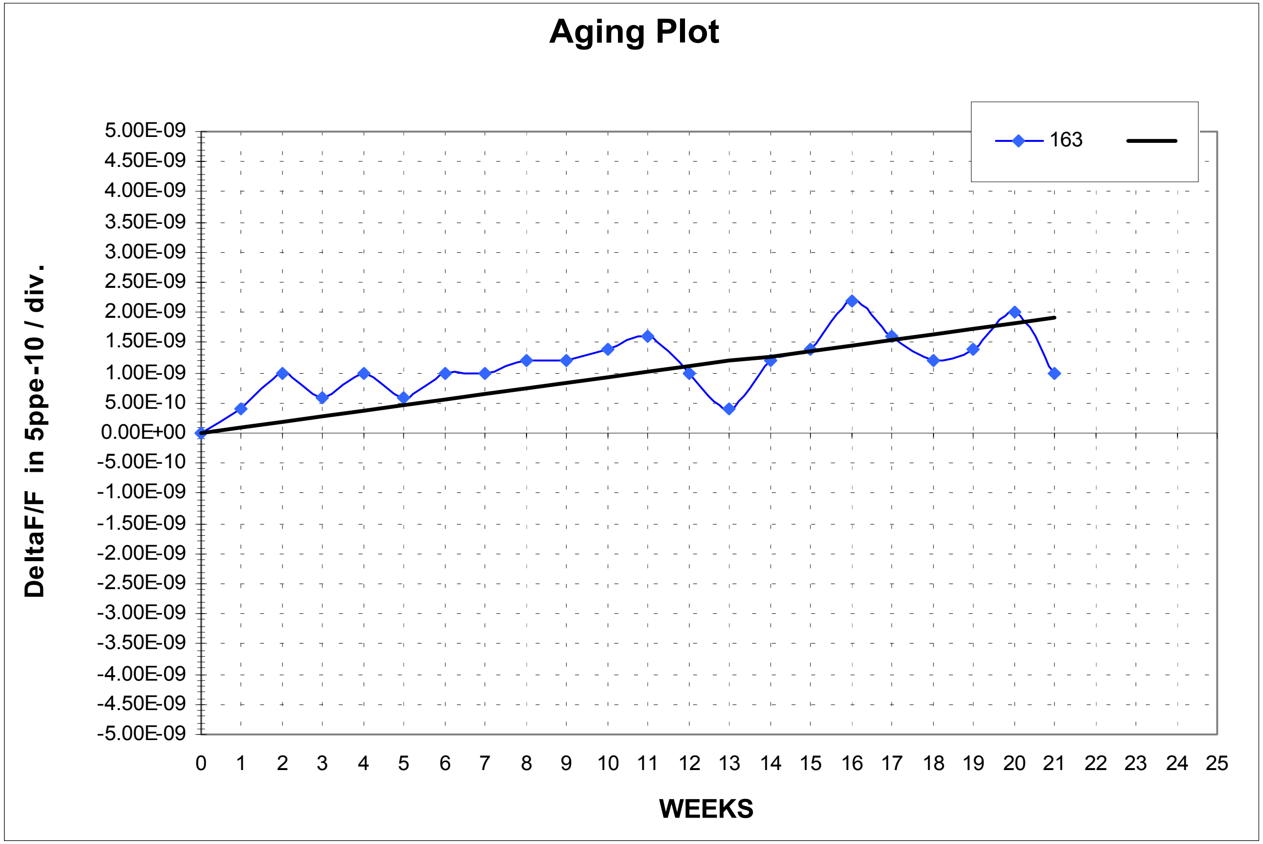
e.g.: $t = \frac{1 \times 65.5}{1} = 65.5$ mils thick for an AT cut Fundamental 1MHz crystal

- THICKNESS SHEAR QUARTZ RESONATORS ARE PREDOMINANTELY USED FOR MOST HIGH PRECISION QUARTZ APPLICATIONS.
- THE MOST USEFUL QUARTZ CRYSTAL CUTS ARE THE AT, FC AND SC.
- THE THICKEST QUARTZ BLANK SHOULD BE USED AT THE HIGHEST PRACTICAL OVERTONE FOR BEST AGING AND RETRACE PERFORMANCE.

CRYSTAL AGING vs RESONATOR THICKNESS



Typical Aging Plot



<u>Aging per day</u>

$18\text{x}10^{-10}/21\text{weekx}7\text{days}$

$\approx 1.2\text{x}10^{-11}$

<u>Aging after 10 years</u> linear approximation

$(1.2\text{x}10^{-11})(365\text{days})(10\text{year})$

$\approx 4.38\text{x}10^{-8}$

$\tau^{1/2} \approx (4.38\text{x}10^{-8})/2 \approx 2\text{x}10^{-8}$

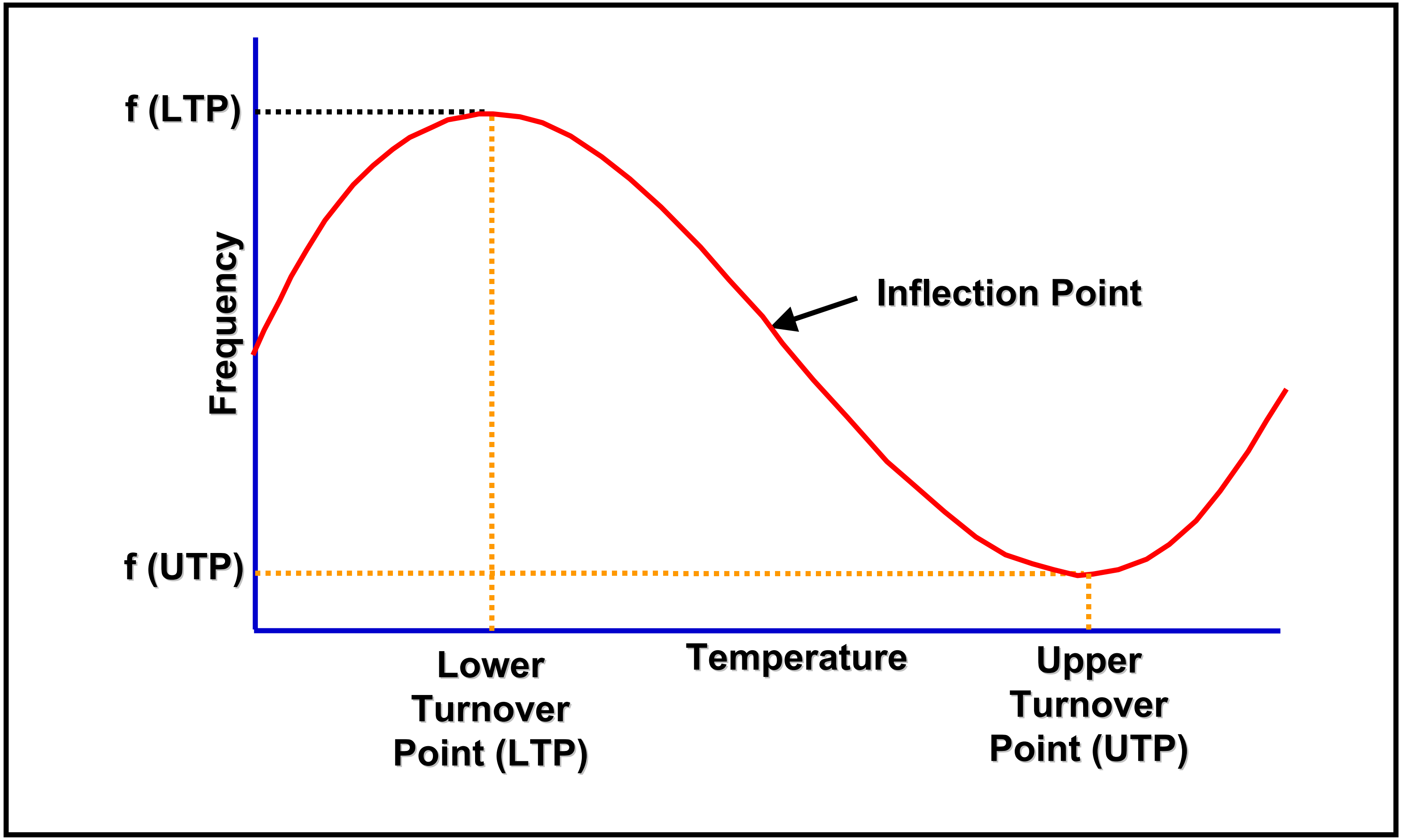
Temperature Effects

- **Crystal must be maintained at constant temperature over entire operating range**
  - Operating range may be from –40C to +85C
  - The more precise is the oven the better is the temperature coefficient

- **Precision ovens are constructed around the resonator and insulation is added around the oven to maintain a more uniform temperature gradient**

- **Ovens come in different sizes and shapes**
  - Single oven
  - Double oven
  - Ovens in Dewar Flasks for super precision

Frequency vs. Temperature Characteristics



Example of Super Precise Double Oven OCXO

(FE-205A Series)

2”W x 2”L x 1.5”H
For Through Hole Package

3”W x 3’’L x 1.4”H
For Rubidium Package

Example:
Effects of Aging and Temperature on a 10 MHz Quartz Oscillator

Example: Stability vs. Aging

- **Example: Aging Rate or Drift**
  - 10 MHz oscillator ages at ±5.1x10^{-9}/day (oscillator frequency may be expected to change by that amount per day times the number of days involved…WORSE CASE)
  - The measured frequency output after 1 days of operation could read:

    (10,000,000)(±5.1x10^{-9})(1 days) = ±0.051 Hz of 10 MHz or between

    10,000,000 +0.051 =10,000,000.051 Hz and

    10,000,000 – 0.051 = 9,999,999.049 Hz

Example: Temperature Effects

- **Temperature effects**
  - Assumptions:
    - 10 MHz oscillator that operates from -20^{o} C to $+70^{o}$ C and exhibits a frequency stability of 2×10^{-9} (temperature coefficient).
    - Oscillator will be used in an environment where the temperature varies only from -5^{o} C to $+50^{o}$ C.
  - The frequency error is calculated as follows:

    Temp Coeff per ^{o}C = Temp Coeff /total temperature range

    = 2×10^{-9} / 90 ^{o}C = 2.2×10^{-11}/ ^{o}C

    Error (-5^{o}C to $+50^{o}$C) = ($2.2\times10^{-11}/^{o}$C)(55^{o}C)= 1.2×10^{-9}

    Freq Error=(10,000,000)(1.2×10^{-9}) =.012 Hz =10,000,000.012

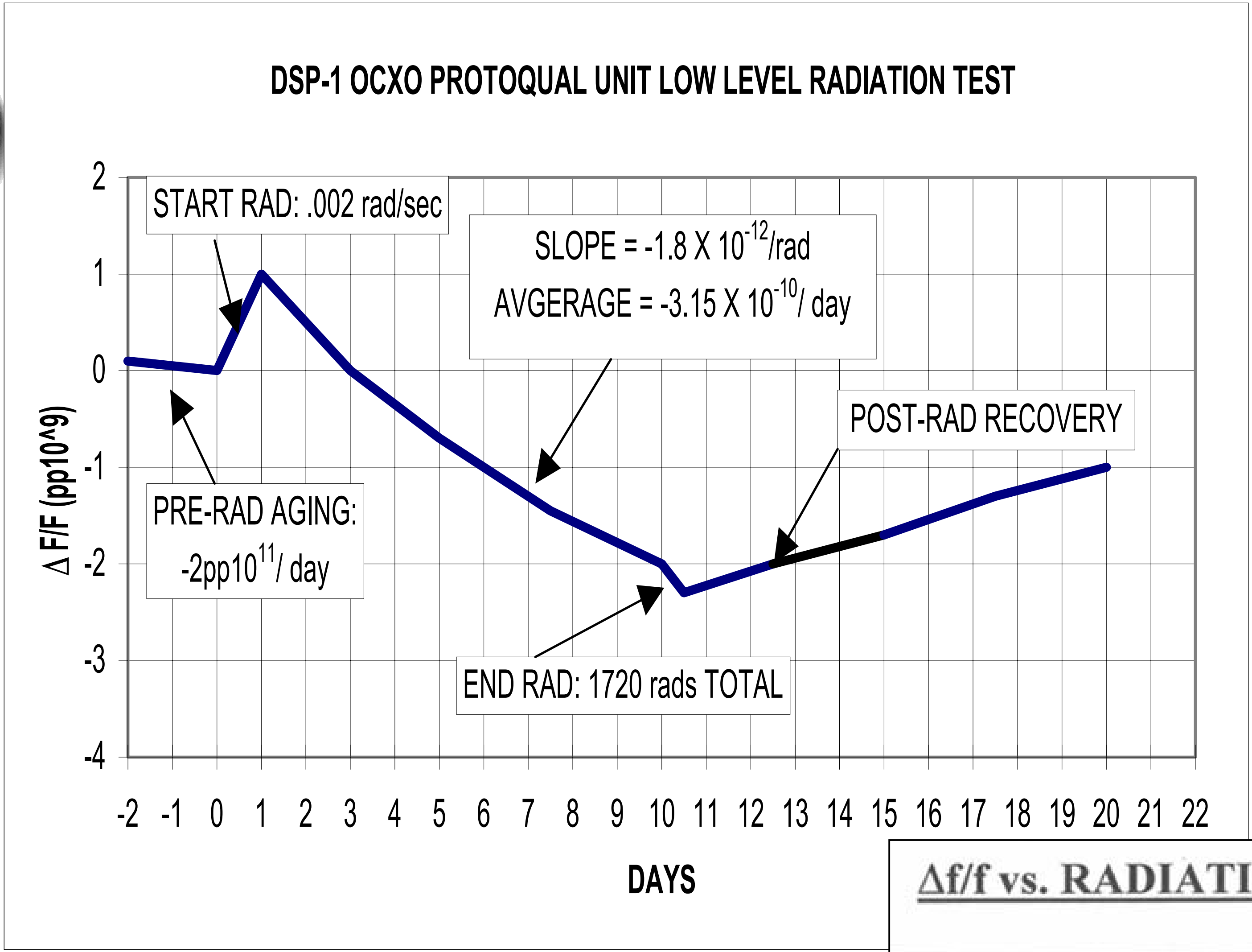
Total Error Due to Aging and Temperature

- **Total Error: Two major components**
  - Linear Drift (fractional frequency drift rate per day or F′) =0.051
  - Temperature (fractional frequency offset or Δf/f) =0.012
  - Total Frequency error 0.063 Hz
- **Or calculate a one day error as follows:**

  Drift (F′) $5.1\text{x}10^{-9}$
  Temp(Δf/f) $1.2\text{x}10^{-9}$
  Total Error at end of 24 hrs $6.3\text{x}10^{-9}$
  Effect on Freq: $(10{,}000{,}000)(6.3\text{x}10^{-9})=0.063$ Hz=10,000,000.063
- **Translate into accumulated *time* error:**

  For Linear Drift Rate Δt (in µsec) $=(4.32\text{x}10^{10})(F'\text{ per day})(\text{Days})^2$
  $=(4.32\text{x}10^{10})(5.1\text{x}10^{-9})(1)^2=$ 220 µsec
  For Linear Temper Δt (in µsec) $=(8.64\text{x}10^{10})(\Delta f/f)(\text{Days})$
  $=(8.64\text{x}10^{10})(1.2\text{x}10^{-9})(1)=$ 103 µsec
  Total accumulated time error in a day = 220 + 103 = 323 µsec
- **See Charts at end of presentation to easily determine accumulated time error**

Effects of Radiation on Aging

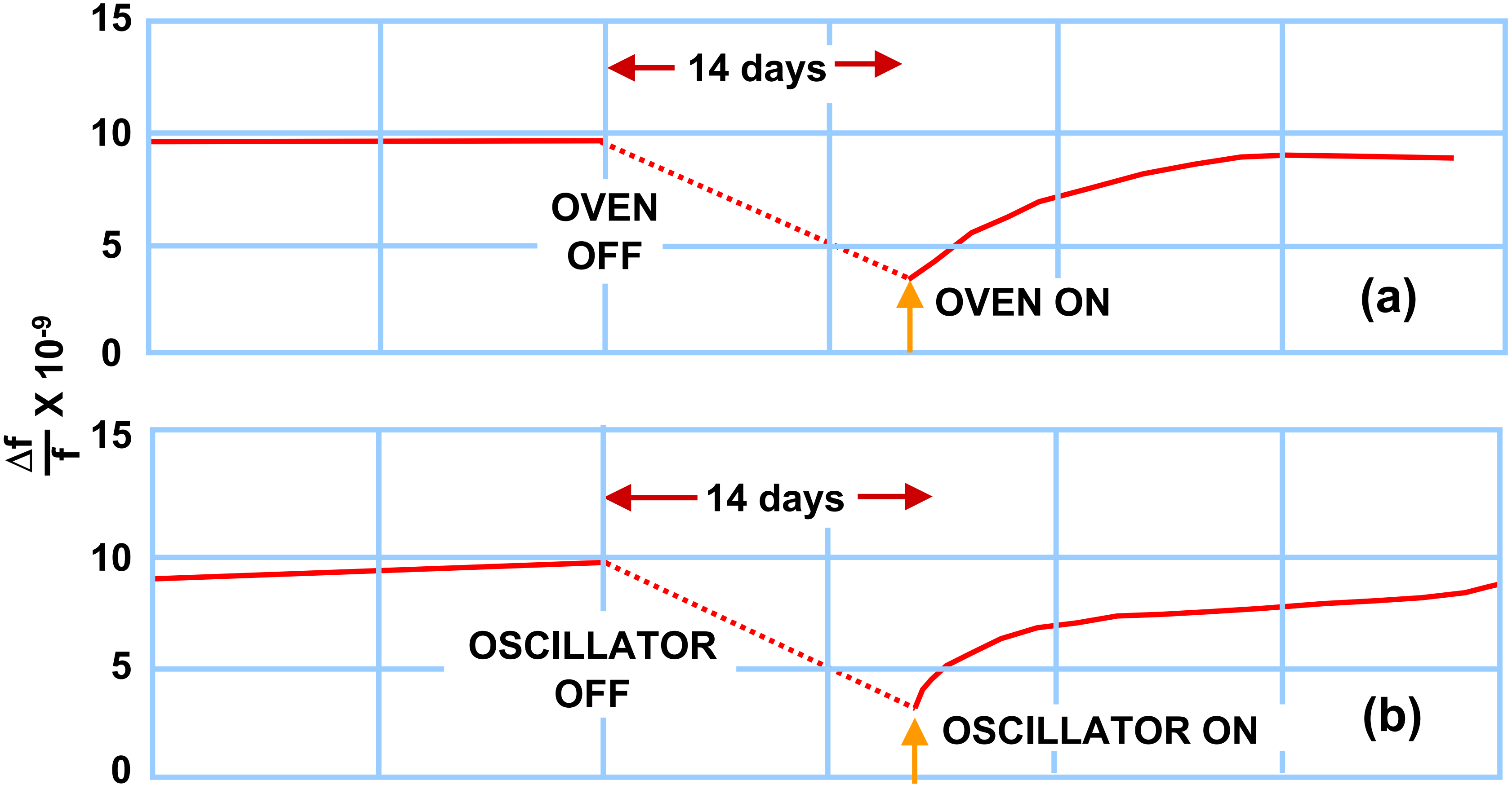


DSP-1 OCXO PROTOQUAL UNIT LOW LEVEL RADIATION TEST

Δf/f vs. RADIATION

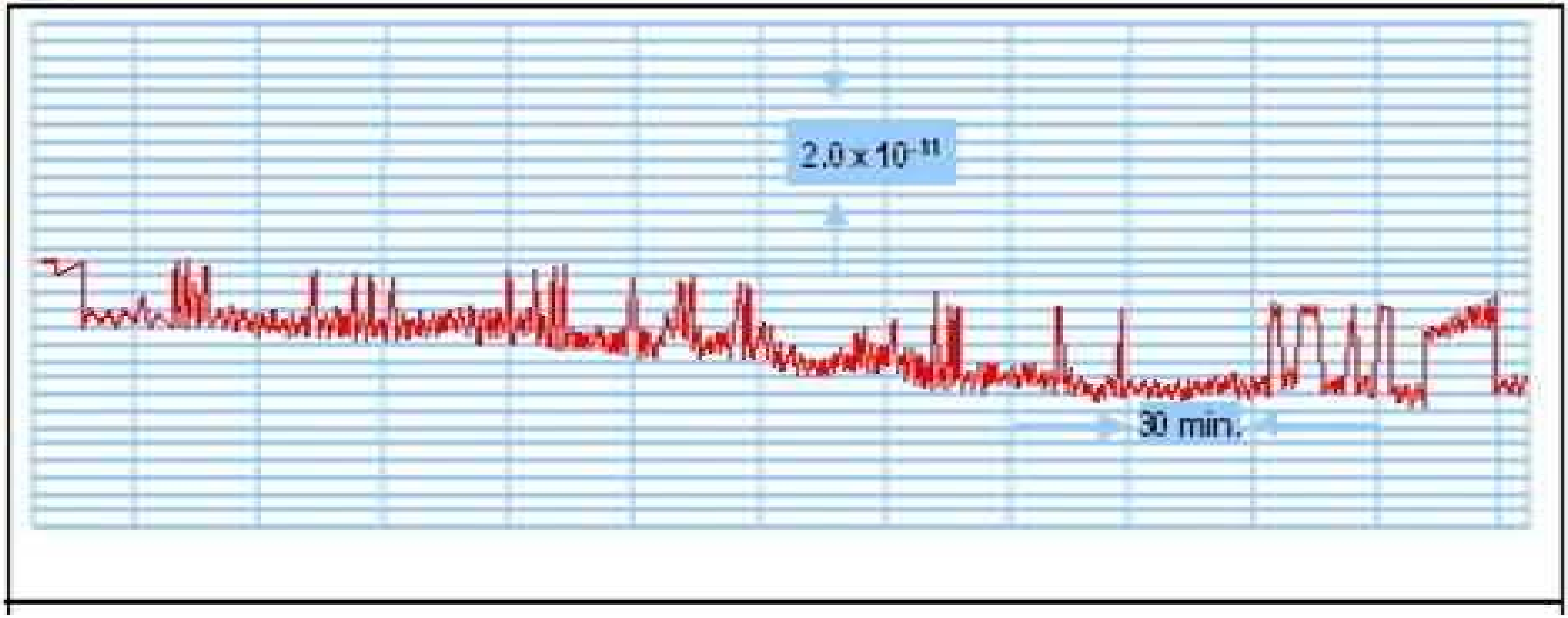
- $\approx -1 \times 10^{-12}$ / rad
- ≈ 6 rads / day
- -0.6×10^{-11} / day

OCXO Retrace



In (a), the oscillator was kept on continuously while the oven was cycled off and on. In (b), the oven was kept on continuously while the oscillator was cycled off and on.

Frequency Jumps
Unexplainable Oscillator Phenomenon



Frequency jumps occur in oscillators--in some many times a day in others less frequent.

Magnitude of jumps in precision oscillators are typically in the range of 10^{-11} to 10^{-9} .

The frequency excursion can be positive or negative.

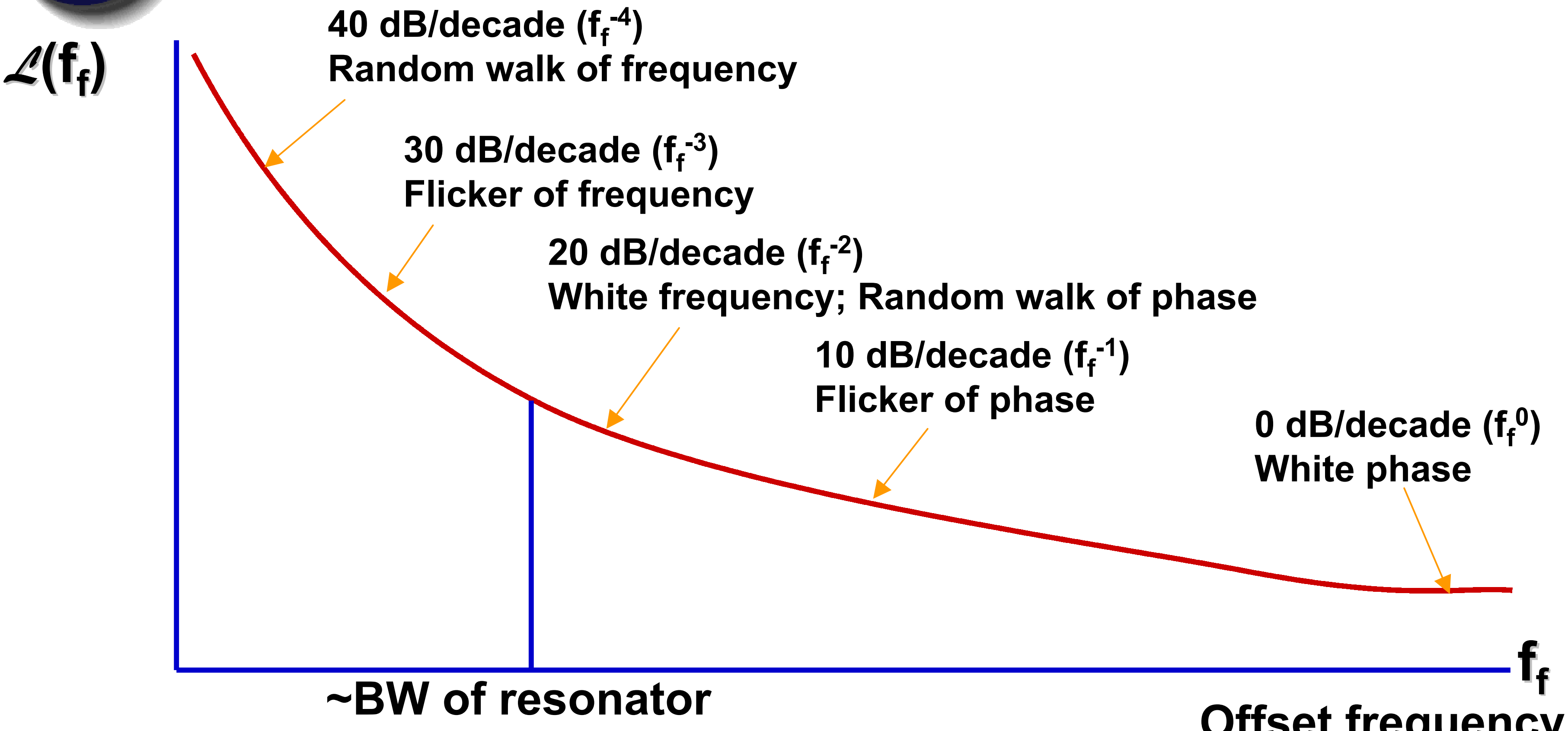
Noise in Crystal Oscillators

- The resonator is the primary noise source close to the carrier; the oscillator sustaining circuitry is the primary source far from the carrier.

- Frequency multiplication by N increases the phase noise by N^2 (i.e., by 20log N, in dB's).

- Vibration-induced "noise" dominates all other sources of noise in many applications
  (acceleration effects discussed later).

Types of Phase Noise



40 dB/decade (f_f^{-4})
Random walk of frequency

30 dB/decade (f_f^{-3})
Flicker of frequency

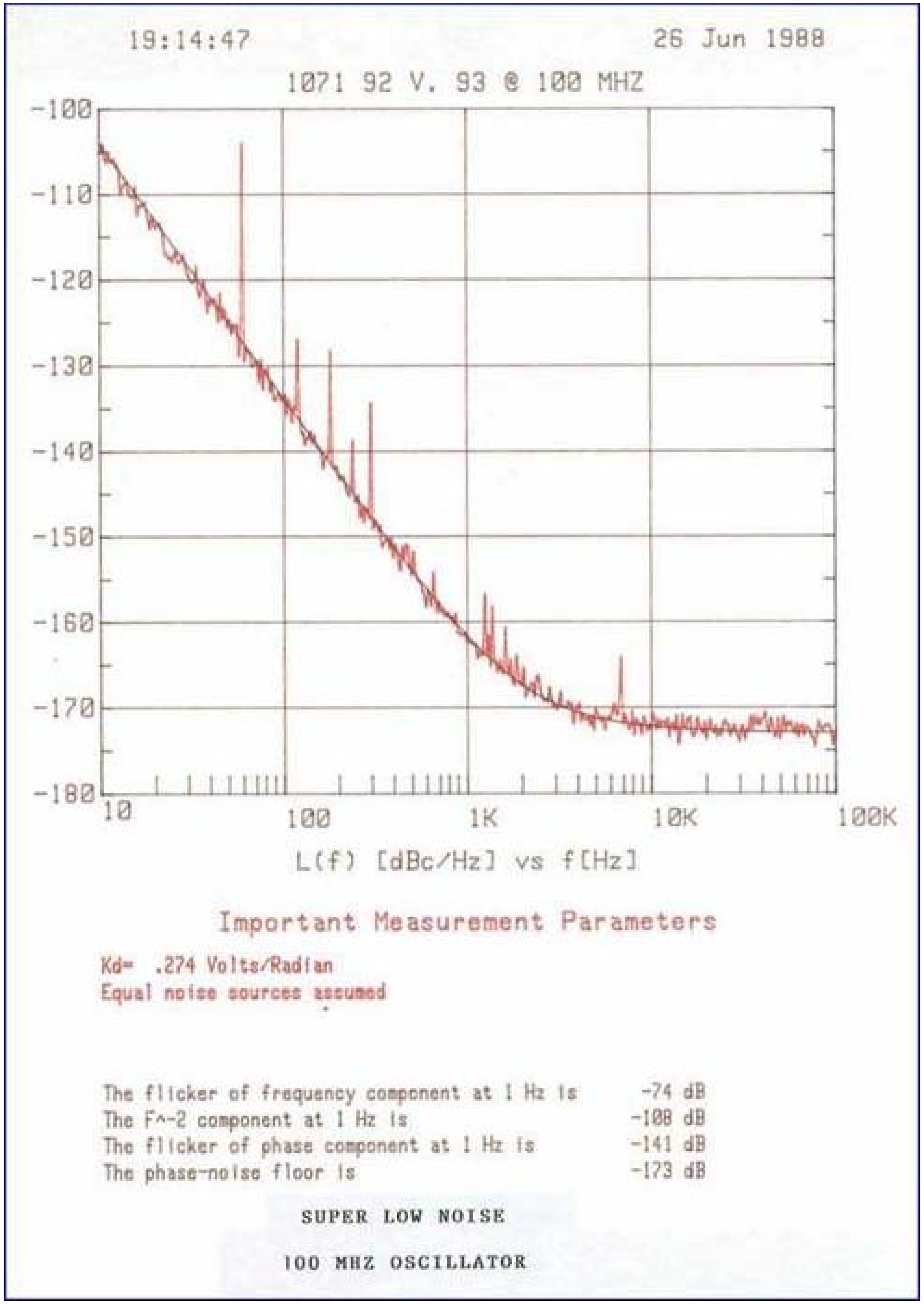
20 dB/decade (f_f^{-2})
White frequency; Random walk of phase

10 dB/decade (f_f^{-1})
Flicker of phase

0 dB/decade (f_f^{0})
White phase

Offset frequency
(also, Fourier frequency,
sideband frequency,
or modulation frequency)

Example of Super Low Noise 100 MHz Quartz Oscillator



19:14:47 26 Jun 1988

1071 92 V. 93 @ 100 MHZ

Important Measurement Parameters

Kd= .274 Volts/Radian
Equal noise sources assumed

The flicker of frequency component at 1 Hz is	-74 dB
The F^-2 component at 1 Hz is	-108 dB
The flicker of phase component at 1 Hz is	-141 dB
The phase-noise floor is	-173 dB

SUPER LOW NOISE

100 MHZ OSCILLATOR

Section 2

Atomic Frequency Standards

Atomic Frequency Standard Basic Concepts

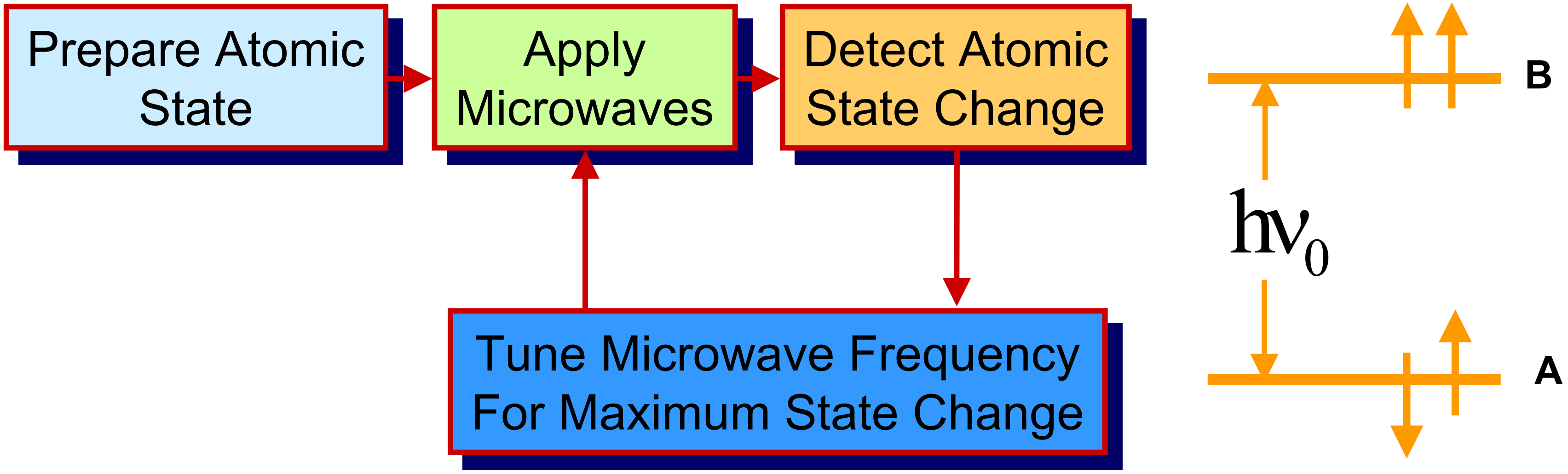
When an atomic system changes energy from an exited state to a lower energy state, a photon is emitted. The photon frequency ν is given by Planck's law

$$\nu = \frac{E_2 - E_1}{h}$$

where E_2 and E_1 are the energies of the upper and lower states, respectively, and h is Planck's constant. An atomic frequency standard produces an output signal the frequency of which is determined by this intrinsic frequency rather than by the properties of a solid object and how it is fabricated (as it is in quartz oscillators).

The properties of isolated atoms at rest, and in free space, would not change with space and time. Therefore, the frequency of an ideal atomic standard would not change with time or with changes in the environment. Unfortunately, in real atomic frequency standards: 1) the atoms are moving at thermal velocities, 2) the atoms are not isolated but experience collisions and electric and magnetic fields, and 3) some of the components needed for producing and observing the atomic transitions contribute to instabilities.

Generalized Atomic Resonator



Prepare Atomic State

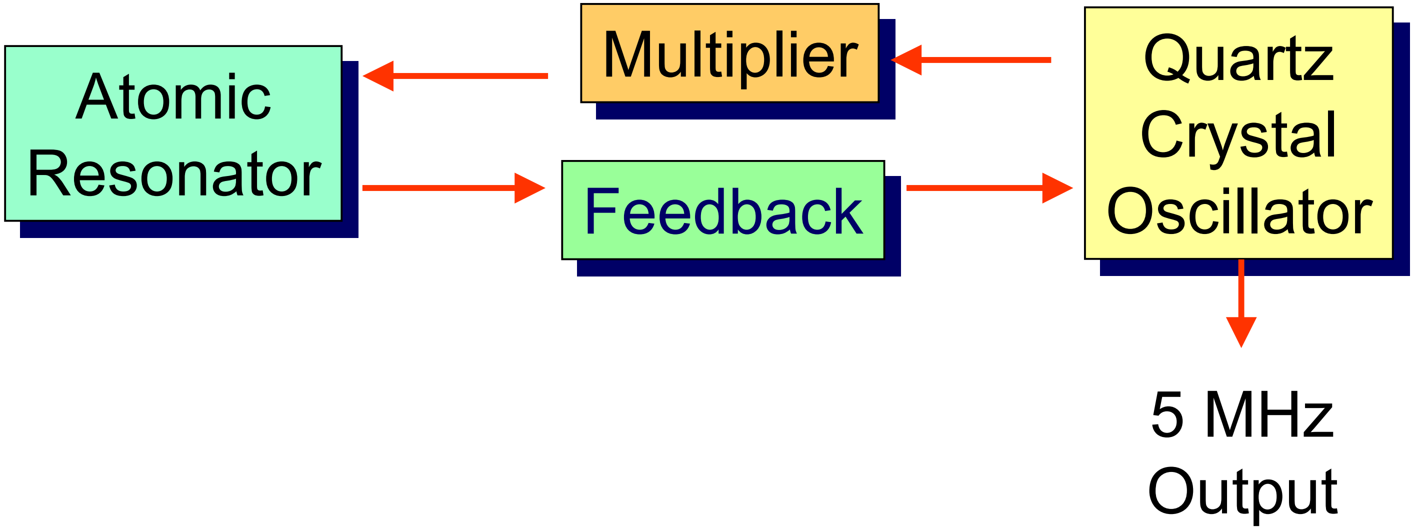
Apply Microwaves

Detect Atomic State Change

Tune Microwave Frequency For Maximum State Change

Atomic Frequency Standard

Block Diagram



Multiplier

Atomic Resonator

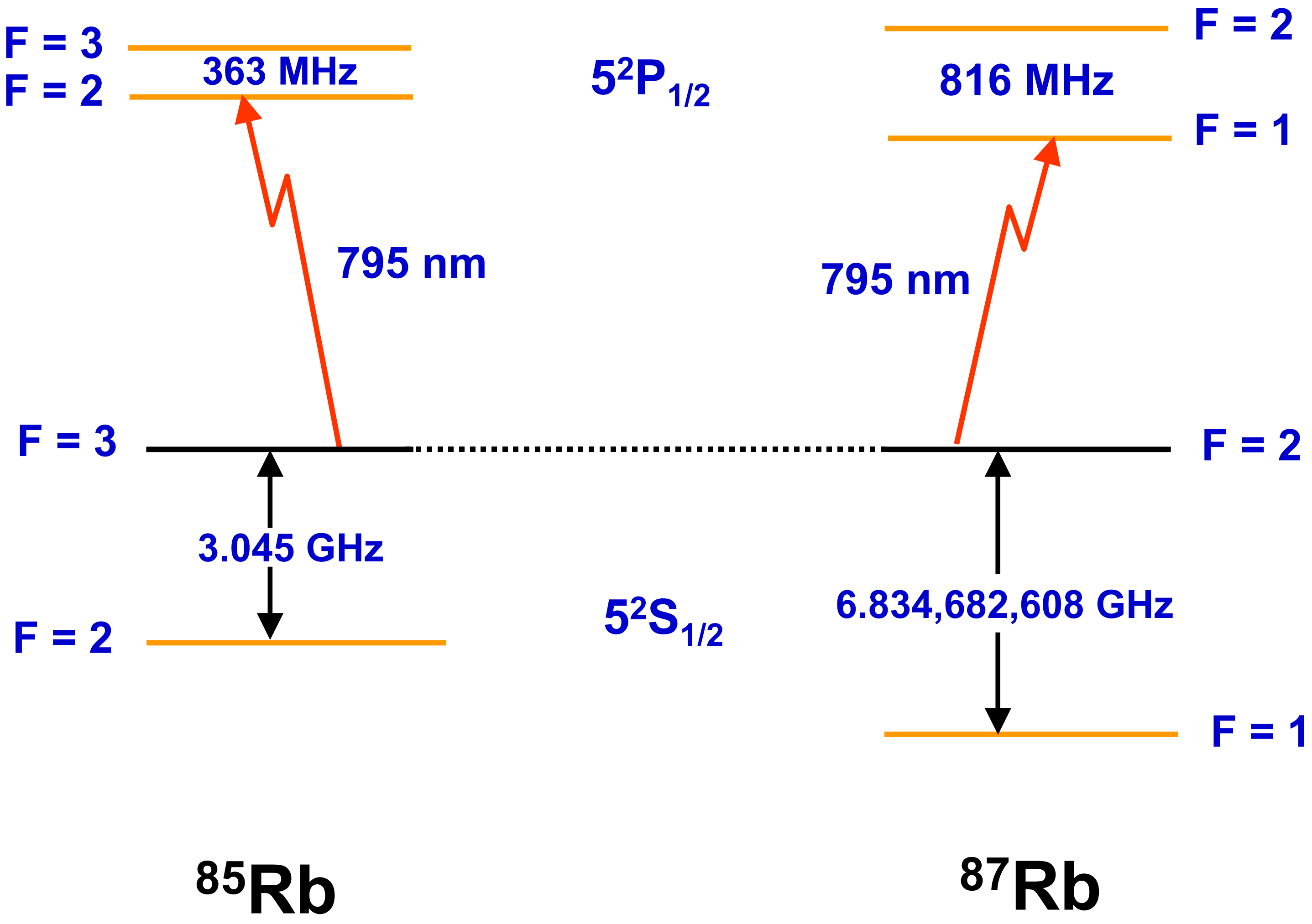
Feedback

Quartz Crystal Oscillator

5 MHz Output

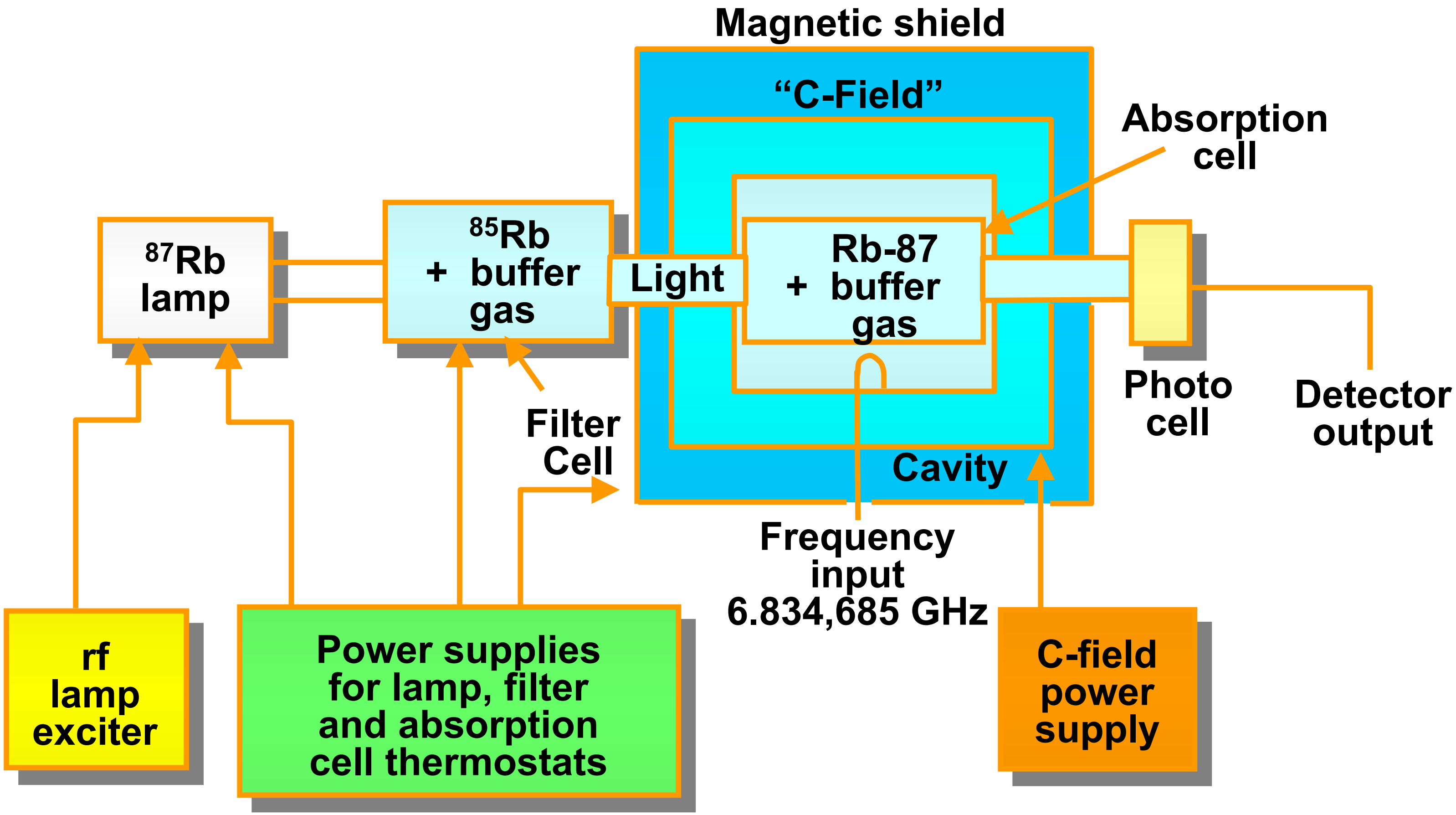
Rubidium Cell Frequency Standard

Energy level diagrams of ^{85}Rb and ^{87}Rb



Rubidium Cell Frequency Standard

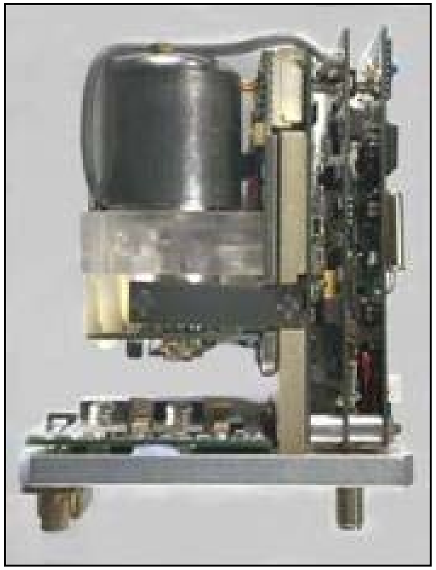
Atomic resonator schematic diagram

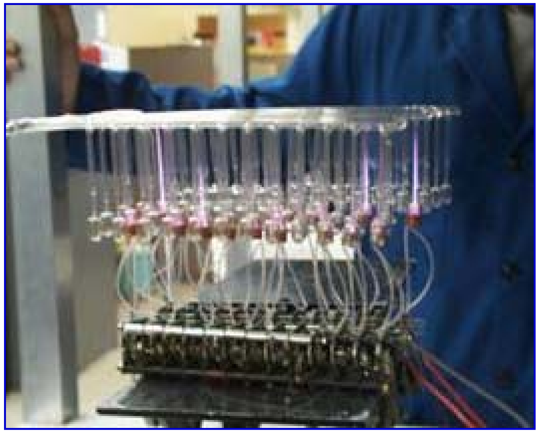


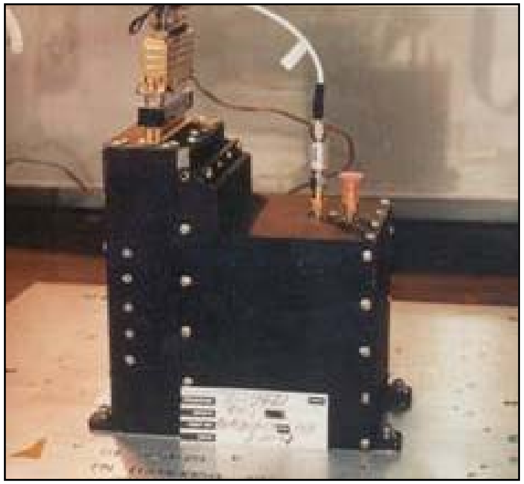
Rubidium Atomic Standards

Wireline and Wireless Applications

Space Time Keeping



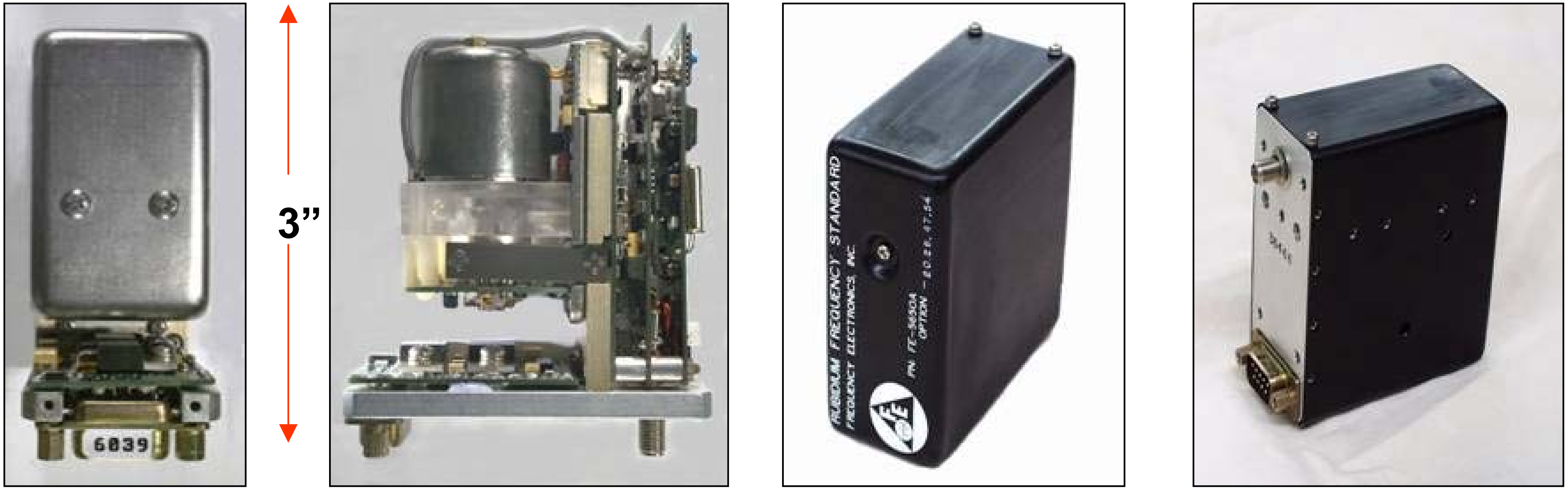




Airborne and Ground-Base

Radar Applications

Example of Rubidium Standard FE-5650 Series



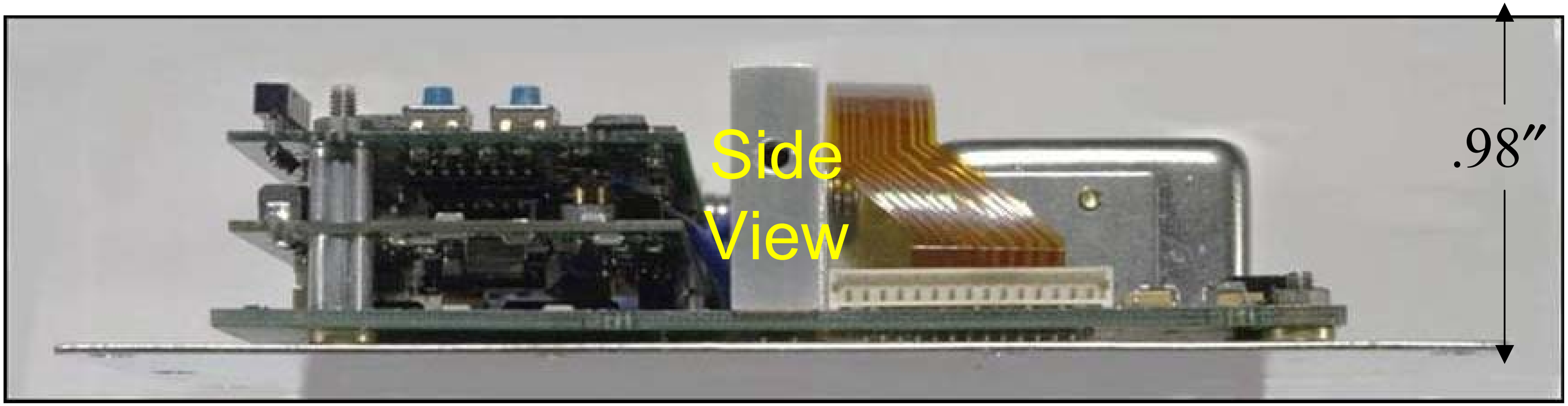
Size: 3x3x1.4 in.

Digitally Programmable

Frequency: 1 Hz to 20 MHz or other desirable frequency

Freq. Vs. Temp. (from -55 to +85^{0}C) **From ± 3x10^{-10} to ±5x10^{-11}**

Example of Rubidium Standard FE-5680 Series

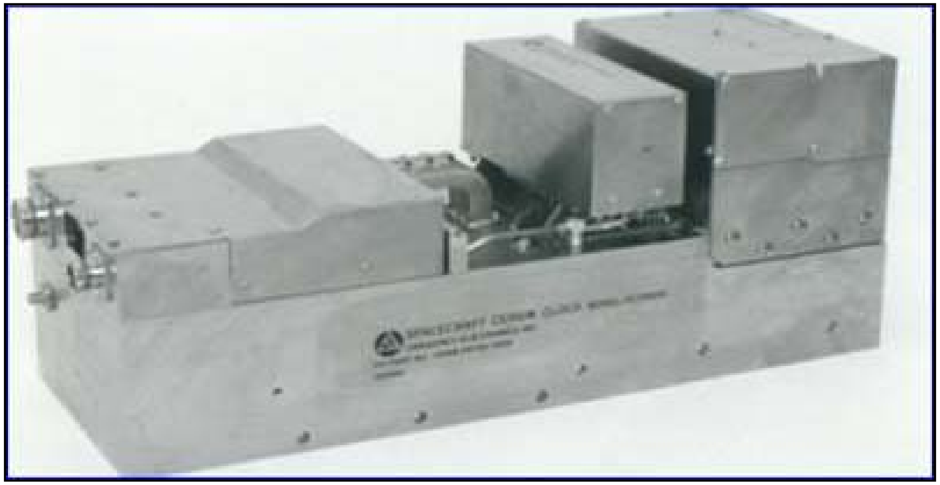


Rubidium Capabilities

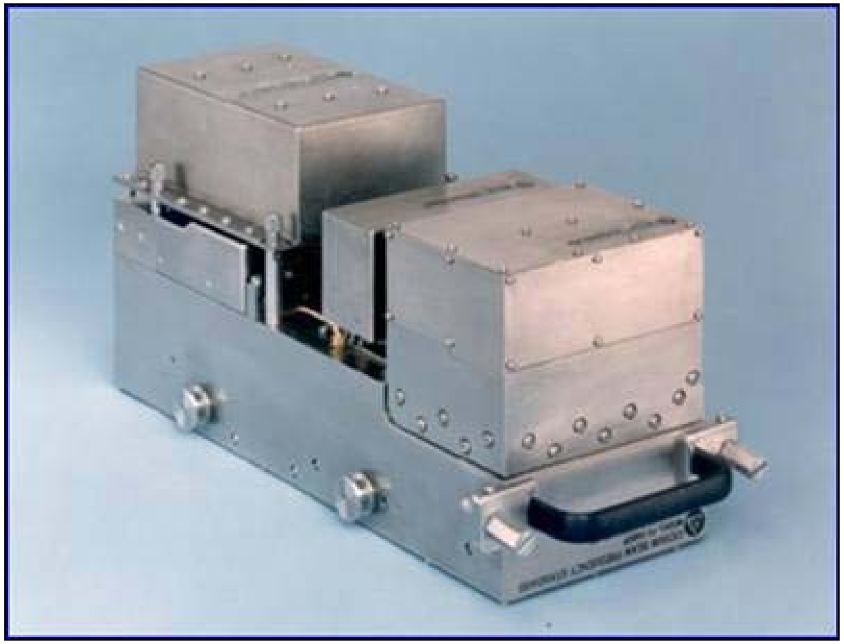
Frequency	Typical 5 MHz, 10MHz, 20 MHz
Aging	10 Year No Adjustment Operation $<1 \times 10^{-9}$/ 10Years
Settability	(1.5×10^{-12} Steps) Range: 2×10^{-7}
Allan Variance	$5 \times 10^{-12}/\sqrt{\tau}$
Input Voltage Sensitivity	$\leq 4 \times 10^{-12}$
Frequency Vs Temperature	1×10^{-10} to 7×10^{-11} (-55°C - +85°C) 1×10^{-10} (-55°C To +95°C) Temperature Compensated with TEC
Input Voltage	Standard Voltages (+15 V To +50v) (-15v To –70v)
Packaging	Configurable
Package Size	Various

Examples of Cesium Clocks

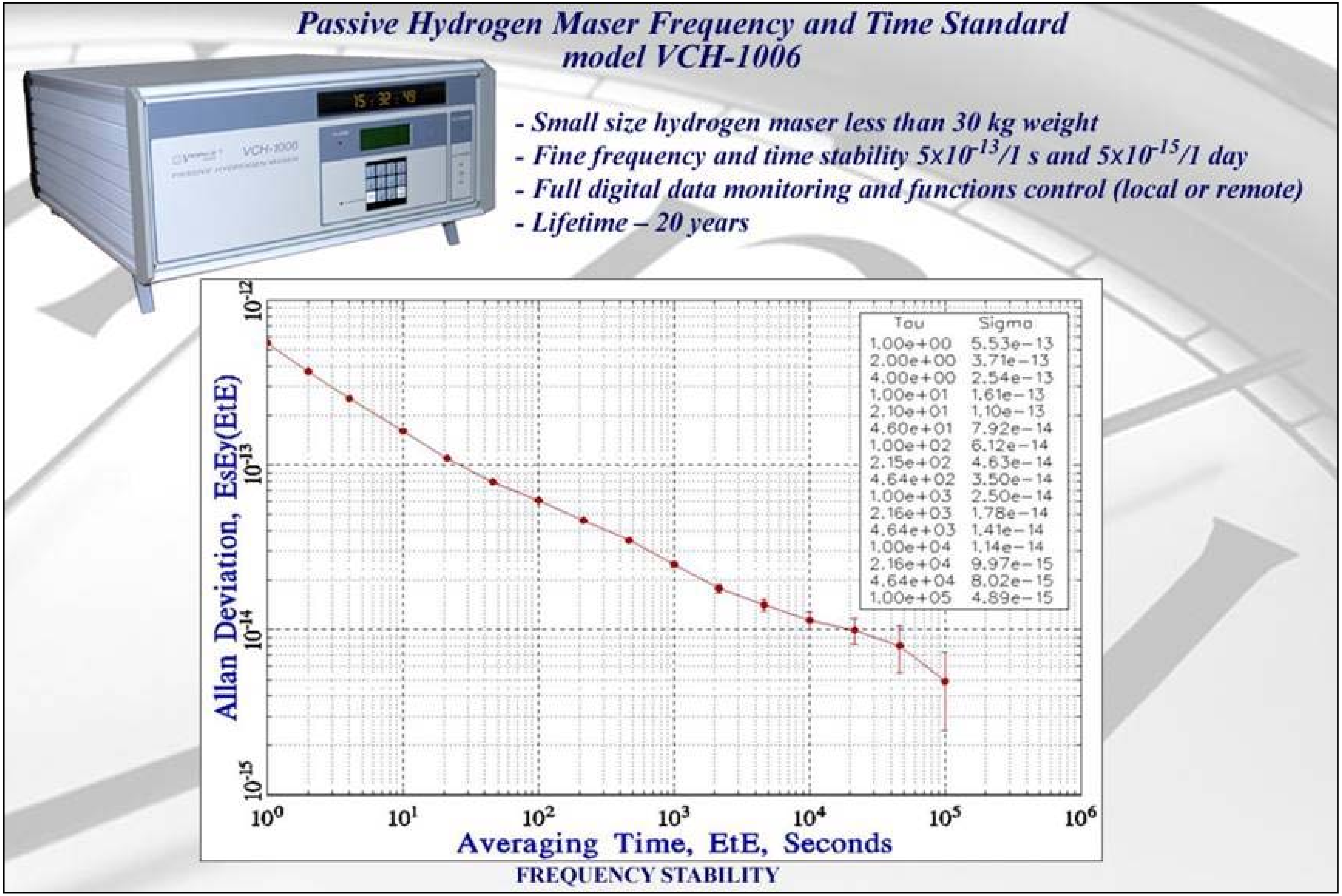
Spacecraft Cesium Clocks Units flown on GPS I sponsored by USNRL



Vibration Isolated Cesium Standard for Low Noise Aircraft Applications



Passive Hydrogen Maser



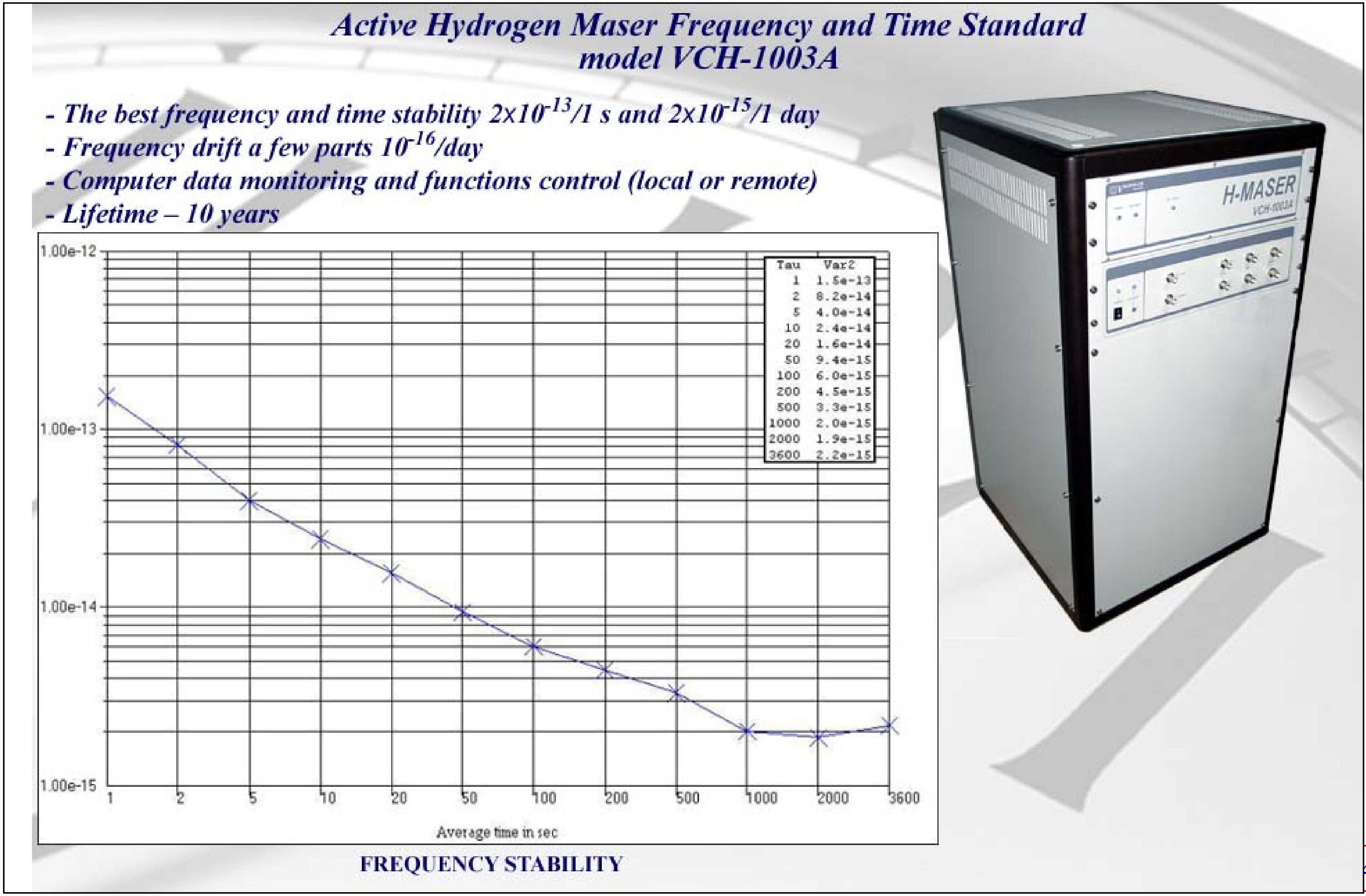
Passive Hydrogen Maser Frequency and Time Standard
model VCH-1006

- *Small size hydrogen maser less than 30 kg weight*
- *Fine frequency and time stability $5x10^{-13}/1$ s and $5x10^{-15}/1$ day*
- *Full digital data monitoring and functions control (local or remote)*
- *Lifetime – 20 years*

Tau	Sigma
1.00e+00	5.53e−13
2.00e+00	3.71e−13
4.00e+00	2.54e−13
1.00e+01	1.61e−13
2.10e+01	1.10e−13
4.60e+01	7.92e−14
1.00e+02	6.12e−14
2.15e+02	4.63e−14
4.64e+02	3.50e−14
1.00e+03	2.50e−14
2.16e+03	1.78e−14
4.64e+03	1.41e−14
1.00e+04	1.14e−14
2.16e+04	9.97e−15
4.64e+04	8.02e−15
1.00e+05	4.89e−15

FREQUENCY STABILITY

Active Hydrogen Maser



Active Hydrogen Maser Frequency and Time Standard
model VCH-1003A

- *The best frequency and time stability $2x10^{-13}$/1 s and $2x10^{-15}$/1 day*
- *Frequency drift a few parts 10^{-16}/day*
- *Computer data monitoring and functions control (local or remote)*
- *Lifetime – 10 years*

Tau	Var2
1	1.5e-13
2	8.2e-14
5	4.0e-14
10	2.4e-14
20	1.6e-14
50	9.4e-15
100	6.0e-15
200	4.5e-15
500	3.3e-15
1000	2.0e-15
2000	1.9e-15
3600	2.2e-15

FREQUENCY STABILITY

Summary: Precision Frequency Standards

- Quartz crystal resonator-based (f ~ 5 MHz, Q ~ 10^6)
- Atomic resonator-based

  Rubidium cell (f_0 = 6.8 GHz, Q ~ 10^7)

  Cesium beam (f$_0$ = 9.2 GHz, Q ~ 10^8)

  Hydrogen maser (f_0 = 1.4 GHz, Q ~ 10^9)

  Cesium fountain (f_0 = 9.2 GHz, Q ~ 5 x 10^{11})

Section 3

Applications

Commercial Applications

New Quartz Technology

FE-205A

FE-405A

FE-505A

(Poor Man's Rubidium)

STATE OF THE ART

QUARTZ CRYSTAL STANDARDS

Models
FE-205A
FE-405A
FE-505A

DESCRIPTION

This new design concept features a precision double oven crystal oscillator capable of analog or digital tuning. The serial digital tuning is ideal for disciplined applications in today's telecommunications industry. The temperature coefficient of this device is less than $1 \times 10^{[illegible]}$. This is accomplished with no frequency over or under shoot, with fast temperature slew rates of 4°C per minute. Performance is Determined by a Double Oven SC Cut 5^{th} Overtone Crystal.Output Frequency is Digitally Synthesized.

TYPICAL APPLICATIONS

- Cellular Base Stations
- Test Equipment
- Stratum Clocks
- GPS Timing Systems
- Rubidium Replacement
- Radar Timing
- Military Communications Systems

"PATENTED DESIGN No. 6,577,201"

FREQUENCY ELECTRONICS, INC.
55 Charles Lindbergh Blvd., Mitchel Field, NY 11553
TEL: 516-794-4500 • FAX: 516-794-4340
E-MAIL: sales@freqelec.com
Visit us at: www.freqelec.com

FE-205A

FE-405A & FE-505A

FEATURES

- Analog or Digital Interface [LSB ~$1.7 \times 10^{[illegible]}$]
- Excellent Temperature Stability <$1 \times 10^{[illegible]}$
- -40° C to +70° C Operation
- Low Aging <$5 \times 10^{[illegible]}$ for 10 yrs.
- Retrace $1 \times 10^{[illegible]}$ after 1 hour, 24 hrs off
- Any frequency 5 MHz to 25 MHz
- Wide Linear Frequency Tuning Greater Than ±50 ppm

FE-205A Quartz Oscillator Series “Poor Man’s Rubidium ???”

- Readily Available, Producible in Large Quantities
- Near Rubidium Accuracy at 1/3 the Cost
- Temperature Stability $<1\text{x}10^{-10}$ From $–40^{0}$ C to $+75^{0}$ C
- Low Aging $<3\text{-}5 \text{ x } 10^{-11}$ / day
- Any frequency from 1 pps to 100 MHz
(10 MHz to 15 MHz standard frequencies)
- Analog or Digital Frequency Control with better than 1 % Linearity
(both for legacy and new all-digital designs)
- Conventional through hole package
- Rubidium packages/interchangeability

2”W x 2”L x 1.5”H

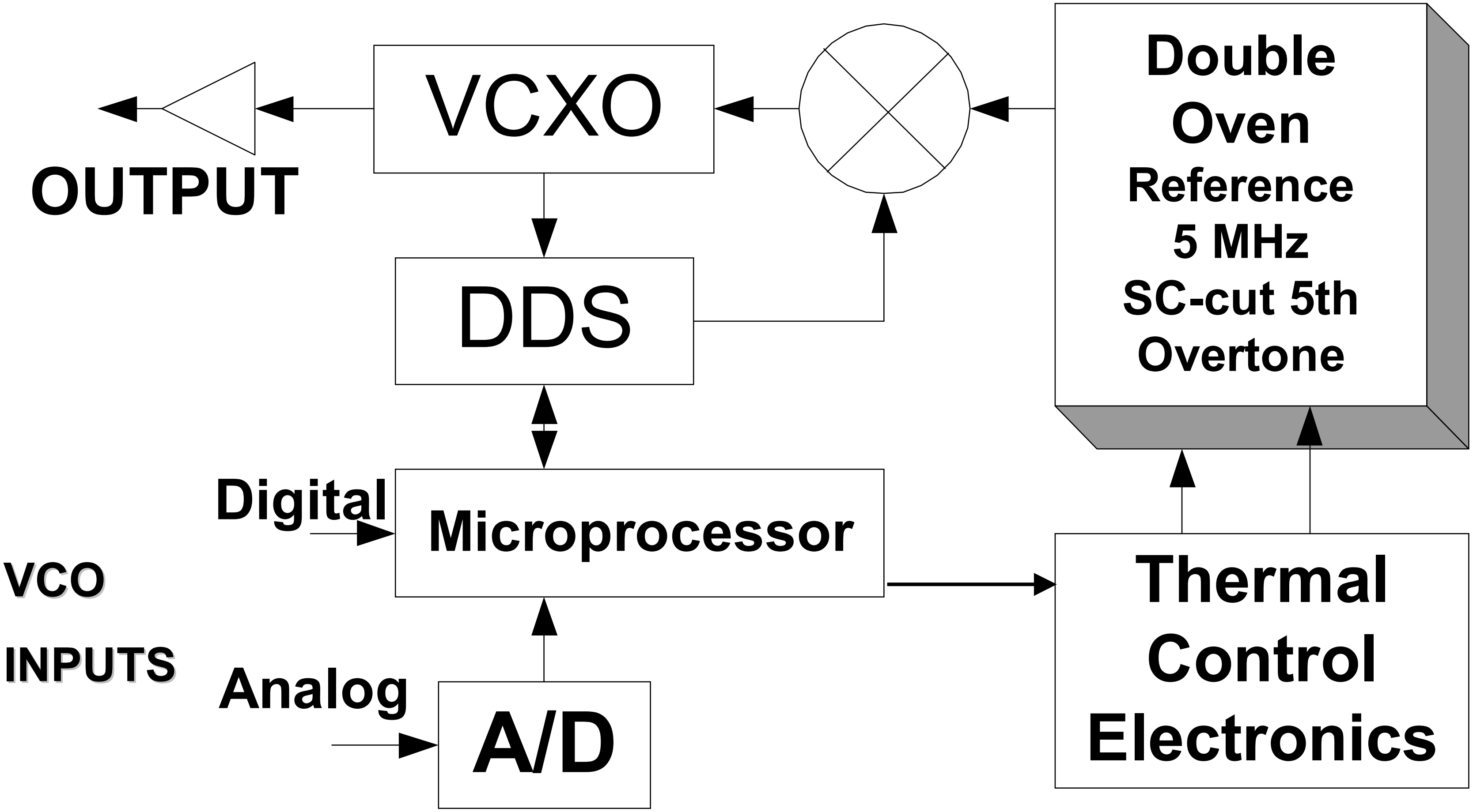
3”W x 3’’L x 1.4”H
3”W x 2.8”L x 0.89H

3”W x 3.5”L x 0.98’’H

FE-205A Series OCXO Characteristics

- SC-cut 5th overtone resonator with good aging and excellent short-term stability.
- Thermal control electronics with inner oven stability of ±1 x 10^{-3} °C over a change in ambient temperature of 115° C
- Stability of internal reference clock electronic circuit is better than $3x10^{-11}$ over ambient temperature of –40°C to +75°C and with a change in Supply Voltage of ±5%
- High-resolution DDS ≈ $2x10^{-14}$
- Microprocessor Controlled
- Less than $1x10^{-12}$ with load variation of ±10%

System Block Diagram



(Patented Design)

Aging: Statistical Data

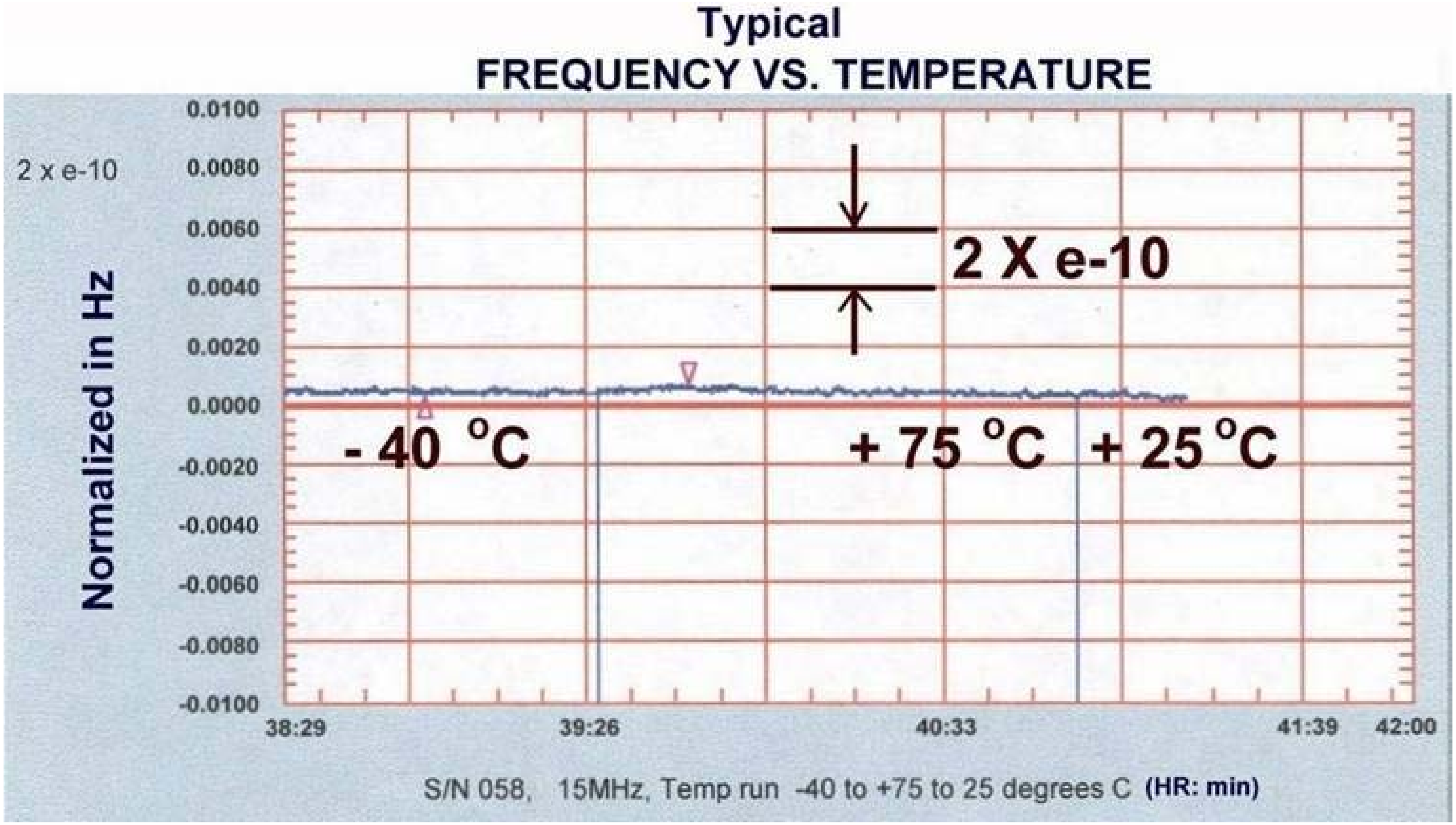
Aging (Drift)

60% better than 3×10^{-11} /day

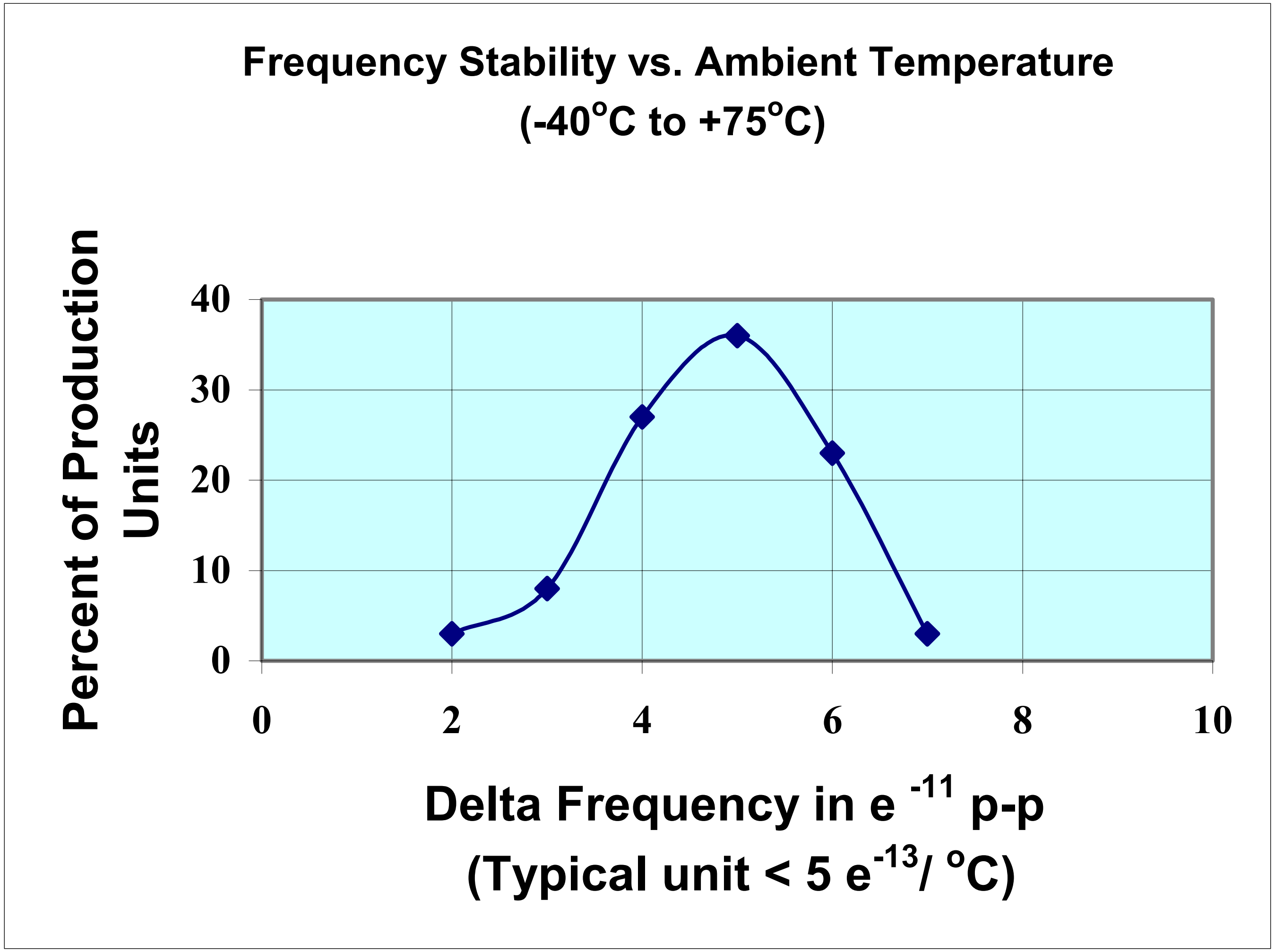
90% better than 5×10^{-11} /day

100% better than 1×10^{-10} /day

Double Oven Precision Crystal Oscillator Temperature Performance



Statistical Data



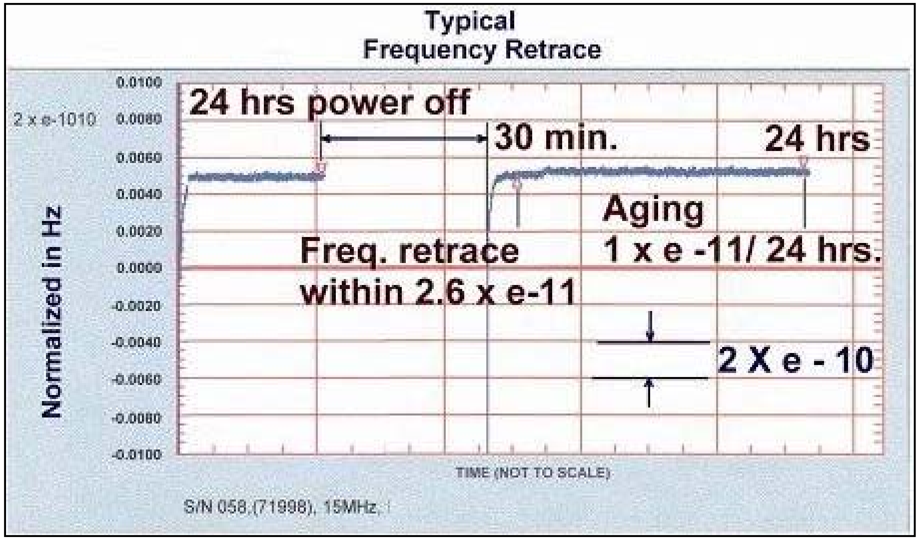
Frequency Stability vs. Ambient Temperature
(-40°C to +75°C)

Comparison of Oscillators Stabilities vs. Temperature

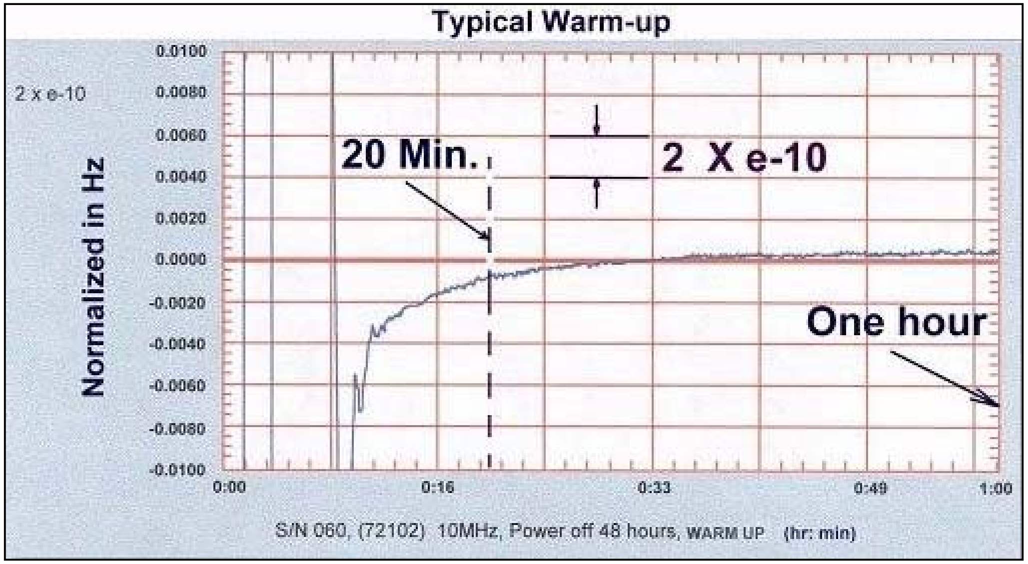
Oscillator Type	Frequency Stability (In severe temperature environments e.g. –40°C to +75 °C, and high slew rates)
Crystal Oscillator (XO)	$1x10^{-4}$ to $1x10^{-5}$
Temperature Compensated Crystal Oscillators (TCXO)	$1x10^{-6}$
Microcomputer Compensated Crystal Oscillators (MCXO)	$1x10^{-7}$ to $2x10^{-8}$
Oven Controlled Crystal Oscillators (OCXO)	$1x10^{-8}$ to $3x10^{-10}$
Poor Man's Rubidium ??? **High-Precision Double Oven Crystal Oscillator (DOCXO)**	**$1x10^{-10}$**
Rubidium Atomic Frequency Standards (Rb) [–10°C to +60 °C]	$3x10^{-10}$ to $7x10^{-11}$
Cesium Atomic Standard (Cs) [0°C to +50 °C]	$3x10^{-11}$ to $3x10^{-12}$

Retrace Data

- **Retrace: After 24 hours of shut off frequency stabilizes within 30 minutes after turn-on to 1×10^{-10} of the previous frequency**

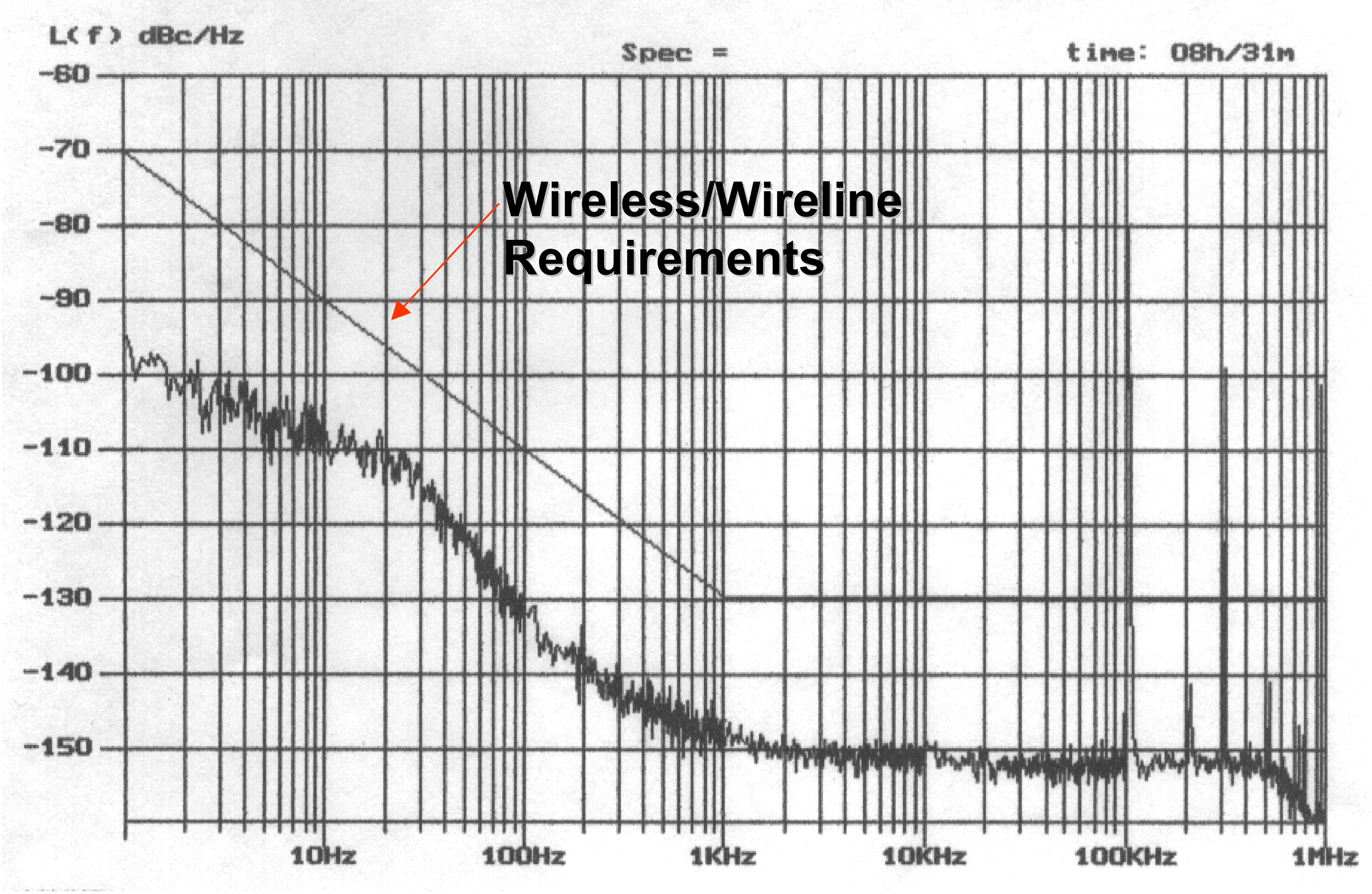


Typical Frequency Retrace of 15 MHz Device



Typical Warm-Up of 10 MHz Device

Phase Noise of 10 MHz Oscillator



Wireless/Wireline Requirements

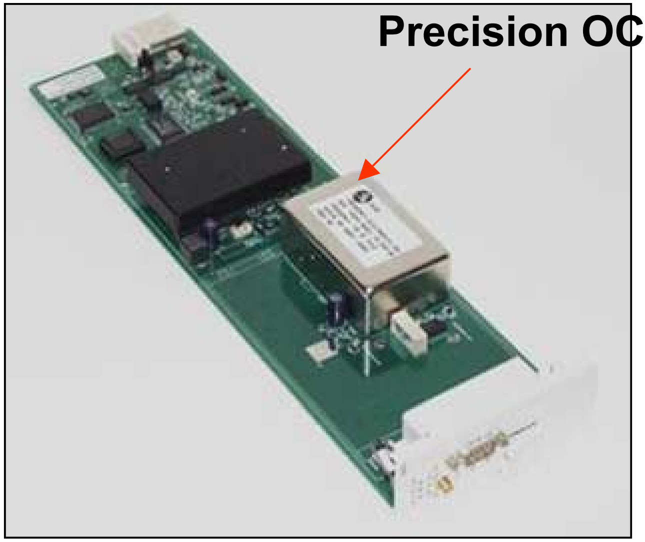
Comparison Chart

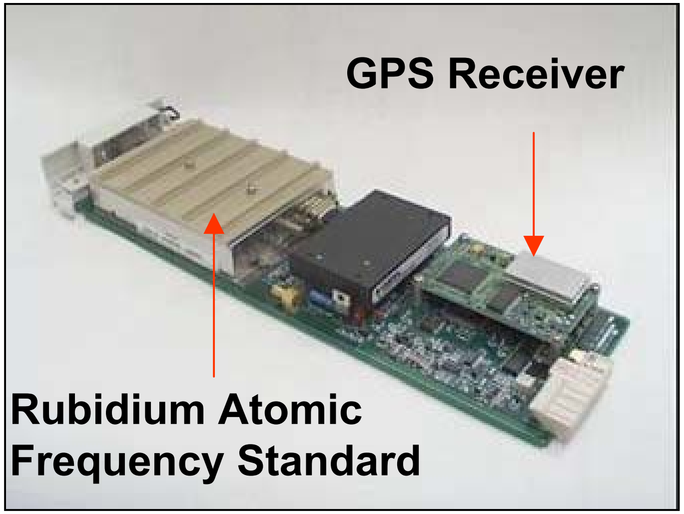
Characteristic	Quartz	Rubidium
Power (w)	1 - 2 W	1 - 15 W
MTBF (Hrs)	500K / 1,000K	100K - 200K
Drift/Aging		
1 Sec	$1 - 2 \times 10^{-12}$	$1 - 2 \times 10^{-11}$
1 Day	3×10^{-11}	1×10^{-11} { 5×10^{-12} }
10 Years	$2 - 5 \times 10^{-8}$	$<1 \times 10^{-9}$
Temperature (-5°C to +50°C)	5×10^{-11}	3.3×10^{-10} { 7×10^{-11} }
Warm up From Cold Storage (off for a long period)	1×10^{-10} in 48-96 Hrs	1×10^{-10} in 1 Hr

Comparison *(Continued)*

Characteristic	Quartz	Rubidium
Warm up Short Power Interrupt 1 to 2 Hrs off 1 Day off	 1 x 10^{-10} in 1 Hr 1 x 10^{-10} in 1 to 24 Hrs	 1 x 10^{-11} in 1 Hr 1 x 10^{-11} in 24 Hr
Phase Noise	Meets Specs	Meets Specs
Spurious	-80 dBc	-70 dBc
Cost	1X	3X
Life	No known wear out mechanism	Rb consumption in 10 to 15 years

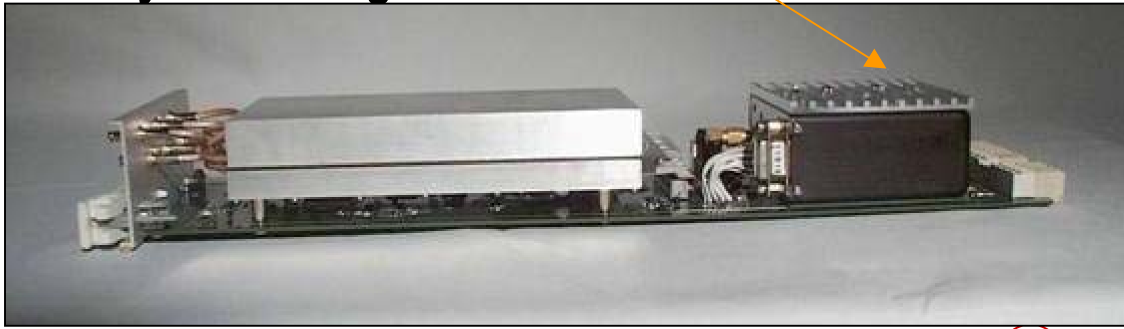
Synchronization for Wireless Base Stations CDMA, UMTS, W-CDMA, TDMA Plug in Assemblies



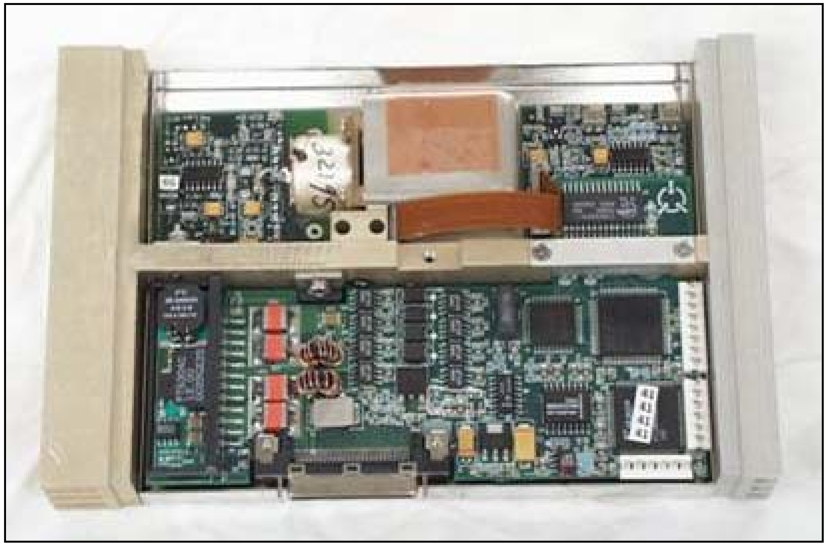


- GPS disciplined Rubidium/Quartz
- Customized packaging
- Optimized for extreme temperature swings
- Excellent aging and temperature stability
- Hot swappable with glitch free operation

Rubidium Frequency Atomic Standard module directly interchangeable with OCXO module



Wireless



SPACE APPLICATIONS

Quartz for Space applications

FE-4220A

OCXO

SPACE QUALIFIED

OVEN CONTROLLED CRYSTAL OSCILLATOR

Model FE-4220A

Description

The FE-4220A Series of Space Qualified Low Noise Quartz Oscillators features operation from 20Mhz to 145Mhz with Low Phase Noise and excellent stability. A unique Class "K" Hybrid Assembly (MIL-PRF-38534) in conjunction with a 5th overtone SC-Cut Crystal achieves Low Aging, Temperature Stability and excellent Radiation Immunity (100Krads) needed in the Space Environment. An External DC Voltage Input or Resistor is provided for Fine Frequency Adjustment.

Features

- Low Phase Noise
- Excellent Temperature Stability < ±2 x 10^{-7}
- -10°C to +60°C Operating
- Low Aging ±1 ppm for life
- Space Qualified
- Radiation Immunity 100 Krads
- Highly Reliable: Over 20 years of space service with zero failures
- Small Size and Light Weight

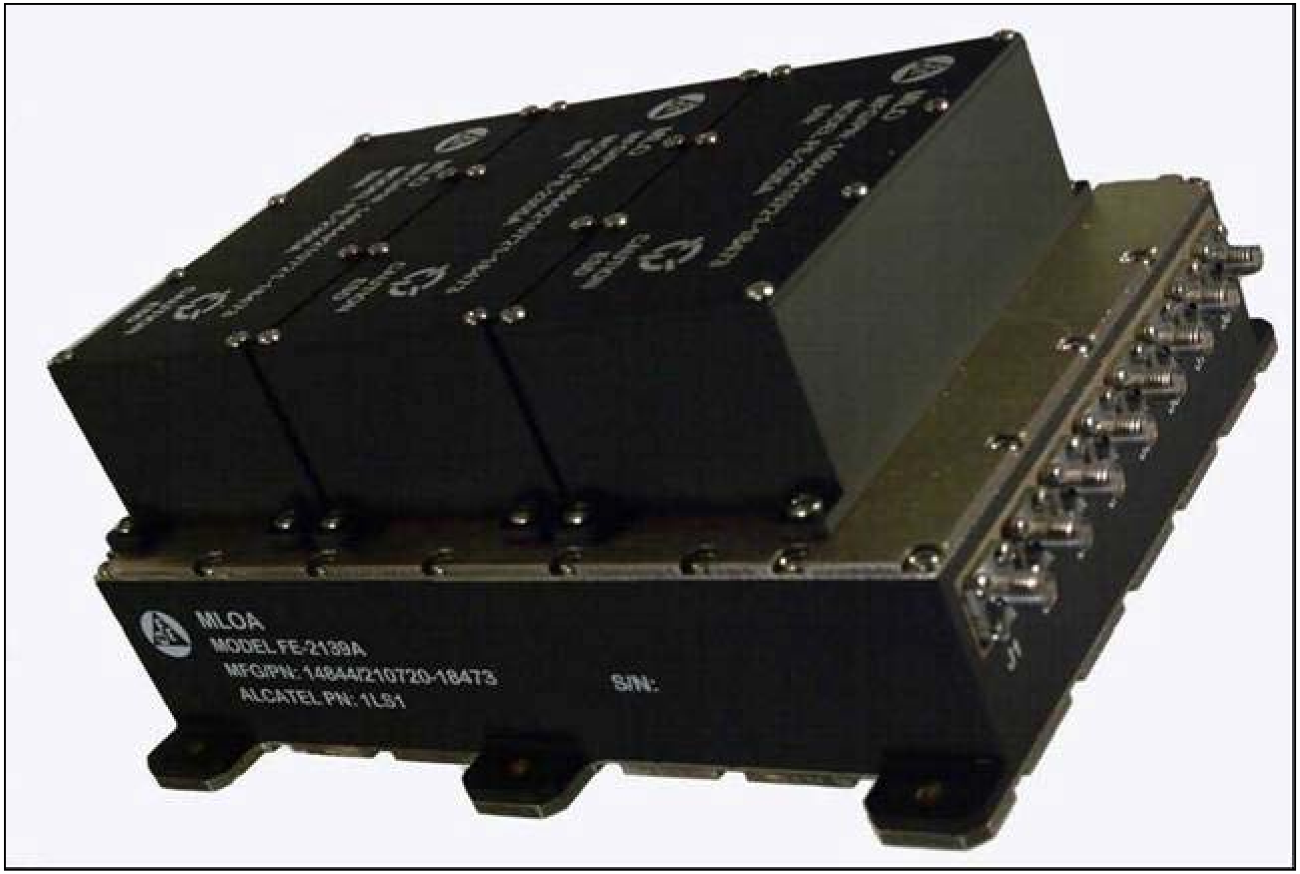
Typical Applications

- Clocks for Spacecraft

Specifications on reverse side

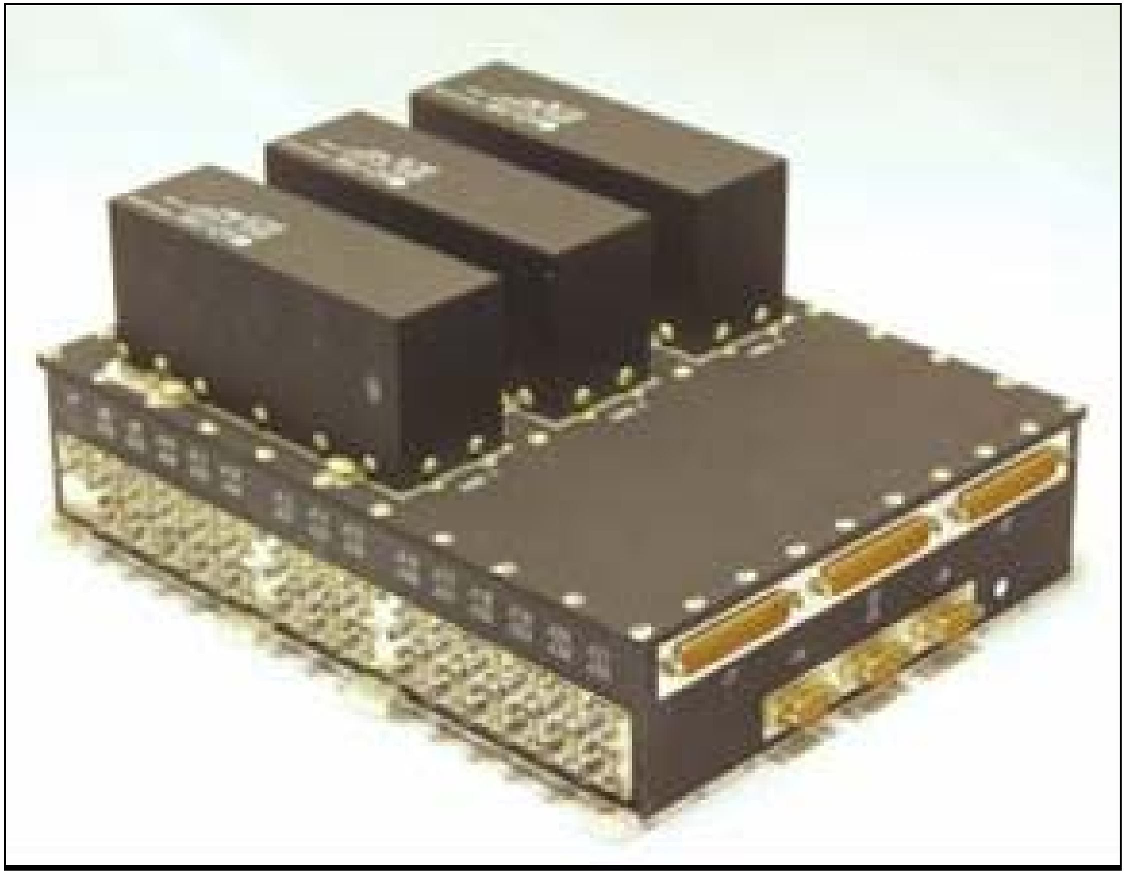
7/26/01 -Rev-A-FEI

MASTER LOCAL OSCILLATOR
MODEL FE-2139A



PRECISION FREQUENCY REFERENCE SOURCES

Triple Redundant Master Local Oscillator (MLO) and Distribution Assembly

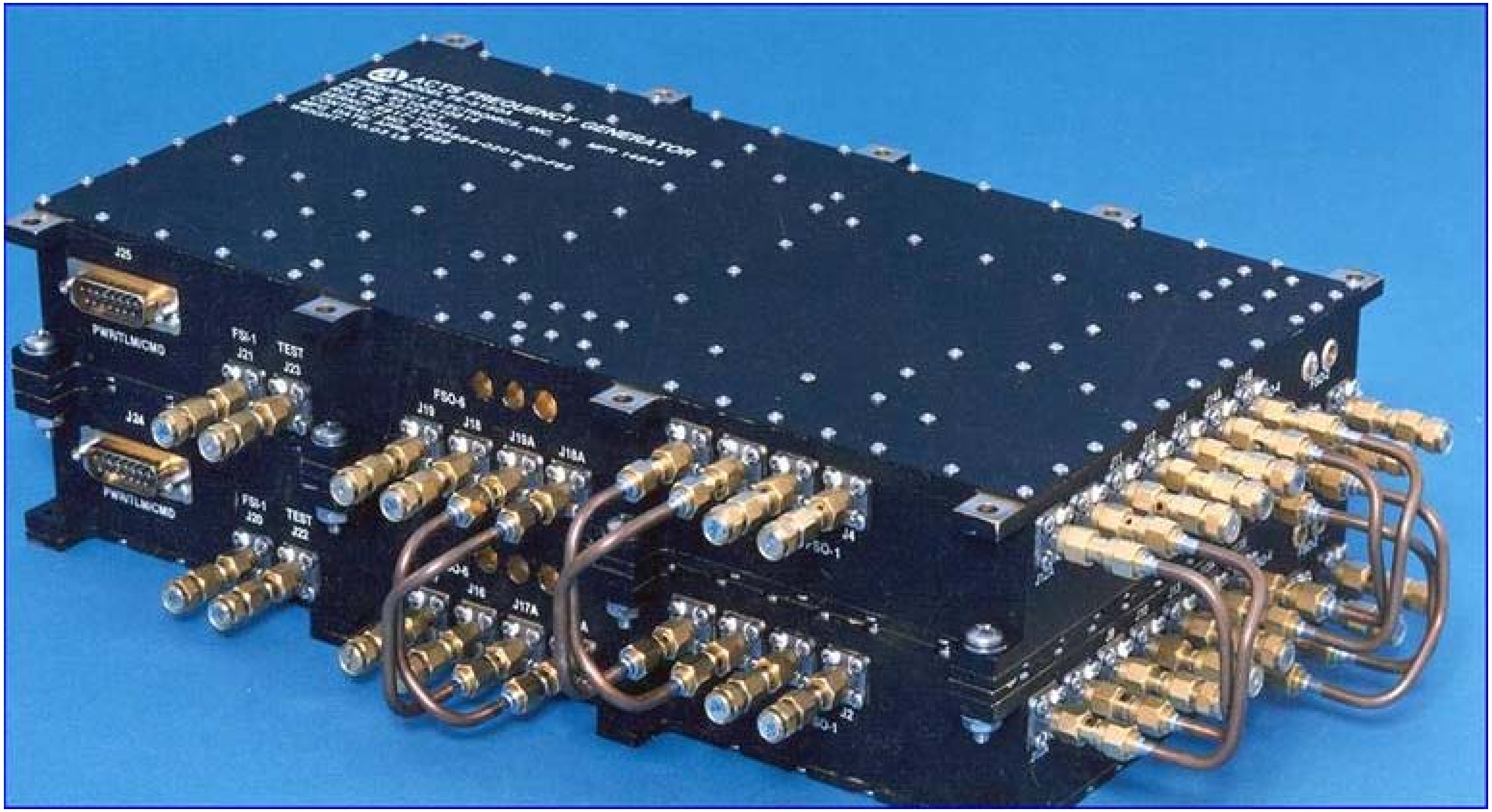


FREQUENCY SOURCES / GENERATORS

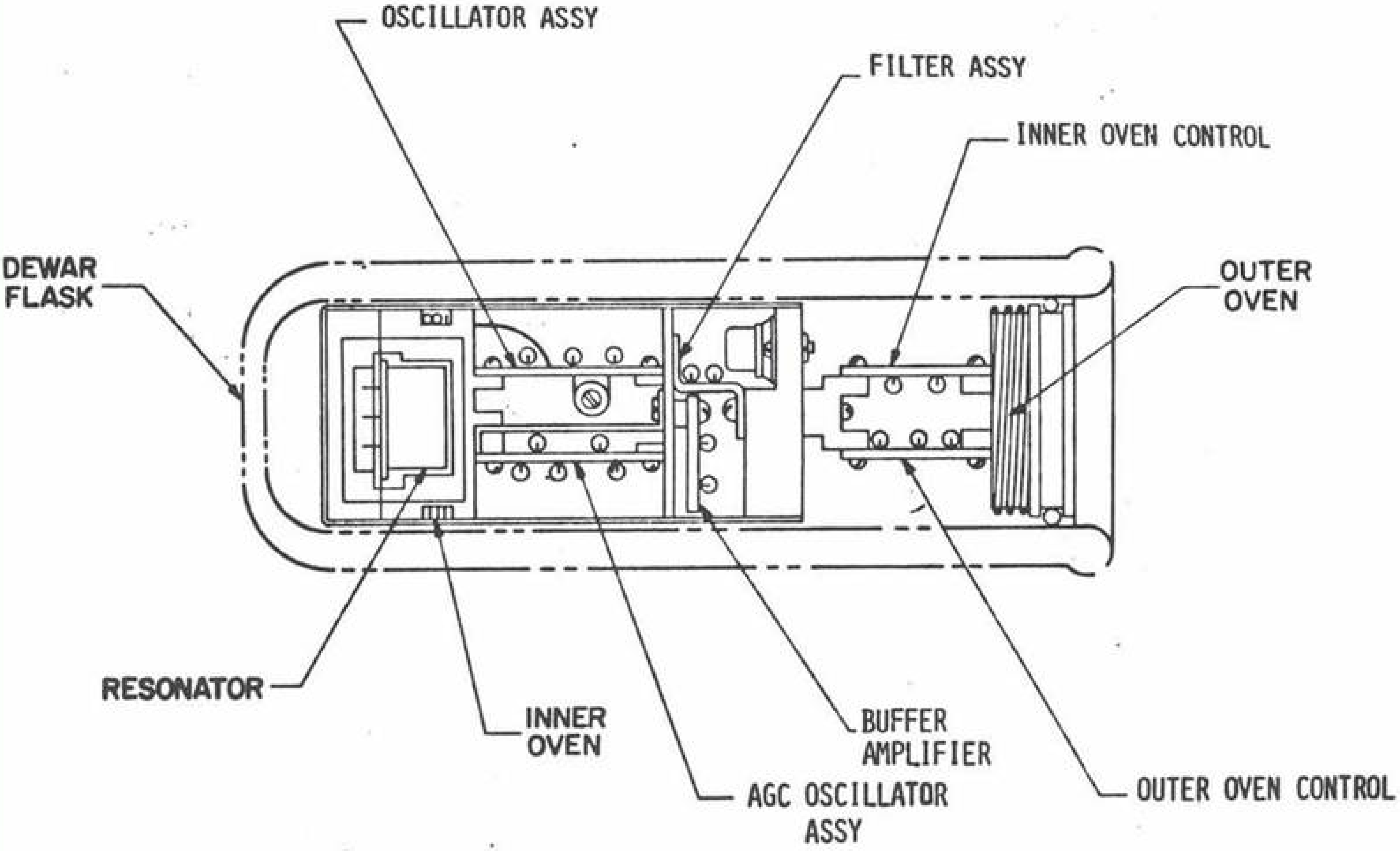
ACTS

Frequency Generator FE-5150A

5 MHz to 6.8 GHz; Fully Redundant; Includes DC / DC Converter



Double Oven Crystal Oscillator with Dewar Flask



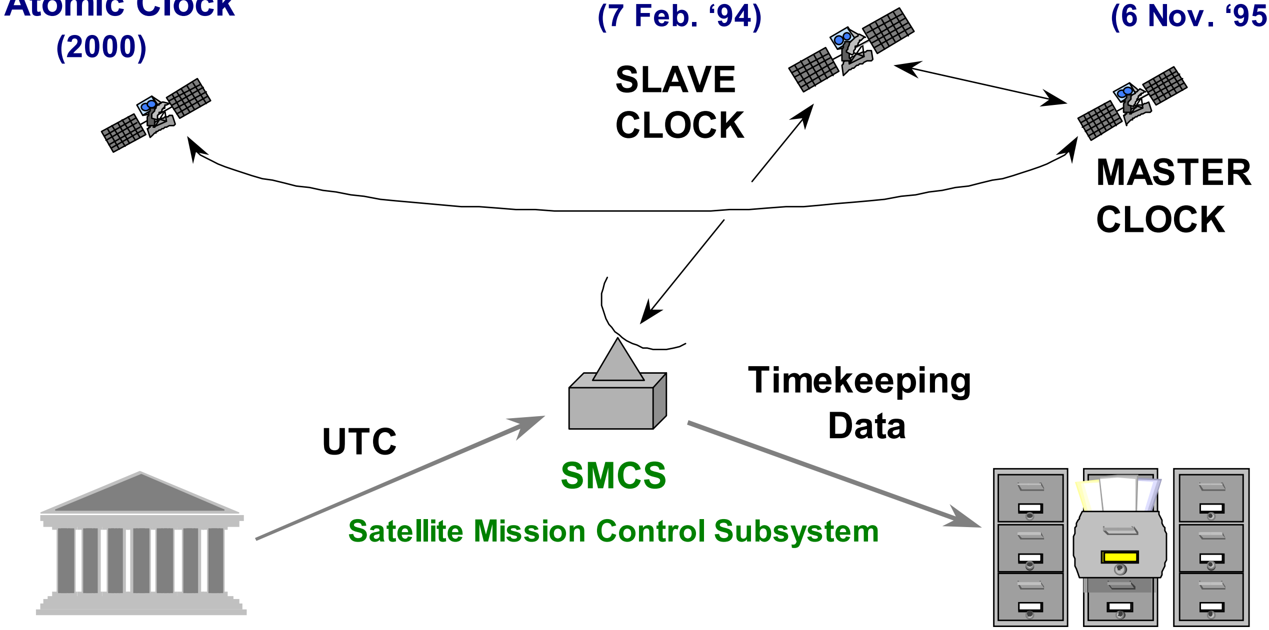
MLO Assembly

Master Oscillator Assembly

DC to DC Converter

MILSTAR TIMEKEEPING With FEI Supplied Clocks

Milstar Today



FLT-4
Rb Atomic Clock
(2000)

FLT-1
Crystal Clock
(7 Feb. '94)

SLAVE CLOCK

FLT-2
Rb Atomic Clock
(6 Nov. '95)

MASTER CLOCK

UTC

Timekeeping Data

SMCS

Satellite Mission Control Subsystem

United States
Naval Observatory

MASC

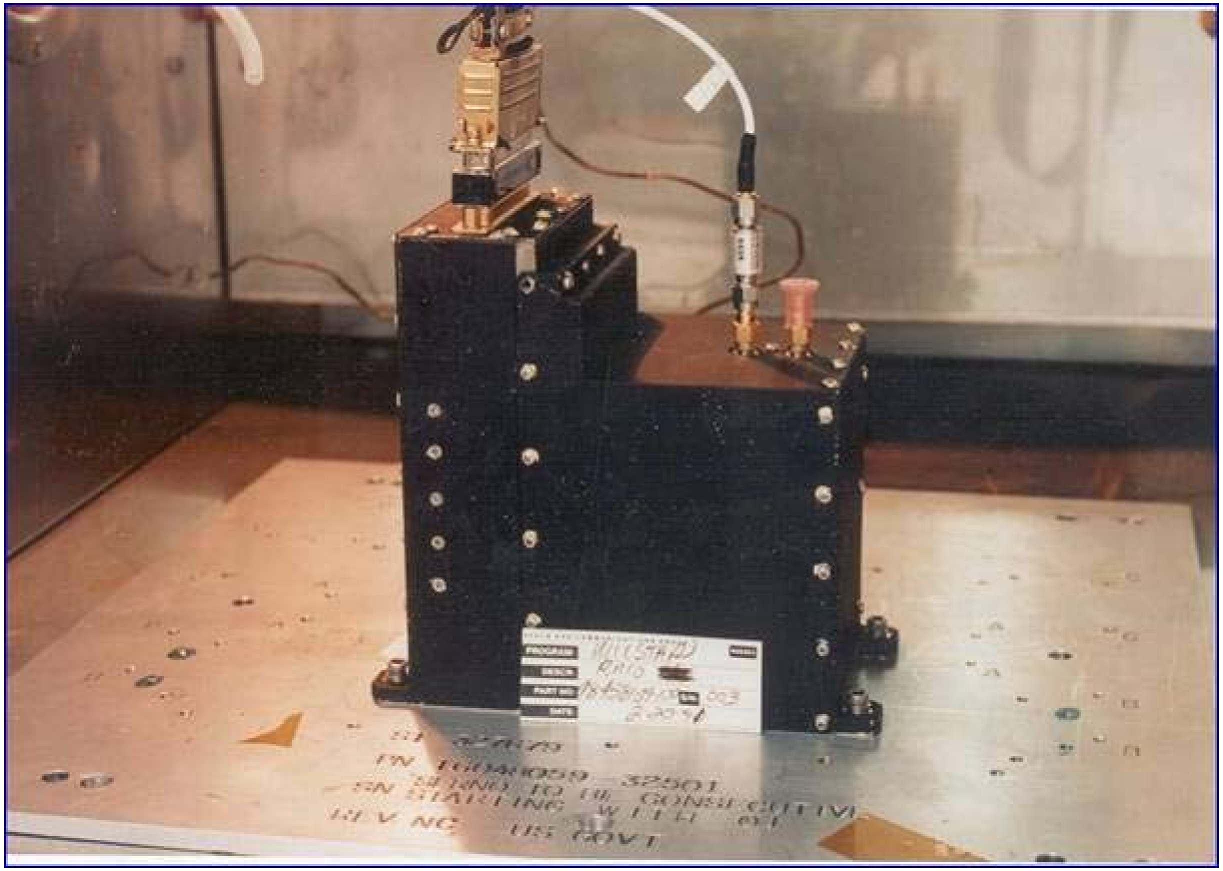
Milstar Auxiliary Support Center

RUBIDIUM PRECISION FREQUENCY REFERENCE SOURCES

MILSTAR

Rubidium Master Oscillator SN 003

Total of 19 systems delivered to MILSTAR



Excellent performance in space

Aging Rate:

≈ $7x10^{-14}$/day

Rubidium in Space Clocks
MILSTAR

- **Rubidium Master Oscillator (RMO) on board MILSTAR Space Craft since 1995**

FLT 2	4 Redundant Rb Clocks
FLT 3	4 Redundant Rb Clocks
FLT 4	4 Redundant Rb Clocks

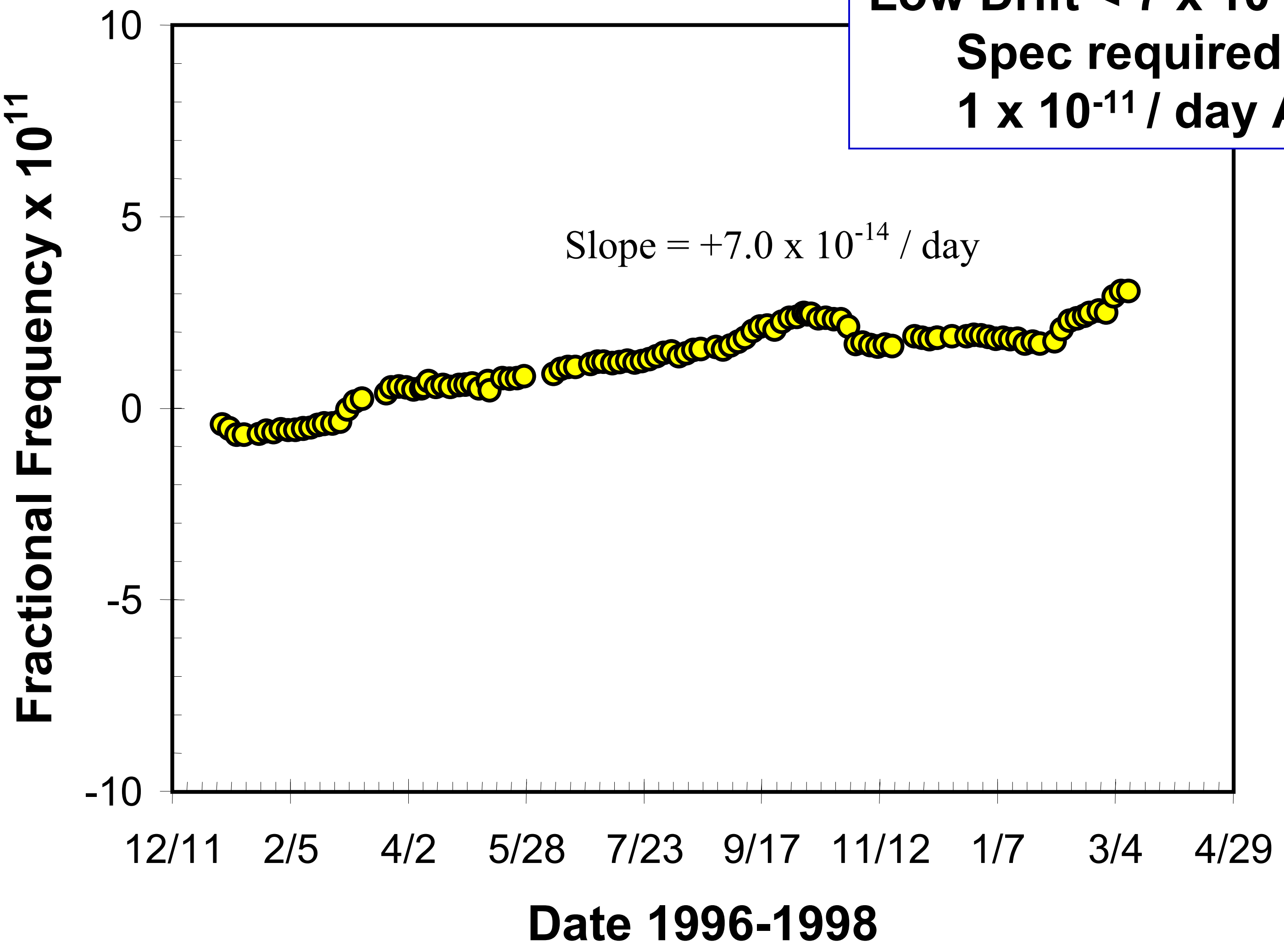
- **Two Satellites soon to be launched**

FLT 5	3 Redundant Rb Clocks
FLT 6	3 Redundant Rb Clocks

Because of the extensive reliability experienced in FLT 2 to 4 the configuration in FLT 5 and FLT 6 were reduced to Three Redundant Rb Clocks

Rubidium in Space Clocks
MILSTAR

Low Drift < 7 x 10^{-14} / day
Spec required only
1 x 10^{-11} / day Actual data



GPS APPLICATIONS

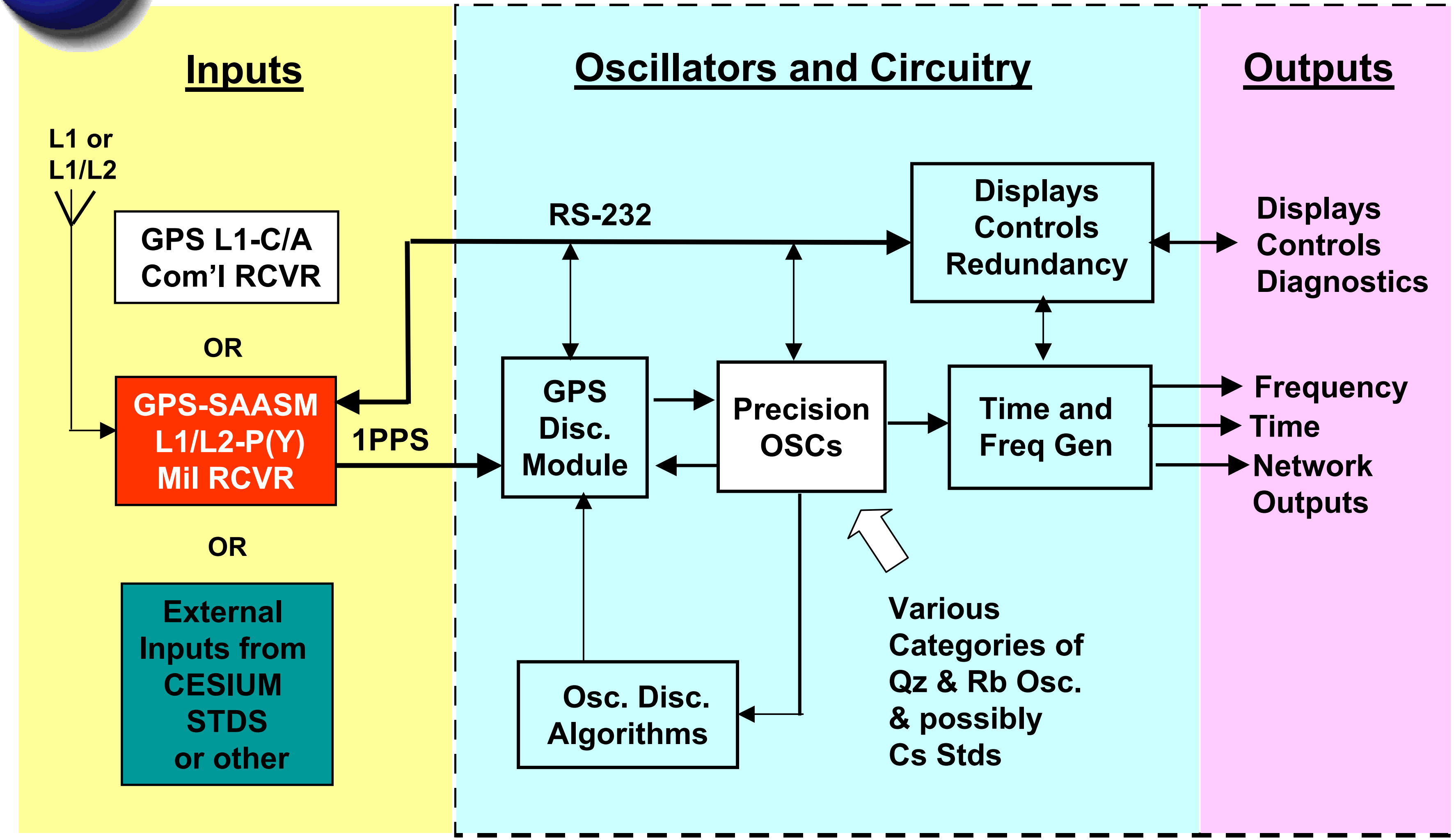
- Commercial
- Military i.e. SAASM

Oscillator’s Impact on GPS

- **Satellite oscillator’s (clock’s) inaccuracy & noise are major sources of navigational inaccuracy.**
- **Receiver oscillator affects GPS performance, as follows:**

Oscillator Parameter	GPS Performance Parameter
Warmup time	Time to first fix
Power	Mission duration, logistics costs (batteries)
Size and weight	Manpack size and weight
Short term stability (0.1 s to 100 s)	Δ range measurement accuracy, acceleration performance, jamming resistance
Short term stability (~15 minute)	Time to subsequent fix
Phase noise	Jamming margin, data demodulation, tracking
Acceleration sensitivity	See short term stability and phase noise effects

Building Blocks of a Time/Frequency System



Inputs

L1 or
L1/L2

GPS L1-C/A
Com'l RCVR

OR

GPS-SAASM
L1/L2-P(Y)
Mil RCVR

1PPS

OR

External
Inputs from
CESIUM
STDS
or other

Oscillators and Circuitry

RS-232

Displays
Controls
Redundancy

GPS
Disc.
Module

Precision
OSCs

Time and
Freq Gen

Osc. Disc.
Algorithms

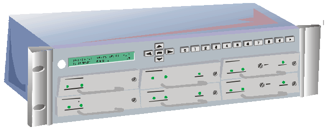
Various
Categories of
Qz & Rb Osc.
& possibly
Cs Stds

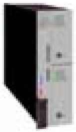
Outputs

Displays
Controls
Diagnostics

Frequency
Time
Network
Outputs

Examples of GPS Based Products


Kstar II and
CommSync


C-GPS and
R-GPS

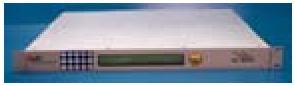
Cell-Site Time/Frequency Generation
and Synchronization


AccuSync and AccuSync-R


GPStarplus

Low Profile, General Purpose Time and
Frequency Synchronization

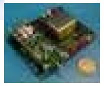

CommSync II – Civil C/A- Code,
Military P(Y)-Code SAASM, and
Distribution Amps (DA)


GSync – Civil C/A and
Military P(Y)-Code SAASM


Portable Clock

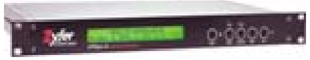
Commercial and Military
Ground and Satellite Link,
High Functionality Time &
Frequency Sync Systems


NanoSync


E911 Engines

Sub-Systems and Modules for E911
and Special Purpose Applications


NTPSync


NTPSync XL

LAN, WAN, MAN GPS-aided Timing

Redundant SAASM CommSync II Modular Time & Frequency System (3U)

CommSync II GTF Module

Plug-In Output Modules

Imbedded Trimble Force-22 SAASM Receiver

OR

Commercial C/A-Code GPS RCVRs

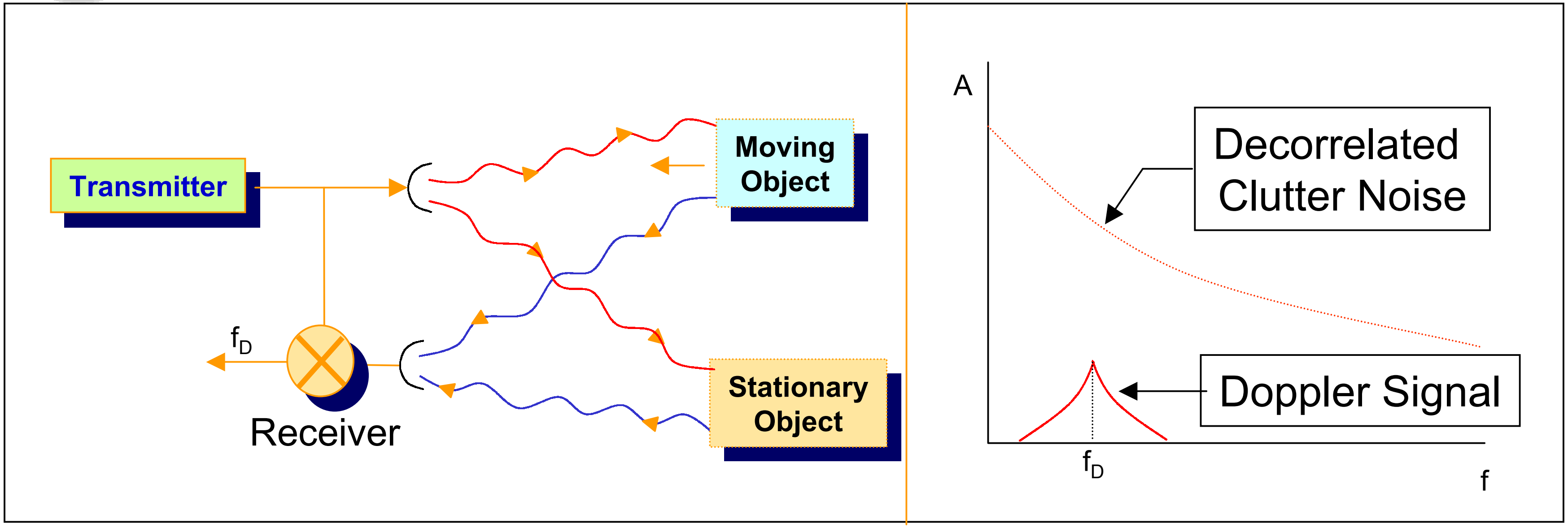
Atomic Oscillators

OR

Qz Oscillators

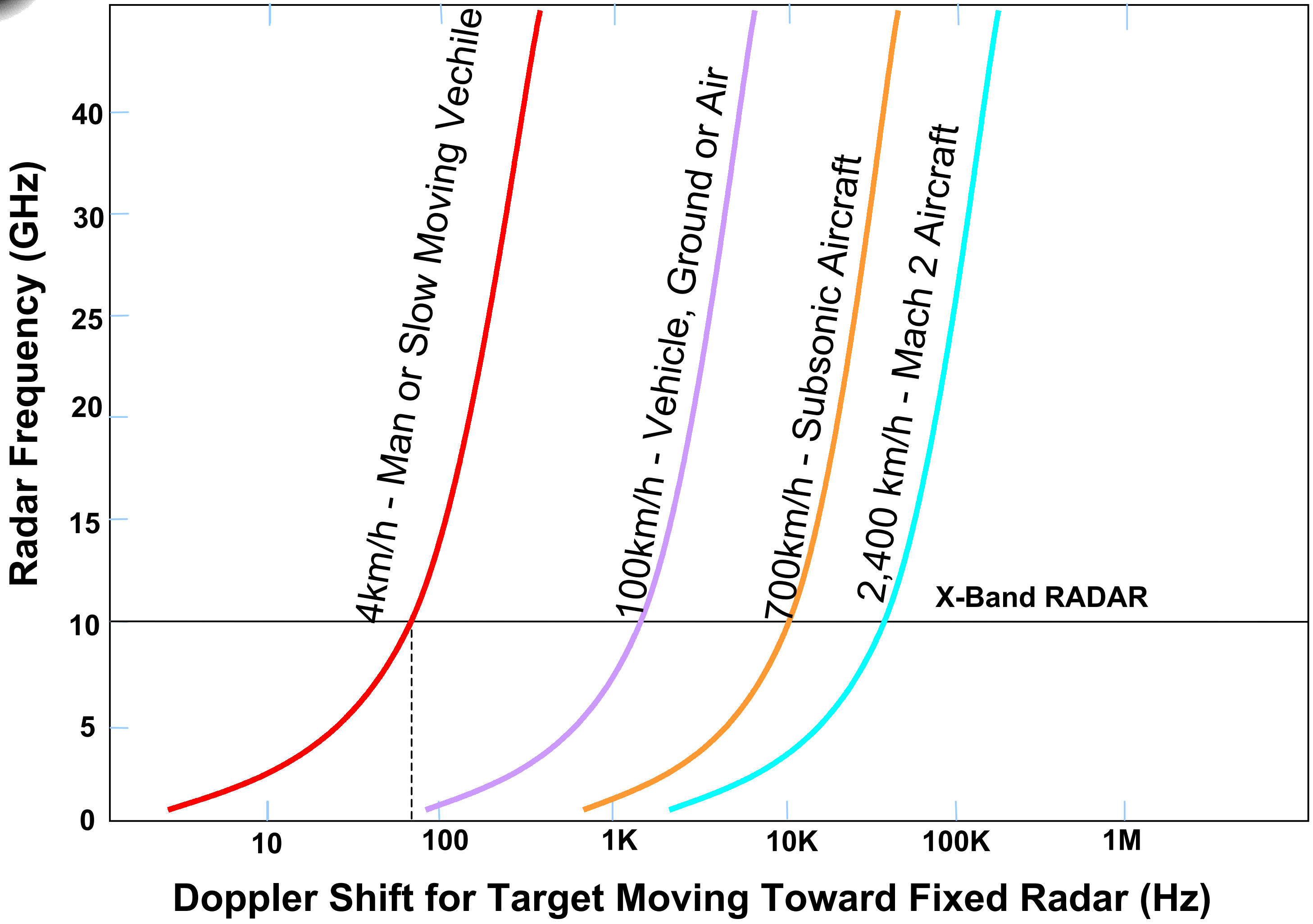
Radar Applications

Effect of Noise in Doppler Radar System



- **Echo = Doppler-shifted echo from moving target + large "clutter" signal**
- **(Echo signal) - (reference signal) --› Doppler shifted signal from target**
- **<u>Phase noise</u> of the local oscillator modulates (decorrelates) the clutter signal, generates higher frequency clutter components, and thereby degrades the radar's ability to separate the target signal from the clutter signal.**

Doppler Shifts



- **Doppler radar require low-phase-noise oscillators. For example to detect slow-moving targets the noise close to the carrier must be low**

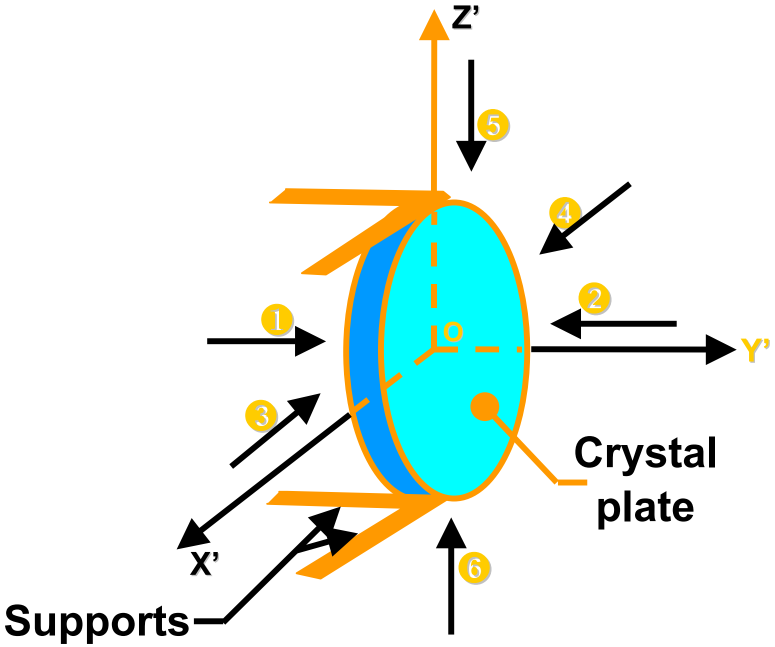
Section 4

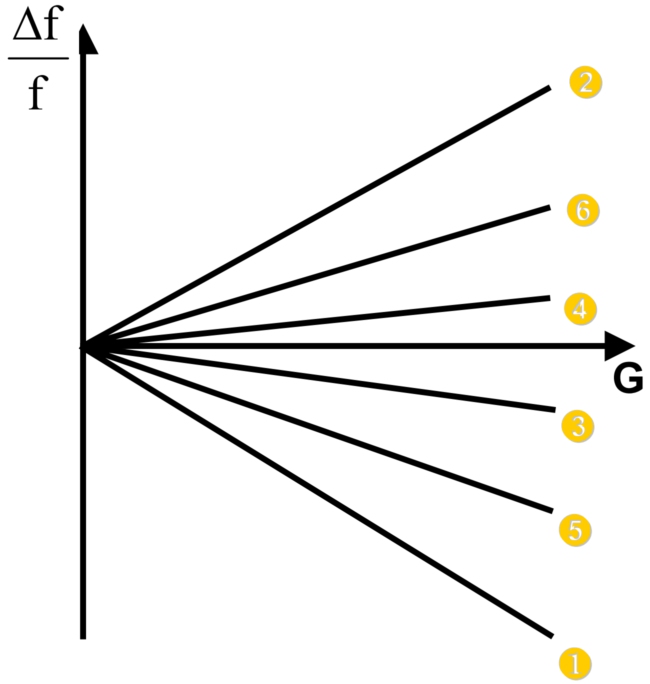
Breakthrough in Vibration Effects on Clocks Stabilities and Side Bands

Vibration Insensitive Oscillators???

Single Side Band Phase Noise Resulting From Vibrations Will Significantly Affect Oscillator Performance

Acceleration vs. Frequency Change





Frequency shift is a function of the magnitude and direction of the acceleration, and is usually linear with magnitude up to at least 50 g's.

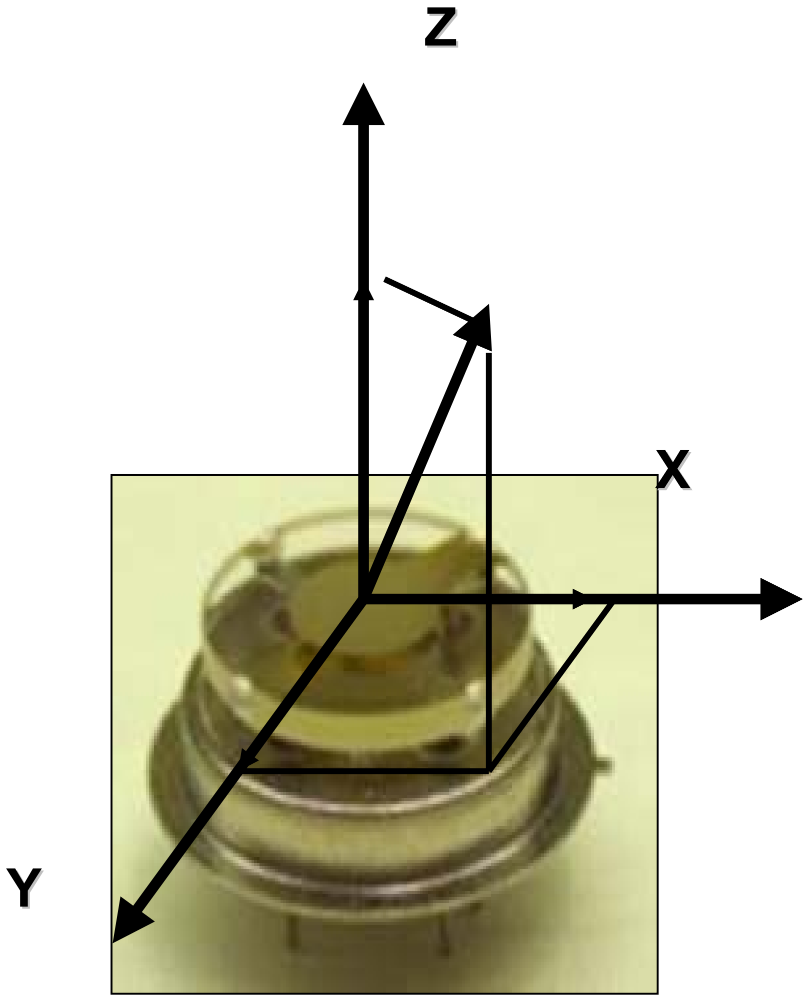
Acceleration Levels and Effects

Environment	Acceleration typical levels*, in g's	$\Delta f/f$ $\times 10^{-11}$, for 1×10^{-9}/g oscillator
Buildings**, quiesent	0.02 rms	2
Tractor-trailer (3-80 Hz)	0.2 peak	20
Armored personnel carrier	0.5 to 3 rms	50 to 300
Ship - calm seas	0.02 to 0.1 peak	2 to 10
Ship - rough seas	0.8 peak	80
Propeller aircraft	0.3 to 5 rms	30 to 500
Helicopter	0.1 to 7 rms	10 to 700
Jet aircraft	0.02 to 2 rms	2 to 200
Missile - boost phase	15 peak	1,500
Railroads	0.1 to 1 peak	10 to 100

*** Levels at the oscillator depend on how and where the oscillator is mounted Platform resonances can greatly amplify the acceleration levels.**

**** Building vibrations can have significant effects on noise measurements**

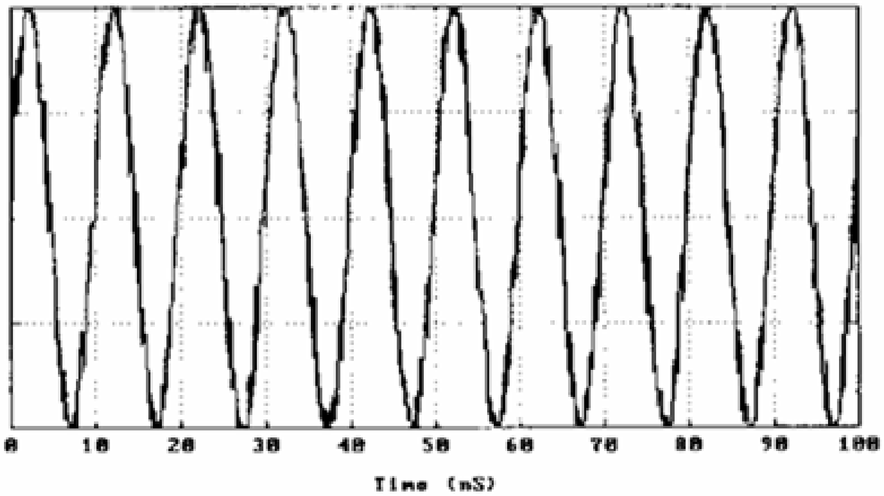
Crystal G-Sensitivity (Gamma)



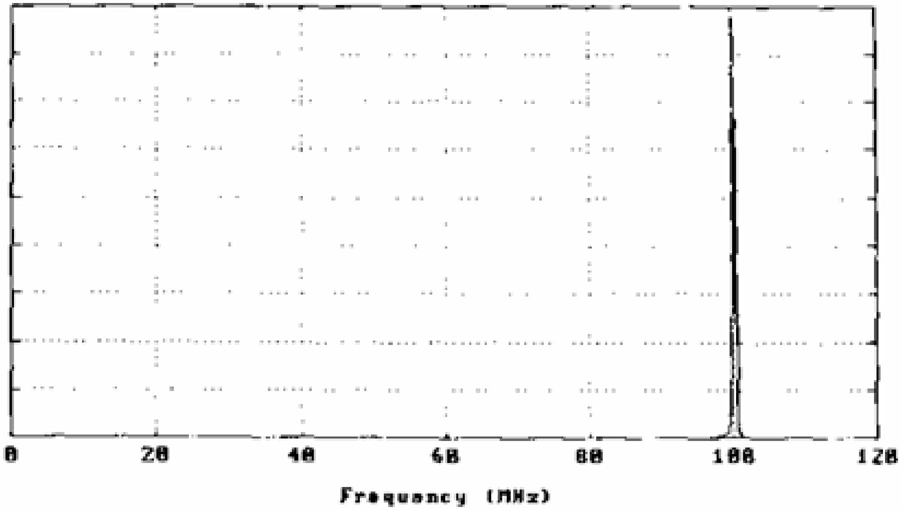
Γ is G sensitivity in Hz/G

$\Gamma = (X^2 + Y^2 + Z^2)^{1/2}$

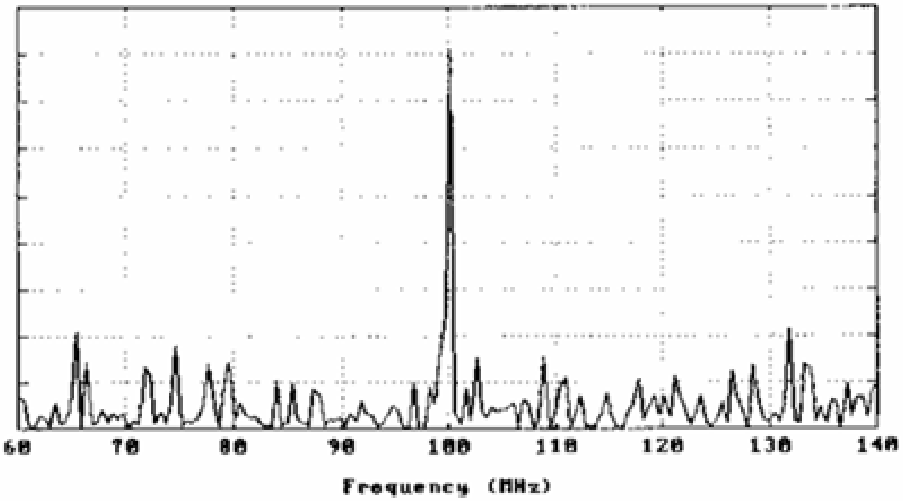
$\Gamma = (3^2 + 3^2 + 3^2)^{1/2} = 5.2 \times 10^{-10}$



100 MHz w/Phase Noise (Time)



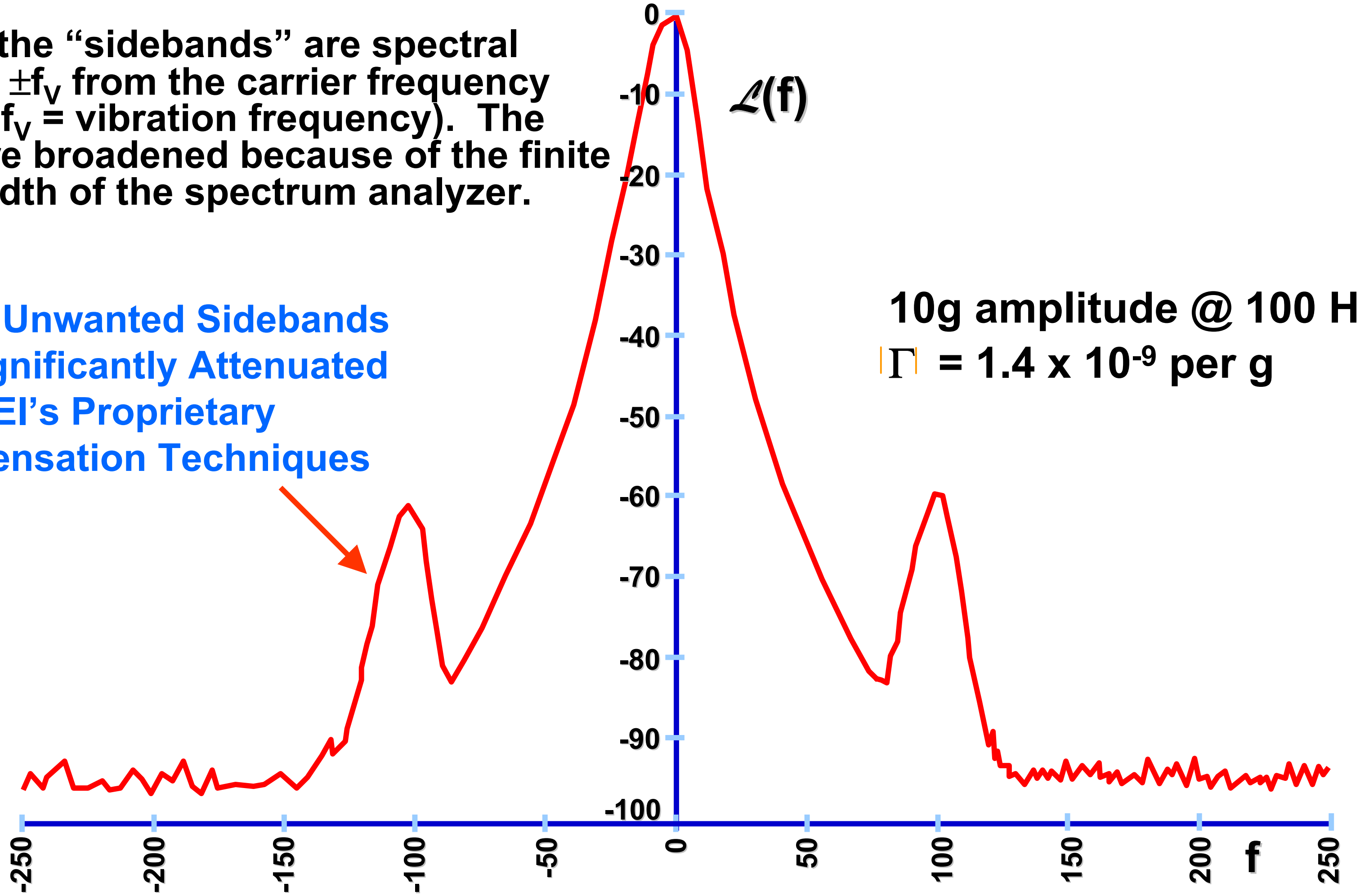
Ideal Sine Wave (Frequency)



100 MHz w/Phase Noise (Frequency)

Vibration-Induced Sidebands

NOTE: the "sidebands" are spectral lines at ±f_V from the carrier frequency (where f_V = vibration frequency). The lines are broadened because of the finite bandwidth of the spectrum analyzer.

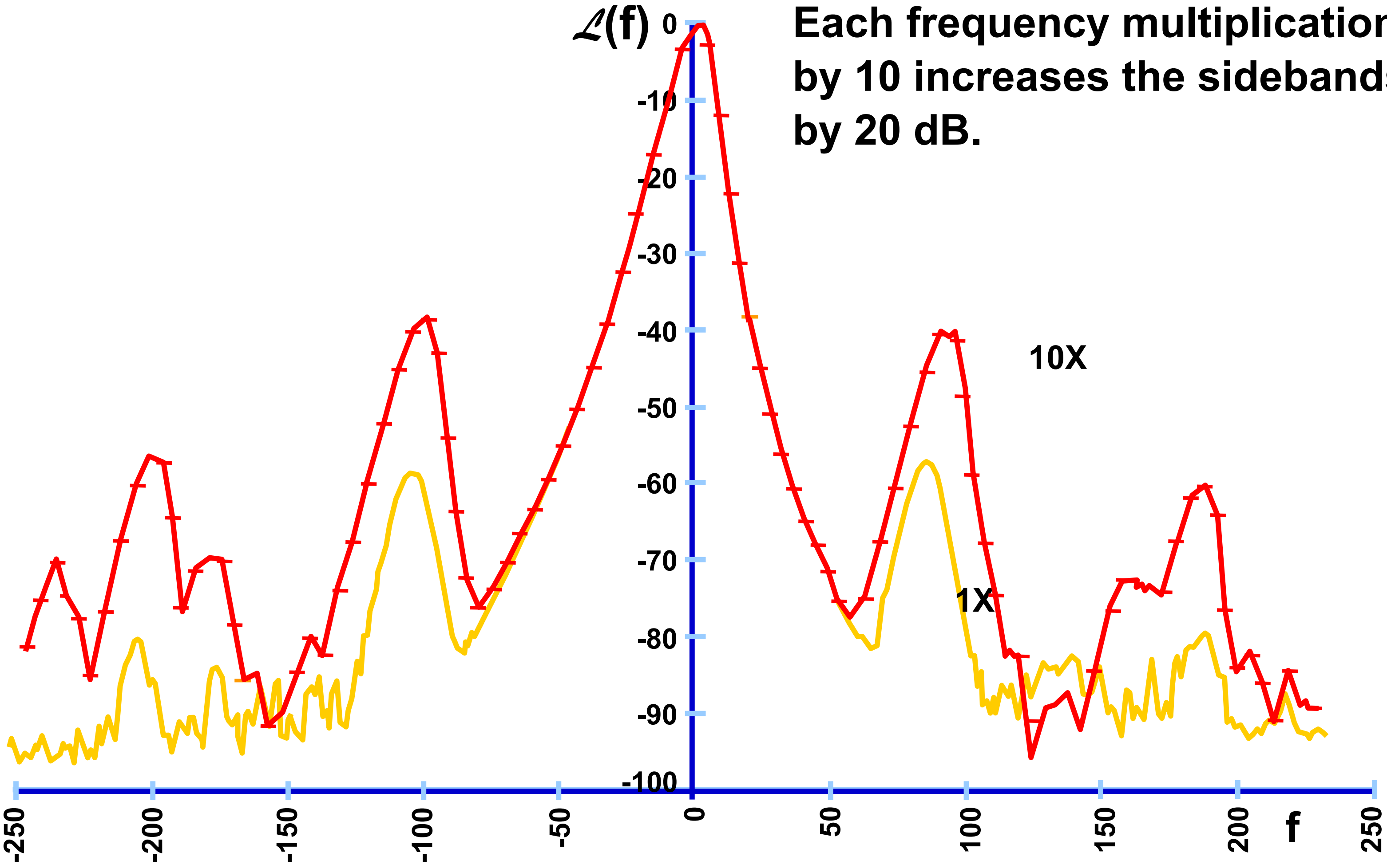


These Unwanted Sidebands are Significantly Attenuated with FEI's Proprietary Compensation Techniques

10g amplitude @ 100 Hz

$|\Gamma|$ = 1.4 x 10^{-9} per g

Vibration-Induced Sidebands After Frequency Multiplication



Each frequency multiplication by 10 increases the sidebands by 20 dB.

Vibration-Induced Phase Excursion

The phase of a vibration modulated signal is

$$\varphi(t) = 2\pi f_0 t + \left(\frac{\Delta f}{f_v}\right)\sin(2\pi f_v t)$$

When the oscillator is subjected to a sinusoidal vibration, the peak phase excursion is

$$\Delta\varphi_{peak} = \frac{\Delta f}{f_v} = \frac{\left(\overline{\Gamma} \bullet \overline{A}\right) f_0}{f_v}$$

Example: if a 10 MHz, 1 x 10^{-9}/g oscillator is subjected to a 10 Hz sinusoidal vibration of amplitude 1g, the peak vibration-induced phase excursion is 1 x 10^{-3} radian. If this oscillator is used as the reference oscillator in a 10 GHz radar system, the peak phase excursion at 10GHz will be 1 radian. Such a large phase excursion can be catastrophic to the performance of many systems, such as those which employ phase locked loops (PLL) or phase shift keying (PSK).

Sine Vibration-Induced Phase Noise

Sinusoidal vibration produces spectral lines at ±f_v from the carrier, where f_v is the vibration frequency.

$$\mathcal{L}'(f_v) = 20\log\left(\frac{\overline{\Gamma}\bullet\overline{A}f_0}{2f_v}\right)$$

e.g., if $\Gamma = 1 \times 10^{-9}$/g and f_0 = 10 MHz, then even if the oscillator is completely noise free at rest, the phase "noise" i.e., the spectral lines, due solely to a sine vibration level of 1g will be;

Vibr. freq., f_v, in Hz	$\mathcal{L}'(f_v)$, in dBc
1	-46
10	-66
100	-86
1,000	-106
10,000	-126

Random Vibration-Induced Phase Noise

Random vibration's contribution to phase noise is given by:

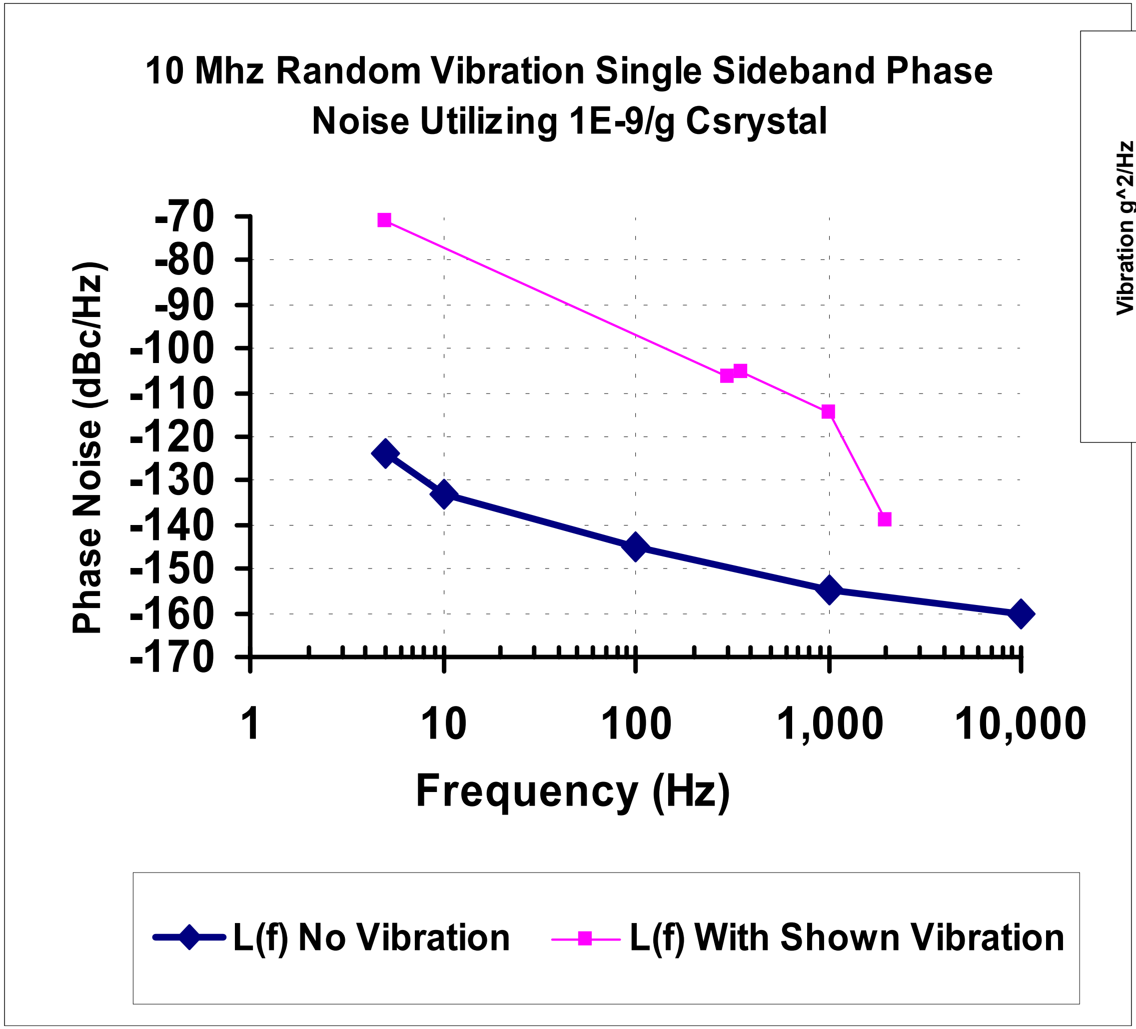
$$\mathcal{L}(f) = 20 \log \left(\frac{\bar{\Gamma} \bullet \bar{A} f_0}{2f} \right), \quad \text{where } |\bar{A}| = [(2)(\mathrm{PSD})]^{1/2}$$

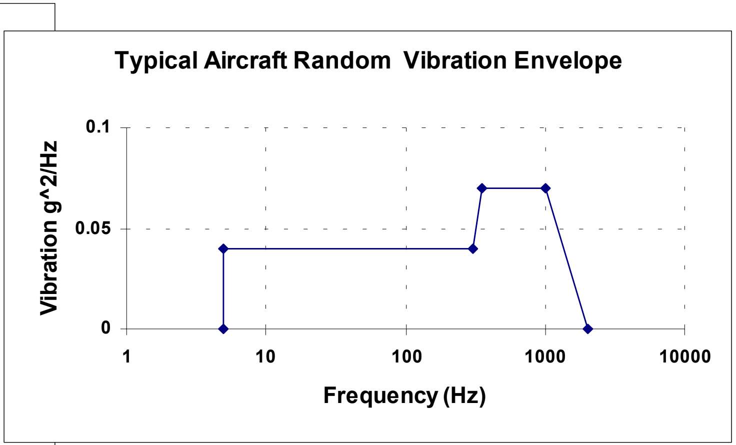
e.g., if $\Gamma = 1 \times 10^{-9}$/g and $f_0 = 10$ MHz, then even if the oscillator is completely noise free at rest, the phase "noise" i.e., the spectral lines, due solely to a vibration PSD = 0.1 g^2/Hz will be:

Offset freq., f, in Hz	$\mathcal{L}'(f)$, in dBc/Hz
1	-53
10	-73
100	-93
1,000	-113
10,000	-133

Typical Aircraft Random-Vibration-Induced Phase Noise

Phase noise under vibration is for $\Gamma = 1 \times 10^{-9}$ per g and f = 10 MHz



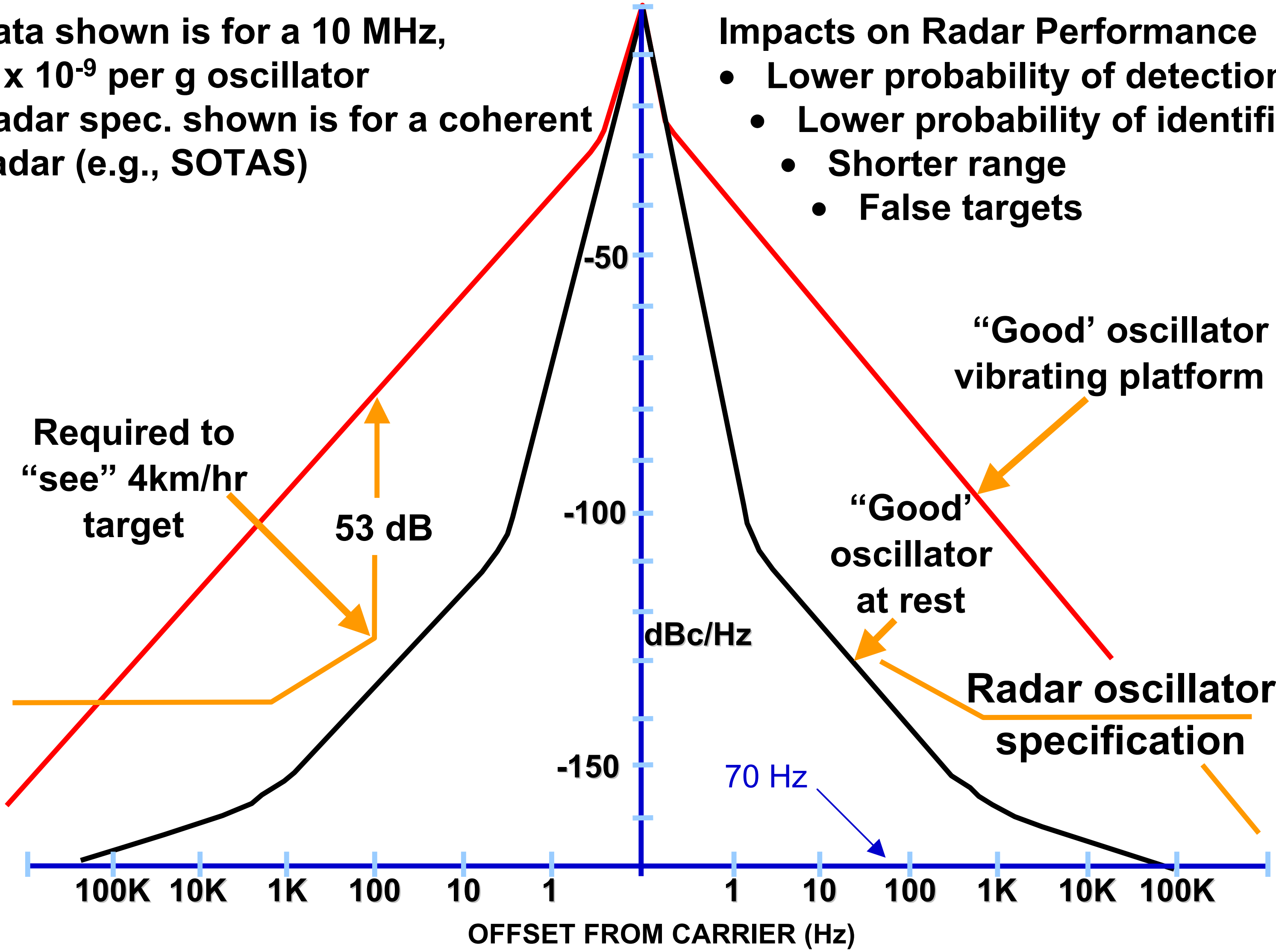


Vib freq Hz	Vib dens g^2/Hz
5	0
5	0.04
300	0.04
350	0.07
1000	0.07
2000	0

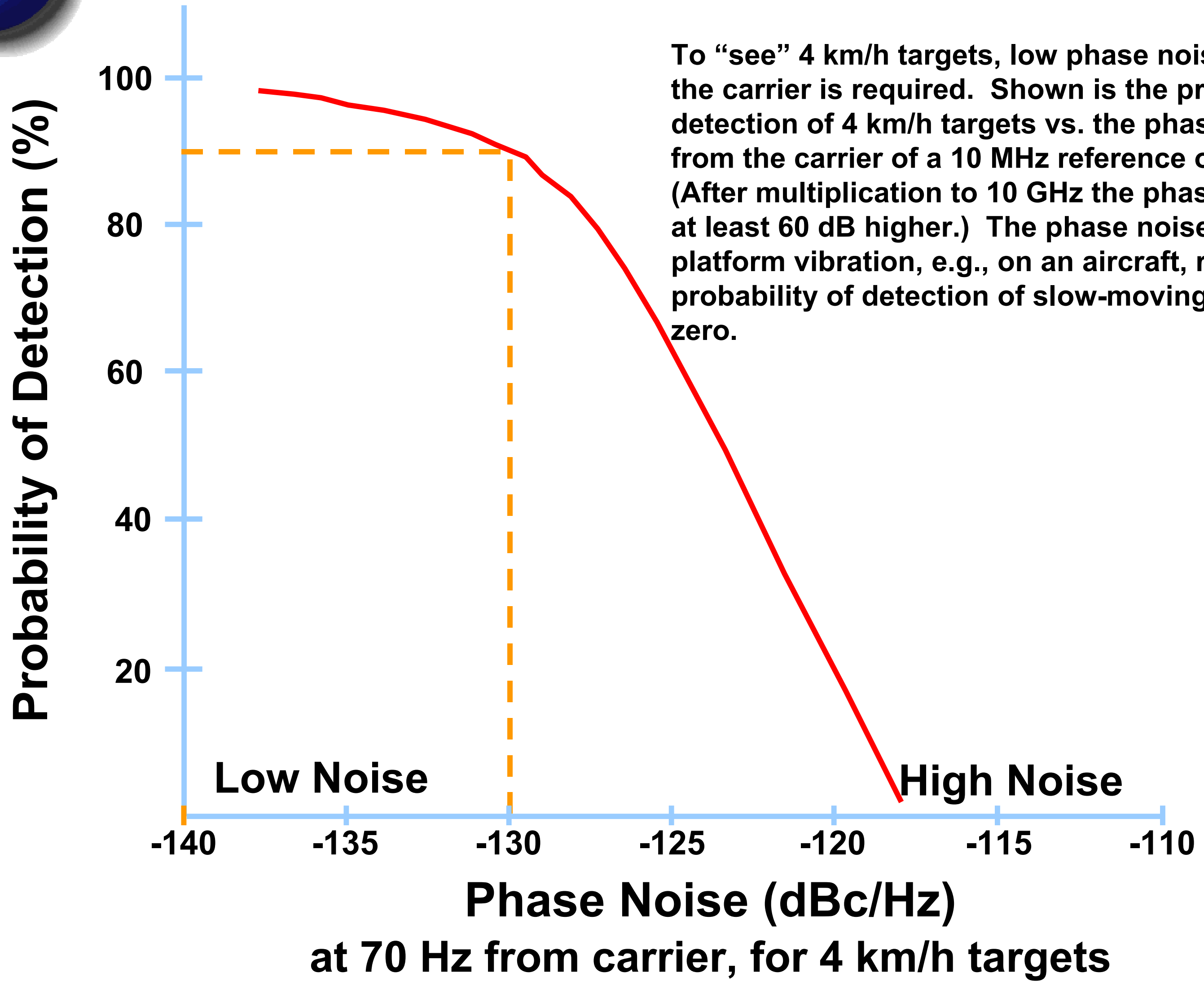
Phase Noise Degradation Due to Vibration

- Data shown is for a 10 MHz, 2 x 10^{-9} per g oscillator
- Radar spec. shown is for a coherent radar (e.g., SOTAS)

Impacts on Radar Performance
- Lower probability of detection
  - Lower probability of identification
    - Shorter range
      - False targets



Coherent Radar Probability of Detection

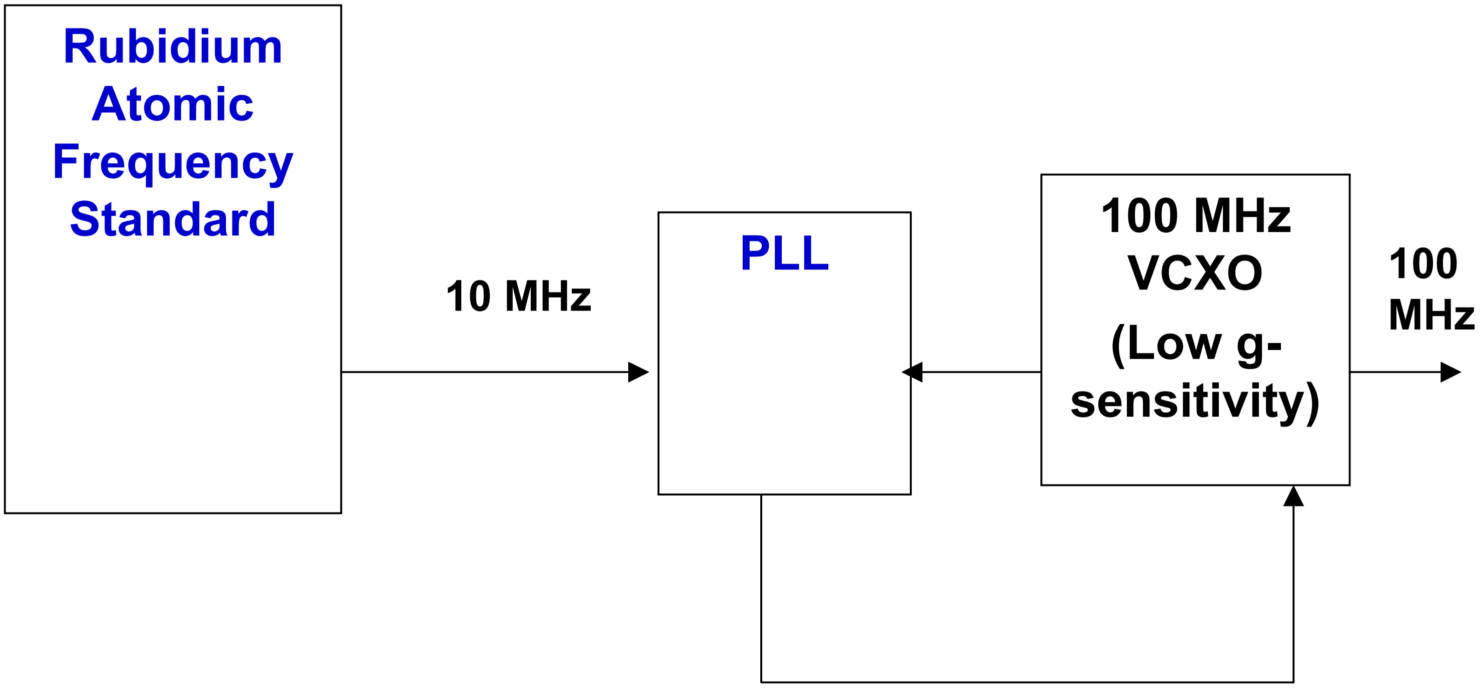


To “see” 4 km/h targets, low phase noise 70 Hz from the carrier is required. Shown is the probability of detection of 4 km/h targets vs. the phase noise 70 Hz from the carrier of a 10 MHz reference oscillator. (After multiplication to 10 GHz the phase noise will be at least 60 dB higher.) The phase noise due to platform vibration, e.g., on an aircraft, reduces the probability of detection of slow-moving targets to zero.

Rugged Clocks

- **Some applications require Rubidium Atomic Standards**
- **Other applications require only Crystal Oscillators**
- **Every Rubidium atomic Standard contains a crystal oscillator that determines its single side band phase noise under vibration**

Clocks are available as Rubidium Standards and/or as Crystal Oscillators



Rugged Clocks

- Rubidium Standard must survive environmental conditions
- Rubidium Standard must not loose lock under any environmental conditions
- OCXO must provide the phase noise performance under vibration
- A phase lock loop with appropriate time constants must be cable of taking long term stability of Rubidium and not deteriorate the short term stability and spectral purity of OCXO
- All components of this frequency and time system must operate under all specified environmental conditions
- Must be producible and affordable

G-Sensitivity of Quartz Resonators

- **Quartz resonators exhibit an inherent g-sensitivity—they are good accelerometers**
- **Present crystal technology:**
  - 1E-9/g typical
  - 3E-10/g low yield and expensive
  - 2E-10/g state-of-the-art

Breakthrough in G-Sensitivity

- Develop of a SC-cut resonator with minimum cross axis coupling
- Typical g-sensitivity of 1E-10/g
- Broadband compensation technique from DC to 2 KHz
- Improvements of 30dB typical
- Compensation is independent of:
  - Temperature
  - Nominal setting of oscillator frequency
  - Aging of components in frequency feedback loop

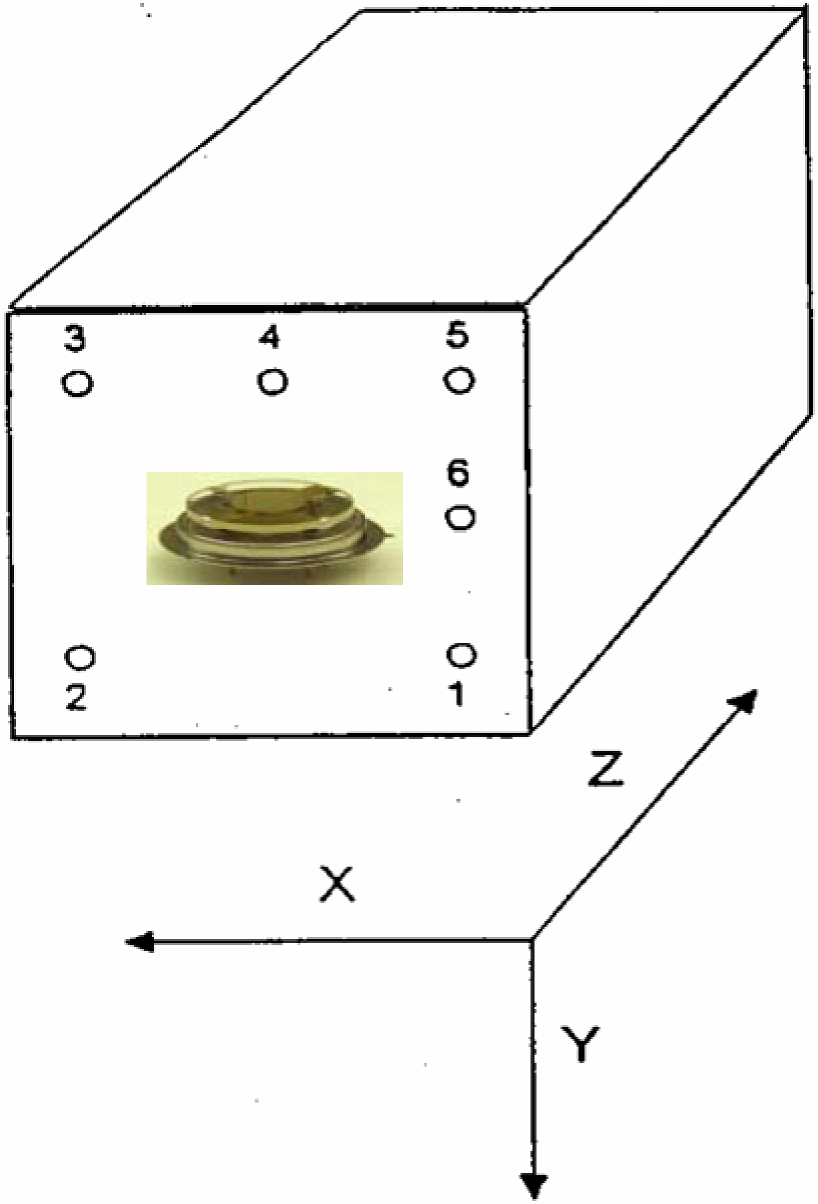
Objectives

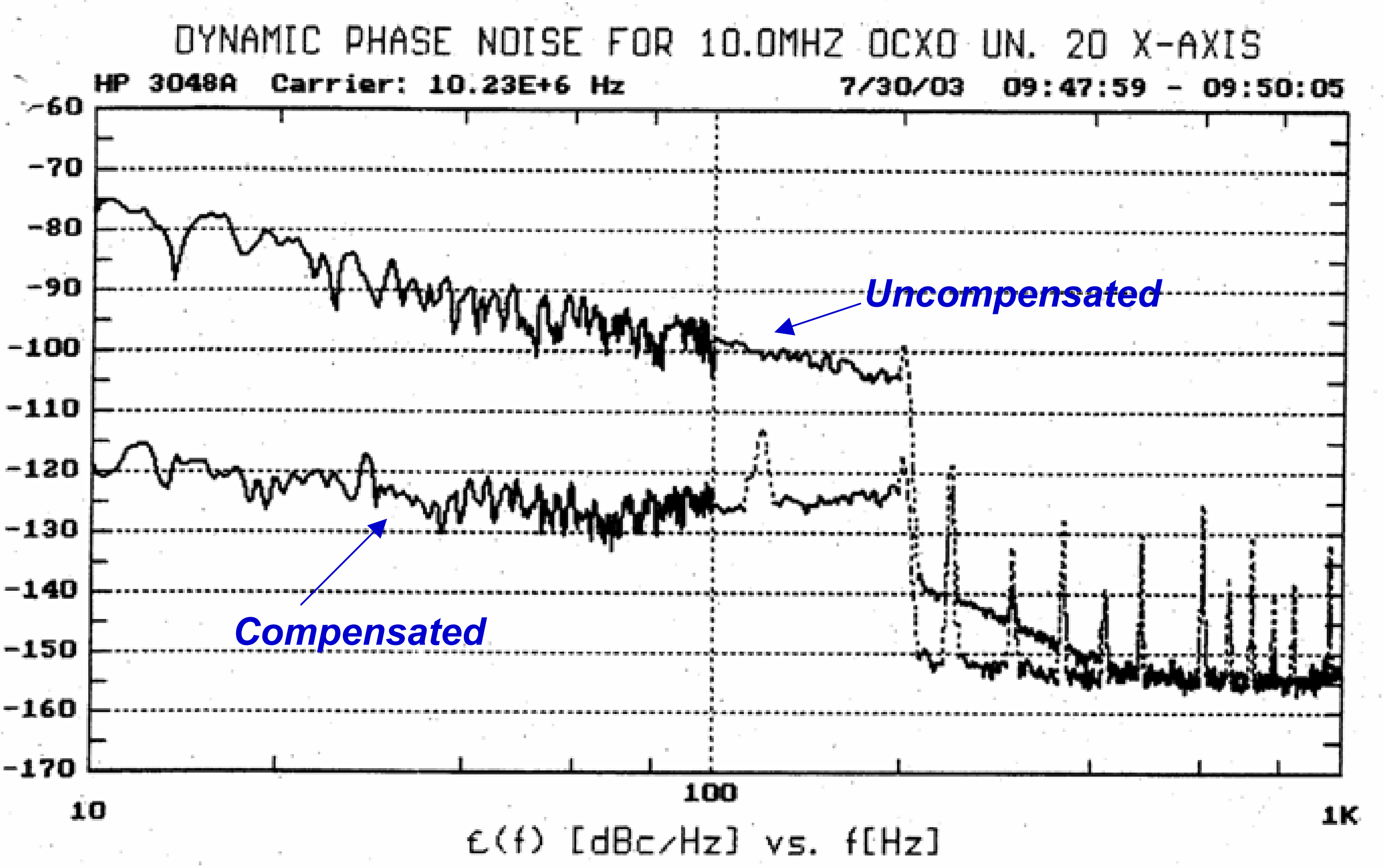
- **Achieve:**
  - 2E-12/g
  - Economies in manufacturability
  - Small package ≈ 3 in^3
- **Combination of low g-sensitivity technology with vibration isolators to accomplish above performance from DC to 2 KHz**
- **The technology is also applicable to Rubidium Standards in moving/vibrating platforms (vibration induced errors in Rb standards is solely due to crystals imbedded in the Rb design)**

Applications

- FEI's recent breakthrough in highly reproducible low-G sensitivity oscillators that are virtually insensitive to acceleration/vibration has resulted in a host of applications:
  - Precision Navigation
  - Radar for helicopters and other challenging platforms
  - Commercial and Secure communications
  - Space exploration
  - Target acquisition
  - Munitions and Missile guidance
  - SATCOM terminals
  - All other applications where the effects of acceleration or vibration effect the output signal of the oscillator

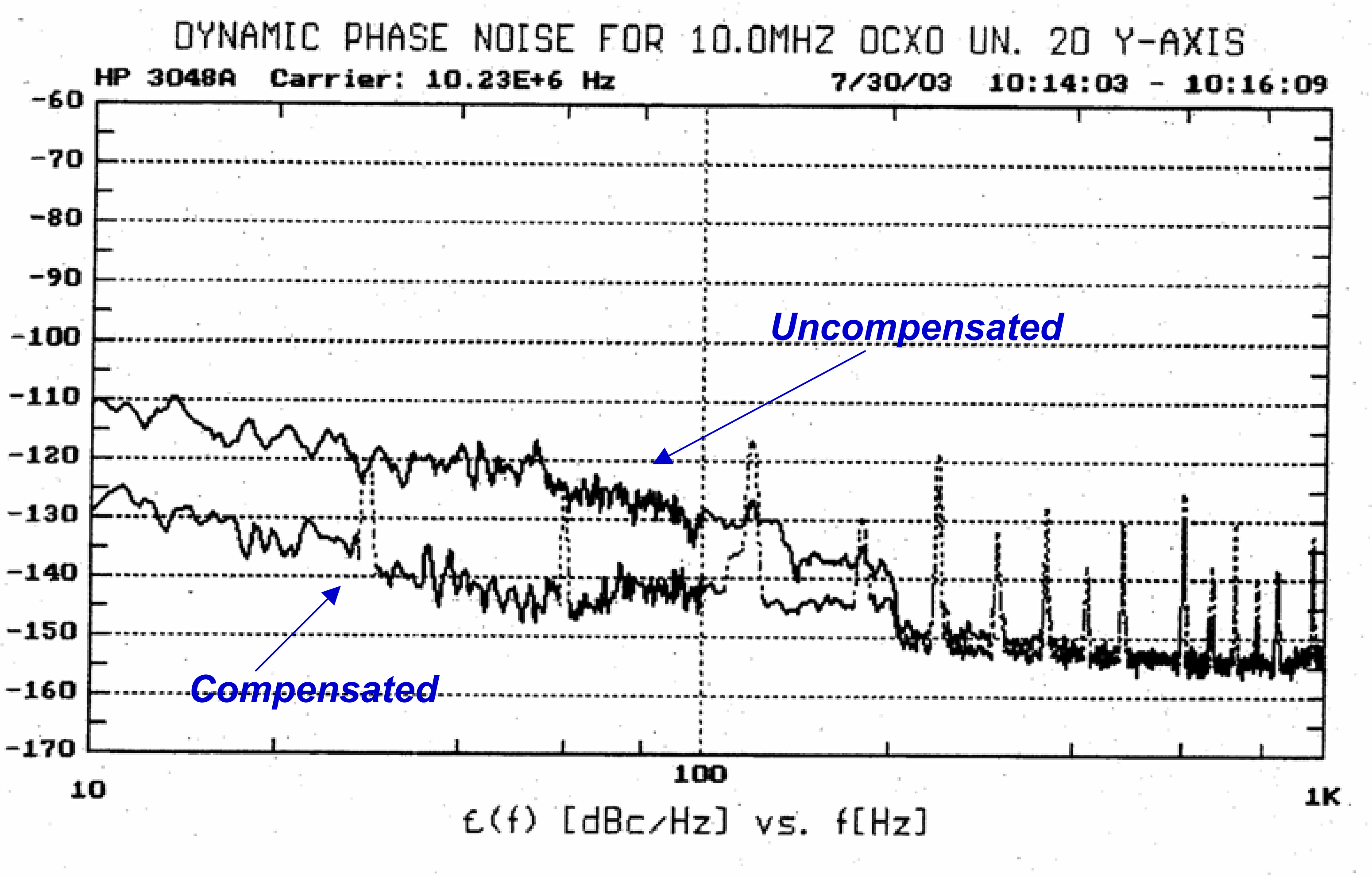
AXIS DEFINITIONS





Vibration Profile: 4 g RMS total, Random; 0.08g^2/Hz 10 to 200 Hz

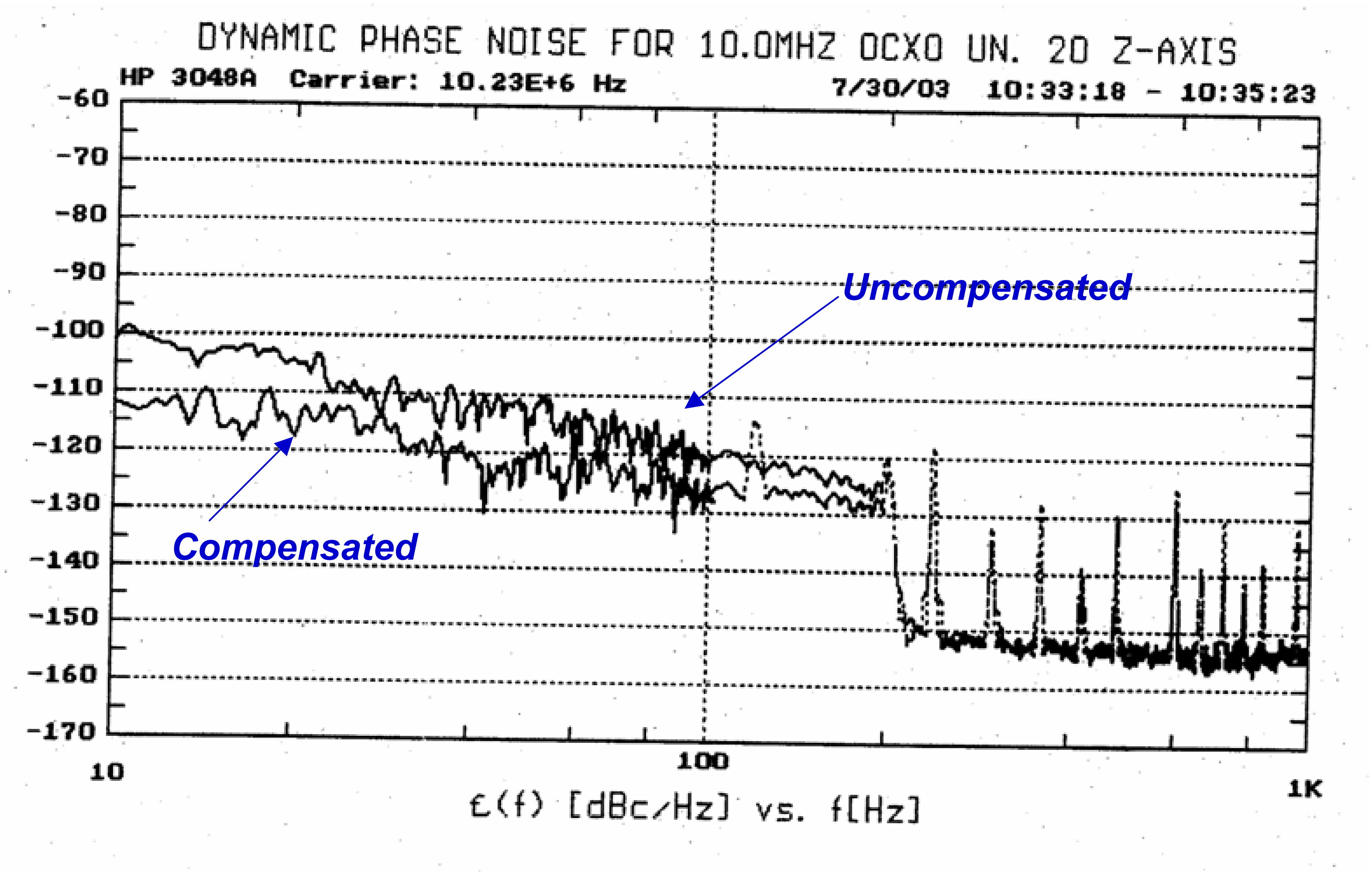
	Approximate Sensitivity per g		
	10 Hz	50 Hz	100 Hz
Uncompensated	1.1×10^{-9}	7.9×10^{-10}	8.9×10^{-10}
Compensated	6.3×10^{-12}	2.2×10^{-11}	4.0×10^{-11}



Vibration Profile: 4 g RMS total, Random; 0.08g^2/Hz 10 to 200 Hz

Approximate Sensitivity per g

	10 Hz	50 Hz	100 Hz
Uncompensated	2.2 x 10^{-11}	2.8 x 10^{-11}	2.2 x 10^{-11}
Compensated	2.8 x 10^{-12}	2.5 x 10^{-12}	5.0 x 10^{-12}

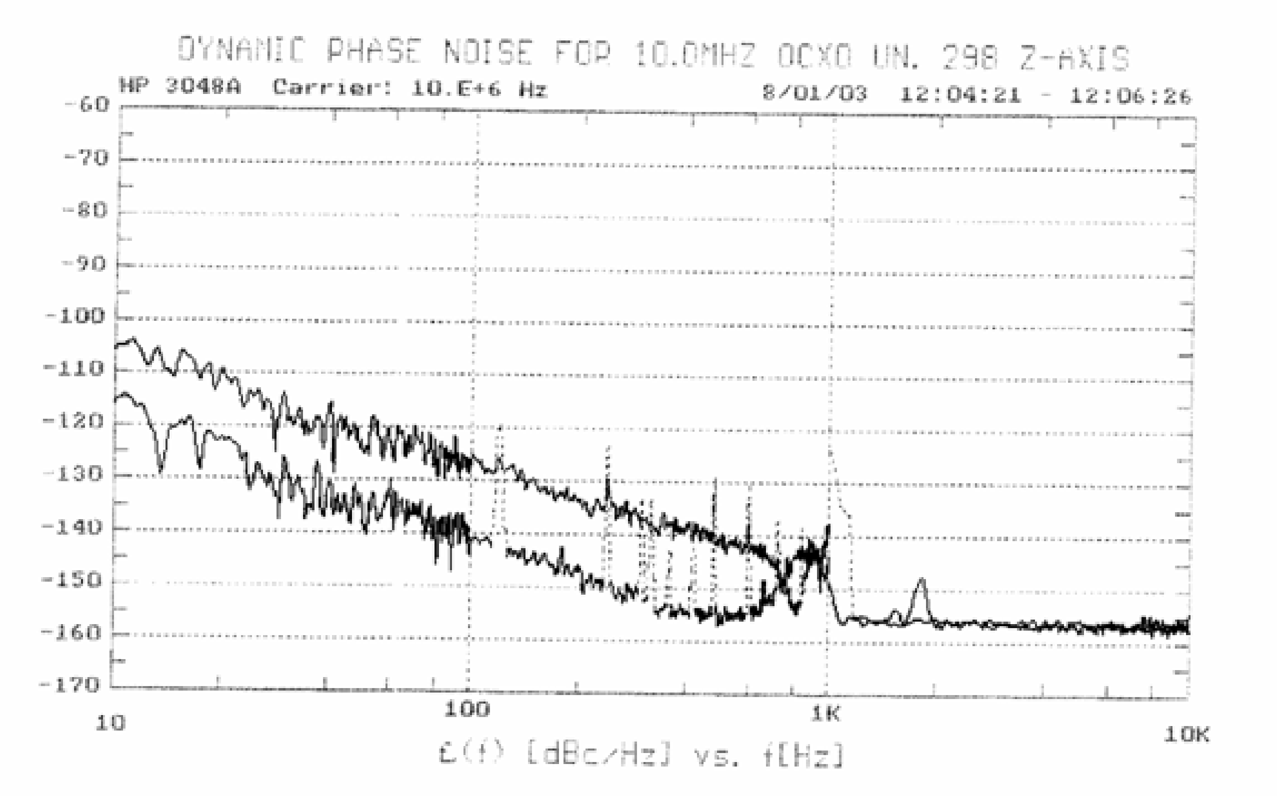


Vibration Profile: 4 g RMS total, Random; $0.08g^2$/Hz 10 to 200 Hz

Approximate Sensitivity per g

	10 Hz	50 Hz	100 Hz
Uncompensated	7.0×10^{-11}	8.9×10^{-11}	7.0×10^{-11}
Compensated	1.8×10^{-11}	3.1×10^{-11}	3.5×10^{-11}

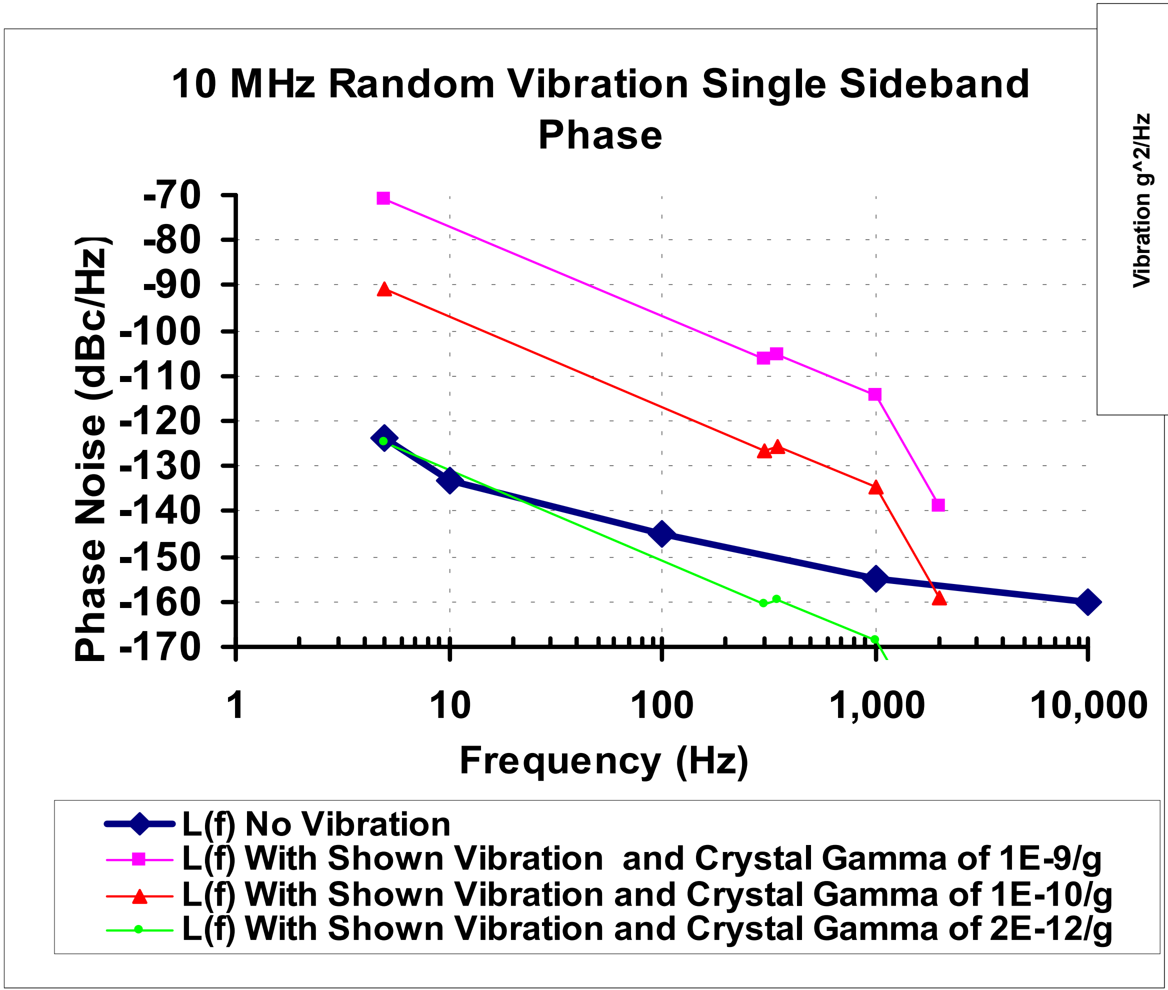
Broadband Vibration
$0.008g^2$/Hz 10 Hz to 1 KHz



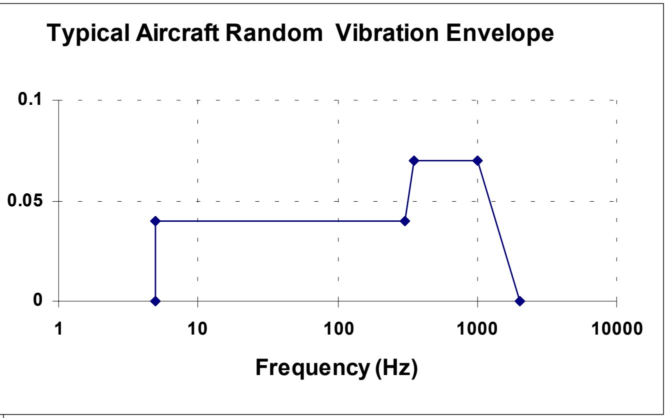
Note: Fixture resonance observed at ≈ 900 Hz

Typical Aircraft Random-Vibration-Induced Phase Noise

Phase noise under vibration is for $\Gamma = 1 \times 10^{-9}$ per g , $\Gamma = 1 \times 10^{-10}$ per g, $\Gamma = 2 \times 10^{-12}$ per g and f = 10 MHz.



10 MHz Random Vibration Single Sideband Phase

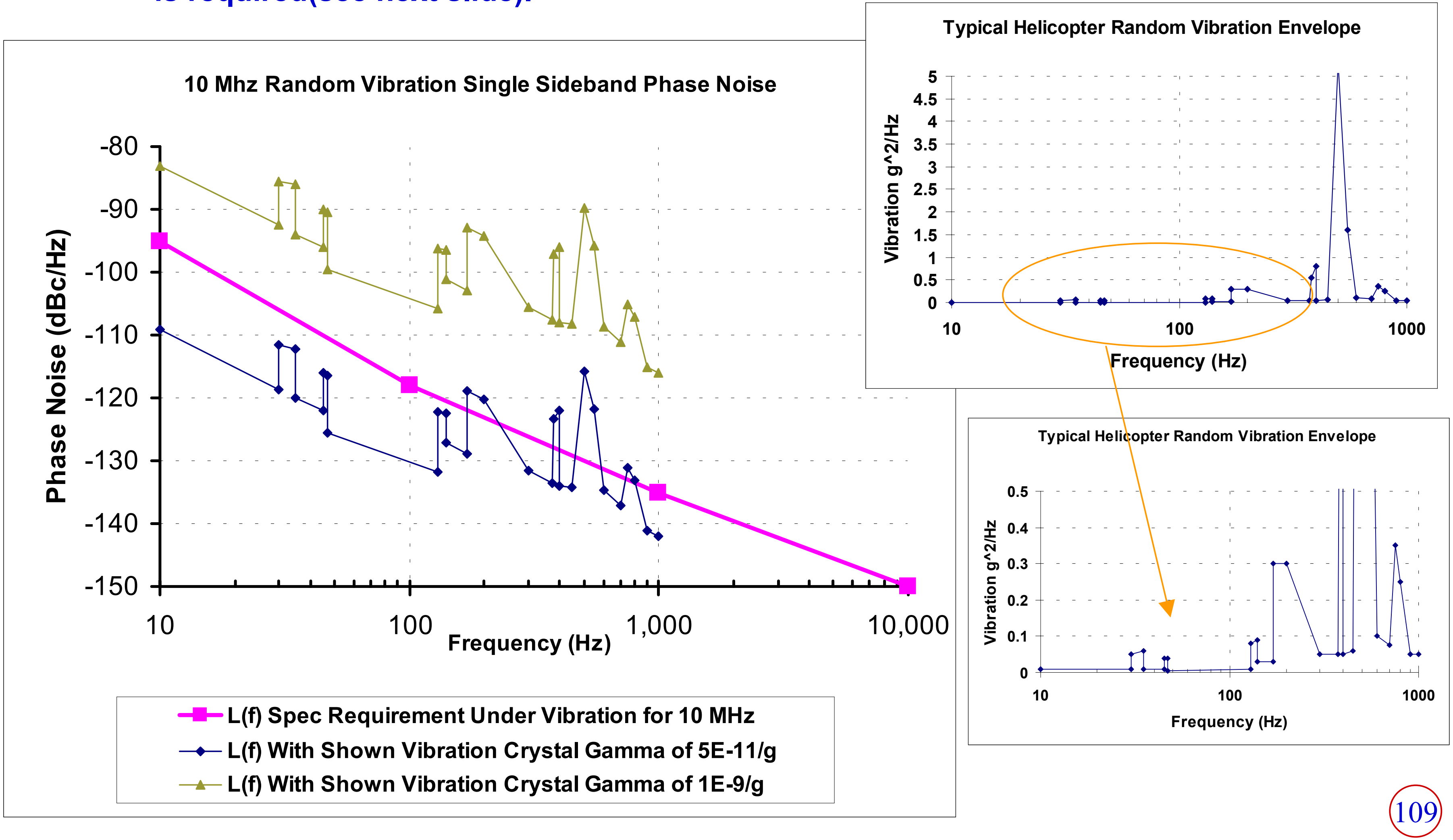


Typical Aircraft Random Vibration Envelope

Vib freq Hz	Vib dens g^2/Hz
5	0
5	0.04
300	0.04
350	0.07
1000	0.07
2000	0

Typical Helicopter Random-Vibration-Induced Phase Noise

Phase noise under vibration is for Γ = 1 x 10^{-9} per g , Γ = 5 x 10^{-11} per g and f = 10 MHz. To meet the specification a Γ = 5 x 10^{-12} per g or better is required. Close to carrier noise is reduced using FEI's low-g sensitivity breakthrough, and above 200 Hz vibration isolation is required(see next slide).



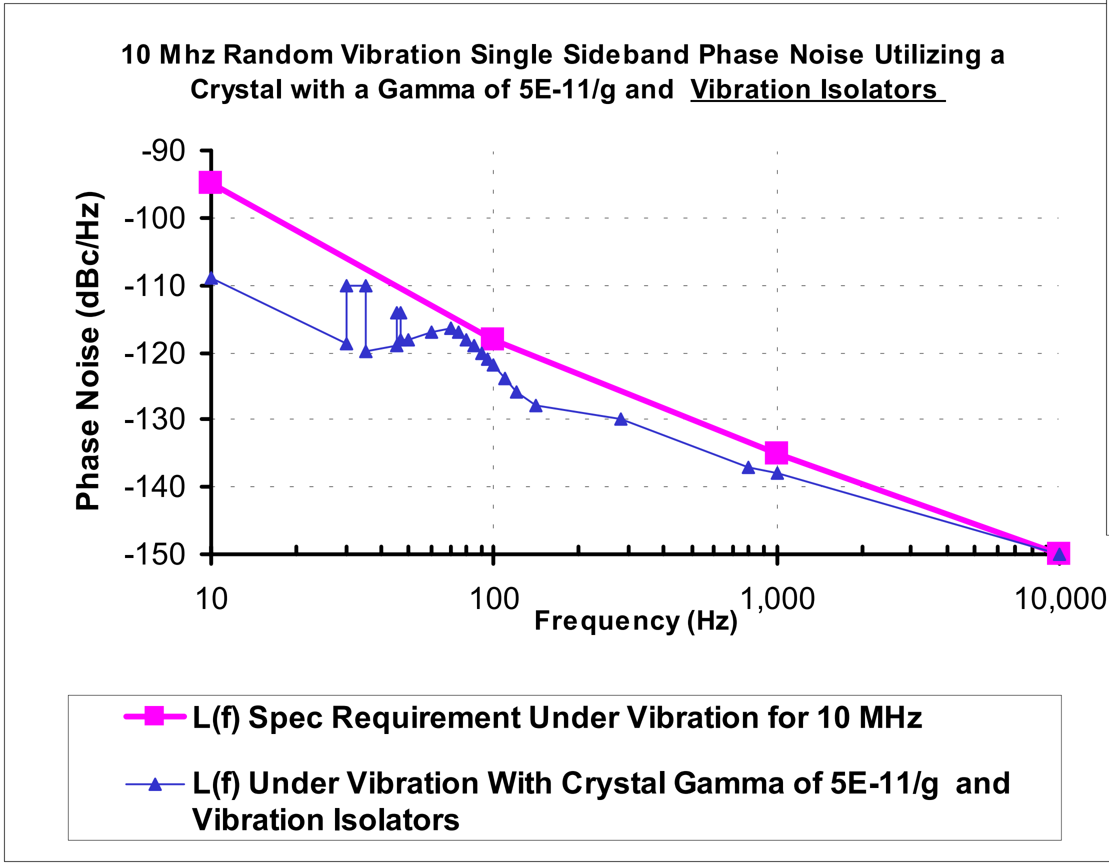
10 Mhz Random Vibration Single Sideband Phase Noise

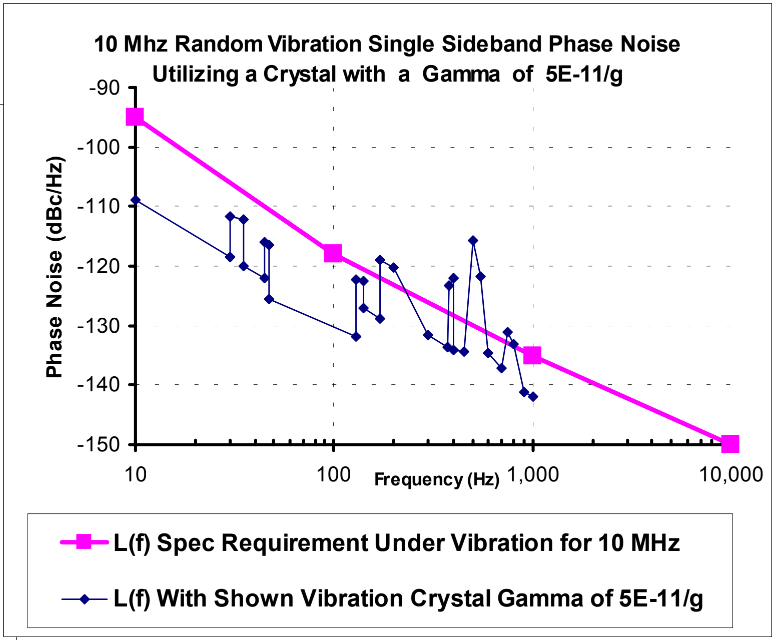
Typical Helicopter Random Vibration Envelope

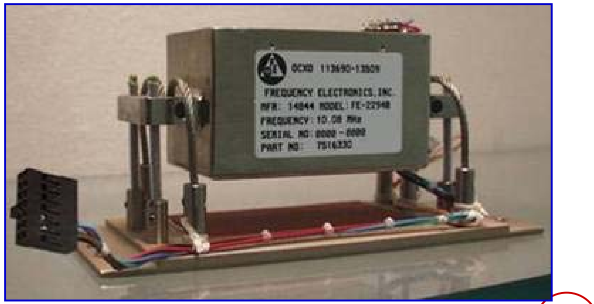
Typical Helicopter Random Vibration Envelope

Typical Helicopter Random-Vibration-Induced Phase Noise

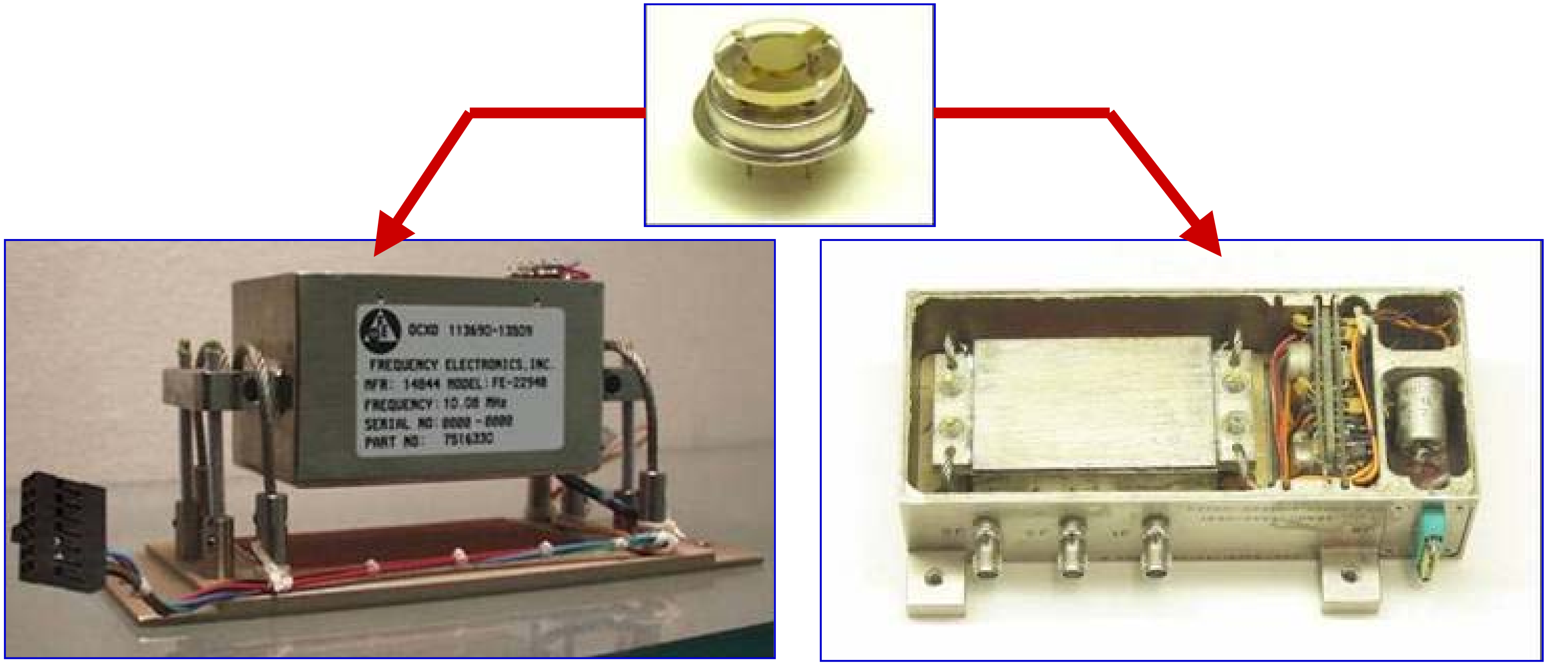
Phase noise under vibration is for $\Gamma = 5 \times 10^{-11}$ per g and f = 10 MHz. Close to carrier noise is reduced using FEI's low-g sensitivity breakthrough, and above 200 Hz vibration isolation are utilized. Vibration Isolators are chosen with resonance frequency of ≅ 70 Hz with damping factor of 0.3 and ≅ -6dB mechanical damping factor per octave.







Summary: Clocks for Challenging Environments



Low G-Sensitivity Clocks

- Internal FEI proprietary compensation techniques to reduce g-sensitivity

- Vibration isolation mounts may be required