THE PHYSICS OF THE ENVIRONMENTAL SENSITIVITY OF RUBIDIUM GAS CELL ATOMIC FREQUENCY STANDARDS

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Abstract

Environmental sensitivity is often the most significant limitation to the practical stability of rubidium frequency standards (RFS). For example, temperature sensitivity can cause a rapid frequency change of several parts in 10^{10} for a tactical RFS that has an aging of only $1x10^{-11}$/month. Other important environmental factors are barometric pressure, vibration, magnetic field, and nuclear radiation.

This paper considers the physical mechanisms that lie behind these environmental sensitivities, and relates them to the performance of actual rubidium frequency standards. It is part of an effort currently underway under NIST and IEEE sponsorship toward a standard characterizing such environmental sensitivities. For the systems designer, a better understanding of the reasons for RFS environmental sensitivity will help in making program tradeoffs. For the user of these devices, a better knowledge of the causes for Rb clock instability will aid in their testing and proper application. For the time and frequency specialist, a review of these factors may prove useful toward improving RFS design.

Some of the RFS environmental sensitivities are due to simple physical mechanisms like the effect of dc magnetic field on the Rb hyperfine resonance frequency. For these, an analysis can be based on physical principles and straightforward design factors. Other environmental factors, like temperature sensitivity, are more complex combinations of many effects, both physical and practical, and the analysis often takes the form of an error budget with large unit-to-unit variations.

Today's rubidium frequency standards span a wide performance range from small, inexpensive units with pp10^{10} error budgets to larger, higher performance versions offering pp10^{14} stabilities. For both extremes, however, environmental sensitivity can be the most significant performance limitation. This paper helps explain why, and offers some insight into how to make improvements.

INTRODUCTION

The rubidium gas cell atomic frequency standard has found widespread use since its introduction about thirty years ago. It offers the best combination of stability, size, weight, power, life, and cost for many commercial and military applications. In many of these applications, environmental sensitivity is the most significant performance limitation.[1, 2] This paper will attempt to summarize the physical basis of the environmental sensitivity of the rubidium frequency standard (RFS).

An understanding of the physical mechanisms that cause environmental sensitivity is of obvious concern to the RFS designer, especially since the device may be intended for a harsh tactical application.

But it is also important for the specifier and user of these devices to have a good understanding of the root causes of RFS environmental sensitivity.

The paper begins with an examination of the principal factors that contribute to RFS instability. These are the causes of environmental sensitivity. It then considers each environmental factor and relates it to the RFS sensitivities. Additional information is presented in the form of tables. The table columns cover the three major RFS sections, while the table rows relate similar sensitivity factors.

RFS SENSITIVITIES

The largest factors contributing to the environmental sensitivity of a rubidium frequency standard are shown in Table 1. Most of these factors are basic characteristics of the physics package (such as magnetic sensitivity) that become environmental sensitivities when the instabilities of the electronics circuits (such as the C–field current source) are considered.[3] Some of these RFS sensitivities are fixed (such as magnetic dependence), while others vary with operating conditions. For example, the effects of servo amplifier and rf chain offsets scale with the strength of the discriminator slope. Environmental constraints can, in turn, affect the realizable Rb signal. An RFS required to operate at an elevated ambient temperature must compromise its S/N ratio and discriminator signal by using an absorption cell oven setpoint higher than optimum.

TABLE 1 RFS SENSITIVITIES

PHYSICS PACKAGE	CRYSTAL OSCILLATOR	ELECTRONICS
C–FIELD SENSITIVITY: Magnetic Bias Field Residual Oven Heater Field		C–FIELD STABILITY: Volt Ref & Current Source Temp Controller Heater Current
LIGHT SHIFT: Light Intensity & Spectrum		LAMP EXCITER: Lamp Excitation Power
TEMPERATURE COEFFICIENTS: Lamp TC Filter Cell TC Absorption Cell TC C-Field Coil Resistance TC Cavity TC		TEMPERATURE CONTROLLERS: Thermal Gain DC Amplifier Stability Thermistor Self–Heating Thermistor Stability Bridge Resistor Stability
RF POWER COEFFICIENT: Buffer Gas Confinement Line Inhomogeneity C-Field Inhomogeneity Abs Cell Temperature Gradient		RF CHAIN: Microwave Excitation Power RF Spurious Components Modulation Distortion
BAROMETRIC COEFFICIENT: Abs Cell Buffer Gas Offset Abs Cell Envelope Deflection		
DISCRIMINATOR SIGNAL: Discriminator Slope	SERVO LOOP: Static & Dynamic Tracking Error	SERVO AMPLIFIER: Finite Gain & Phase Error Static & Dynamic Offsets Mod Deviation Change 2nd Harmonic Ripple
OPTICAL PATH: Light Beam Motion	CRYSTAL: G–Sensitivity	SERVO AMPLIFIER: Servo Interference

Magnetic Field Sensitivity: The magnetic field sensitivity of an RFS is a result of the hyperfine magnetic resonance on which it depends. The physics package uses an internal longitudinal dc magnetic bias field to orient the Rb atoms and separate the Zeeman sublevels. The "field independent" clock transition has a quadratic dependence $\Delta f = 573\,H^2$, where Δf is the frequency change in Hz and H is the magnetic field in Gauss. The incremental magnetic sensitivity varies linearly with the magnetic bias field $\frac{\Delta f}{f} = \frac{1146}{f_o}\,H\,\Delta H$, where $\frac{\Delta f}{f}$ is the fractional frequency change, f_o is the Rb frequency ($\approx$6835 MHz), and ΔH is the magnetic field change. The fractional magnetic sensitivity therefore varies as $\frac{\Delta f}{f} = 1.68\text{x}10^{-7}\,H^2\,\frac{\Delta H}{H}$, where $\frac{\Delta H}{H}$ is the fractional field change.

Light Shift: Light shift is one of the fundamental stability limitations of the rubidium frequency standard.[4] Because optical pumping is usually done in the same place, and at the same time, as interrogation of the Rb atoms, asymmetry in the pumping light spectrum causes a frequency offset.[5] For good performance, it is necessary to operate the unit at the condition of zero light shift (ZLS) where the frequency is independent of light intensity. This is accomplished by adjustment of the Rb lamp isotopic ratio for an integrated cell and adjustment of the length and/or temperature of a discrete filter cell.[6] The condition of zero light intensity coefficient, zero lamp TC, and zero lamp rf excitation power coefficient are not exactly the same, and there is always some residual light shift sensitivity.

Temperature Coefficients: A closely related fundamental RFS limitation is lamp and cell temperature sensitivity. Lamp and filter cell TCs are light shift effects. Absorption cell TC is primarily due to buffer gas effects. Two configurations offer overall optimization of RFS physics package operating conditions.[4] For the integrated cell, optimization of the lamp isotopic mix and the cell buffer gas mix can provide an overall zero light shift/zero TC condition.[7] For the discrete filter cell, an Rb^{87} lamp with a Rb^{85} filter cell and a Rb^{87} absorption cell, with the two cells in the same oven, and with optimized operating temperatures and buffer gas mixes, provides an overall ZLS/ZTC condition.[8] An RFS physics package using this arrangement can be easily adjusted for optimum operating conditions by setting the lamp oven temperature (light intensity) for zero cell oven TC and setting the cell oven temperature (hyperfine filtration) for zero lamp oven TC (ZLS). This also provides a homogeneous light spectrum for low rf power sensitivity. Typical residual TCs are a few $\text{pp}10^{11}/^\circ\text{C}$ for the RFS lamp and cell ovens. A wall coated cell without buffer gas has a relatively large TC ($\approx 2\text{pp}10^{10}/^\circ\text{C}$).

RF Power Coefficient: RFS rf power sensitivity is due primarily to inhomogeneity within the absorption cell.[9] The microwave field strength is not uniform within the cavity, and most of the signal comes from whatever region has the optimum rf level. The buffer gas confines a particular Rb atom to a small region of the cell. If some other frequency–determining variable, such as C–field, temperature, light intensity, or light spectrum, is also inhomogeneous, then a change in rf power that shifts the region of optimum signal will also cause a frequency change.

Barometric Coefficient: The primary RFS pressure sensitivity is due to volumetric change of the absorption cell envelope. This is caused by the pressure shift coefficient of the buffer gas,[10] and scales with the net buffer gas frequency offset. Typical buffer gas offsets range from a few 100 Hz to a few kHz. An RFS using a wall–coated cell with no buffer gas would have a lower barometric sensitivity.

Modulation Distortion: Modulation distortion is a primary cause of frequency offsets and instability in passive atomic frequency standards. Low frequency phase modulation (PM or FM) is applied to the physics package rf excitation to produce an ac discriminator signal. This error signal is synchronously detected and used to generate a control voltage to lock a crystal oscillator to the atomic resonance. Even–order modulation distortion shifts the center of gravity (CG) of the microwave excitation and causes a frequency offset; any change in this offset causes a frequency change.

This effect may be understood by considering the spectrum resulting from distortionless FM at f_{mod} and $2f_{mod}$. The 1st order upper and lower FM sidebands have opposite sense while the 2nd order sidebands have the same sense. Thus, with 2nd harmonic distortion, the lower 2nd order sidebands subtract and the upper 2nd order sidebands add, shifting the CG of the overall spectrum toward a higher frequency. This shifts the locked frequency in the opposite direction by an amount given by $\frac{\Delta f}{f} = \frac{\delta_2}{2Q_l}$, where δ_2 is the relative amount of 2nd harmonic distortion and Q_l is the Rb line Q.[4] For a −70 dB 2nd harmonic distortion level in an RFS with a 300 Hz line width, this produces a fractional frequency offset of $7\text{x}10^{-12}$. A 15% change in the amount of distortion, due to an environmental effect, would result in a frequency change of $1\text{x}10^{-12}$. Another way to visualize this is to consider the effect of even–order distortion on the shape of a fundamental sinusoidal modulation waveform. For worse–case phasing, one side of the waveform is flattened, causing a shift in the average frequency.

Modulation distortion can be introduced in several ways: Distortion on the modulation signal itself, distortion in the phase modulator, and distortion introduced by asymmetrical rf selectivity and AM–to–PM conversion in the multiplier chain. The modulation signal can be made very pure (free from even–order distortion) by generating it from a precise square–wave followed by passive filtration and/or integration. Low–distortion phase modulation is possible with a hyperabrupt tuning varactor in an all–pass network. The latter also suppresses AM, which helps avoid subsequent AM–to–PM conversion. The phase modulation should be done at a relatively low rf frequency where the required deviation is low. An active phase modulator, such as a phase–lock loop (PLL), can introduce distortion because of coherent ripple in the modulation transfer function, and a passive network is generally better.

Many subtle modulation distortion effects can occur in a rf multiplier chain. Each stage of a harmonic multiplier enhances the PM index and can suppress AM by limiting. AM–to–PM and PM–to–AM conversion can cause frequency sensitivity to rf stage tuning and level. PLL multipliers can have problems due to finite loop bandwidth and phase detector distortion. Step recovery diode (SRD) multipliers exhibit sensitivity to drive and bias conditions. The first stages in a multiplier chain are usually the most critical since that is where the AM and PM indices are closest and the spurious components are closest to the carrier. Interstage selectivity is critical in a harmonic multiplier chain; it is vital to avoid spectral asymmetry caused by complex mixing between subharmonic components. The output of each stage must be well–filtered before driving the next stage, and yet selective networks must be symmetrical and stable against temperature and drift. It is especially important to have a pure drive signal to the final SRD multiplier. A direct multiplier chain is preferable to one using mixing to avoid asymmetrical microwave spectral components. Modulation of the VCXO by 2nd harmonic ripple from the servo amplifier has the same effect as even–order modulation distortion, producing a frequency offset that is subject to change versus environmental conditions.

Amplitude Modulation: Amplitude modulation on the microwave excitation is another form of modulation distortion that can cause frequency offset and instability. AM at the fundamental servo modulation rate on the microwave excitation will produce a spurious fundamental component on the recovered signal that the servo will null by making a corresponding frequency offset.

The frequency offset caused by AM at the servo modulation frequency is given by $\frac{\Delta f}{f} = \frac{\alpha_1}{2Q_l}$, where α_1 is the relative amount of AM.[4] As for the 2nd harmonic PM distortion, a −70 dB AM level with a line Q of $23\text{x}10^6$ results in a frequency offset of $7\text{x}10^{-12}$.

Spurious RF Components: Spurious rf spectral components can pull the locked frequency by causing a shift in the CG of the microwave excitation. The amount of pulling depends on the relative spurious level, its asymmetry, and its separation from the carrier. The change in frequency due to a spurious component is given by $\frac{\Delta f}{f} = \frac{1}{2} \cdot \frac{\gamma H^2}{4\pi^2 f_o (f_o - f_2)}$, where γ is the ratio of Larmor frequency to magnetic field and H is the spurious microwave magnetic field at frequency f_2.[11, 12] Experiments have shown that an interfering signal equal to the normal microwave excitation at a separation of 5 MHz causes a frequency offset of $5\text{x}10^{-13}$. Those values may be scaled to predict the pulling at other relative amplitudes and separations. For example, a SSB component with a 25 kHz separation at a level of −98 dBc at 13.4 MHz would, after multiplication by 510 to the Rb resonant frequency, have a relative level of −44 dBc and would cause a frequency offset of $1\text{x}10^{-13}$. Such a pulling effect could be caused by slightly asymmetrical sidebands due to ripple from a switching power supply.

Subharmonics: Subharmonics are a particularly bothersome spectral component in the drive signal to the SRD multiplier. Subharmonic spectral components introduce time jitter between the impulses that generate the microwave energy, and can change the average rf power as the spectrum changes versus temperature or some other environmental condition. The period of the Rb microwave excitation is about 150 psec, so time jitter of the SRD multiplier drive waveform on the order of 10 psec can have a significant effect on its amplitude. The average of two waveforms differing in phase by 10/150 = 7% or 24° reduces the effective amplitude by $1-\cos(24^o)$ = 9%, or about −0.8 dB. Changes in rf power will give frequency shift on the order of $1\text{pp}10^{10}$/dB, which corresponds to a frequency change of $8\text{x}10^{-11}$ for the example above. For a typical multiplication factor of 80, this corresponds to a PM index, m, of $10 \cdot 2\pi/(150 \cdot 80) = 5\text{x}10^{-3}$ rad, or a subharmonic level of −52 dBc. Thus even a relatively "clean" SRD multiplier drive spectrum can introduce significant frequency offsets.

ENVIRONMENTAL FACTORS

Magnetic Field: The inherent RFS sensitivity to dc magnetic field is useful for initial frequency calibration and to correct for aging, but it also causes external magnetic sensitivity. Magnetic shielding is the primary means to reduce this sensitivity. It is also desirable to operate the unit at the lowest possible value of C–field. This requires a tight tolerance on absorption cell buffer gas fill pressure or the use of a frequency synthesizer for tuning.

At a C–field of 250 mG (a typical value that provides a total frequency adjustment range of about $5\text{x}10^{-9}$), the incremental C–field sensitivity is $\frac{\Delta f}{f} = 4.19\text{x}10^{-8}\Delta H$. For a magnetic sensitivity of $1\text{x}10^{-11}$/Gauss, this dictates a maximum internal field change of 240 μG and a shielding factor of about 4200. This can be realized with two nested magnetic shields.

The design of magnetic shields is outside the scope of this paper,[13] but it is worthwhile to mention some important considerations. The RFS magnetic sensitivity is greatest along the optical axis of the physics package (the direction of the internal C–field). Generally at least one shield is located directly around the physics package. The longitudinal shielding factor of nested shields depends critically on their end spacings. Rounded corners are desirable to avoid fringing. The shielding factor depends on the applied field strength since the permeability of the shielding material is nonlinear.

RFS magnetic sensitivity can be reduced by periodically switching the polarity of the C–field, thus obtaining 1st order cancellation of the external field.[14] While this may be effective under some circumstances, there is no entirely satisfactory way to perform the switching.

Internal residual magnetism, if stable and uniform, is not especially critical for Rb frequency standards. Residual magnetic fields from oven heaters can be an important consideration however. The latter can cause a "pseudo–TC" effect as the ambient temperature and heater power varies. The most significant factors contributing to RFS magnetic sensitivity are shown in Table 2.

TABLE 2 RFS MAGNETIC SENSITIVITIES

PHYSICS PACKAGE	CRYSTAL OSCILLATOR	ELECTRONICS
C–Field: Magnetic Sensitivity Residual Oven Heater Field	None	Temperature Controllers: Oven Heater Current

Pressure: The volumetric change in the absorption cell that causes barometric pressure sensitivity is due mostly to "oil–can" deflection of the end windows. This deflection scales with the 4th power of the cell diameter and inversely with the cube of the window thickness. Cell window thickness is limited by glassworking and dielectric loading considerations, and the typical barometric sensitivity is about $1\text{x}10^{-10}$/atm. This sensitivity can be a very significant contributor to RFS frequency instability in an otherwise benign environment. Atmospheric barometric fluctuations of 5% cause $5\text{x}10^{-12}$ frequency fluctuations that limit the RFS noise floor. The absence of this form of environmental disturbance is an important factor in the excellent stability of GPS Rb clocks.[15] The barometric sensitivity can also be important for aircraft applications, and may dictate the use of a hermetically sealed unit.[16]

Another RFS pressure sensitivity mechanism is change in convective and conductive heat transfer. The latter does not change significantly until the barometric pressure is reduced to below about 1 Torr. All devices with non–negligible power dissipation must be conductively heat sunk. Within the physics package, thermal gradients change, oven power drops, and the stabilization factor improves in vacuum. An RFS does not use high voltages and can be safely operated throughout the full pressure range from sea level to hard vacuum without any corona discharge hazard. The most significant factors contributing to RFS pressure sensitivity are shown in Table 3.

TABLE 3 RFS PRESSURE SENSITIVITIES

PHYSICS PACKAGE	CRYSTAL OSCILLATOR	ELECTRONICS
Absorption Cell: Envelope Deflection		
Lamp & Cell Ovens: Thermal Effects	Crystal & Other Devices: Thermal Effects	Electronic Devices: Thermal Effects

Temperature: Temperature sensitivity is often the most significant environmental sensitivity of a rubidium frequency standard. A stability of $3\text{x}10^{-10}$ is typical for a small tactical RFS over a military temperature range, whereas the unit will not have that much frequency aging over several years. Furthermore, there is considerable unit–to–unit variation of this important parameter, which is not necessarily monotonic and which may have regions of high incremental sensitivity. Many physical mechanisms can contribute to RFS temperature sensitivity, and large unit–to–unit variations are often observed since the performance of a particular unit may be the algebraic sum of several factors. The most significant factors contributing to RFS temperature sensitivity are shown in Table 4.

These TC mechanisms are categorized as involving either the Rb physics package, the crystal oscillator, or the electronics. In most cases, it is physics package sensitivity that causes an electronic sensitivity. Each of the physics package elements (lamp, filter cell, and absorption cell or combined filter/absorption cell) has an intrinsic TC, but the overall Rb physics package can be designed so that it has low temperature sensitivity. Consider, for example, a classic design using a Rb^{87} lamp, a discrete Rb^{85} filter cell, and a Rb^{87} absorption cell. A change in lamp temperature causes a change in light intensity, which, due to the light shift effect, can cause a frequency change. This sensitivity can be nulled by proper filter cell length and operating temperature. But, at this ZLS condition, the filter cell will have a relatively large negative TC ($\approx -1\text{x}10^{-10}/^{\circ}\text{C}$). The absorption cell TC, however, can be changed from a significant positive to a significant negative TC by adjusting its buffer gas mix.

TABLE 4 RFS TEMPERATURE SENSITIVITIES

PHYSICS PACKAGE	CRYSTAL OSCILLATOR	ELECTRONICS
LAMP TC: Light Intensity/Spectrum Rb Vapor Pressure		LAMP OVEN TEMP CONTROLLER: Thermal Gain Temperature Setpoint
FILTER CELL TC: Light Shift Hyperfine Filtration		FILTER TEMP CONTROLLER: Thermal Gain Temperature Setpoint
ABSORPTION CELL TC: Buffer Gas TC		CAVITY TEMP CONTROLLER: Thermal Gain Temperature Setpoint
LAMP EXCITATION SENSITIVITY: See Lamp TC		LAMP EXCITER TC: RF Power Oscillator/Regulator
CAVITY RF POWER COEFF: Spatial Inhomogeneity		RF CHAIN: RF Power/ALC
C–FIELD SENSITIVITY: Magnetic Bias		C–FIELD SOURCE: Volt Ref/Current Source
RF SPECTRUM: CG Change		RF CHAIN: Mod Distortion, Spurious
CAVITY PULLING: Line Q/Cavity Q Ratio		CAVITY TEMP CONTROLLER: Thermal Gain, Setpoint
	CRYSTAL OSC TC: Static & Dynamic Tracking Error	SERVO AMPLIFIER: Static & Dynamic Servo Gain

Suppose, then, that the filter and absorption cells share the same thermal environment (oven). Then the absorption cell TC can be made to cancel that of the filter cell giving an overall net zero TC. In fact the situation is particularly favorable because, on a unit–to–unit basis, the lamp oven TC can easily be nulled by adjusting the cell oven temperature to the ZLS condition while the cell oven TC can simultaneously be nulled by adjusting the lamp oven temperature. (The latter is possible because the magnitude of the negative filter cell TC varies with the light intensity while the positive TC of the absorption cell is constant.) The residual TC of each oven can easily be held to $\pm\ 2\text{x}10^{-11}/^{\circ}\text{C}$. This approach, along with ovens having a modest stabilization factor (200), can thus reduce the overall physics package TC to $\pm\ 4\text{x}10^{-13}/^{\circ}\text{C}$, or about 10% of the temperature error budget for a small tactical RFS.

Another significant physics package consideration is rf power shift. Any resonance line spatial inhomogeneity or asymmetry will make the locked frequency vary with rf power. Spatial inhomogeneity gives a different frequency versus rf power as the position of maximum signal moves within the microwave cavity. Use of a discrete filter cell is critical here to avoid spatial inhomogeneity due to nonuniform light shift within the resonance cell. Other factors are C–field uniformity (use a Helmholtz coil configuration), a clean, symmetrical rf spectrum (avoid synthesis and mixing), and employment of a high thermal conductivity oven to avoid temperature gradients along the absorption cell. Still another physics package TC factor is residual magnetic field from the oven heaters (see above).

However, the most significant TC mechanisms are likely to be electronic. Items of particular concern are C–field stability, RF power stability, modulation distortion, and servo offsets. Temperature sensitivity due to the C–field current source is dependent on the C–field setting. At 250 mG, the fractional

C-field sensitivity is about $1\text{x}10^{-10}/\%$. For a tactical RFS with a $3\text{x}10^{-10}$ stability requirement over a $-55°\text{C}$ to $+75°\text{C}$ temperature range the C-field current must be stable to about 100 ppm/°C. C-field temperature compensation can cause disparate frequency-temperature characteristics at different frequency adjustments.

A typical RFS rf power coefficient is about $1\text{pp}10^{10}/\text{dB}$. This imposes a stringent requirement on the stability of the rf power that excites the Rb physics package.

Cavity pulling is usually a negligible contributor to RFS temperature sensitivity. Vanier and Audoin[4] derive a cavity pulling factor $P = \frac{Q_c}{Q_l} \cdot \frac{\alpha}{1+S} \approx 10^{-7}$, where Q_c is the cavity loaded Q ($\approx$ 200), Q_l is the Rb line Q ($\approx 10^7$, α is the maser gain parameter ($\approx 10^{-2}$), and S is the rf saturation factor ($\approx$ 2 for optimum discriminator slope). It should be noted that P is not equal to $\frac{Q_c}{Q_l}^2$ as is often assumed for a passive atomic frequency standard because the maser gain parameter, although small, is not negligible. A cavity TC of 200 kHz/°C and an oven stabilization factor of 300 yields an RFS TC of about $1\text{x}10^{-14}/°\text{C}$.

Another minor cavity-related temperature sensitivity is caused by rf power variations due to cavity detuning. An rf power shift coefficient of $5\text{x}10^{-11}/\text{dB}$ with the same cavity mistuned at the -3 dB point would cause an RFS TC of about $2\text{x}10^{-14}/°\text{C}$.

Servo offset can be a significant contributor to RFS TC. A typical value for the discriminator slope at the input of the servo integrator is $1\ \text{mV}/\text{pp}10^{11}$. Servo offset can be introduced by integrator dc offset or by pickup of synchronous detector reference drive. A 10% change in a 1 mV servo offset would cause a $1\text{x}10^{-11}$ frequency change.

Exposure to rapid temperature change can impose significant stress on an RFS. A particularly severe case is warmup after a cold soak. Nevertheless, a well-designed RFS can withstand thousands of such cycles with little effect on long-term stability.[17] Rapid change in ambient temperature can also produce pseudo frequency offset due to rate-of-change-of-phase in selective circuits such as crystal filters, or VCXO tracking error due to finite servo gain.

Shock: The most significant factors contributing to RFS shock sensitivity are shown in Table 5. Exposure of an RFS to mechanical shock can cause timing error and permanent frequency offset. Movement of optical elements can cause light shifts, movement of rf elements can cause rf power shifts, and movement of thermal elements can cause TC shifts.

TABLE 5 RFS SHOCK SENSITIVITIES

PHYSICS PACKAGE	CRYSTAL OSCILLATOR	ELECTRONICS
LAMP ASSEMBLY: Lamp Movement		LAMP EXCITER: Component/Wiring Disturbance
OPTICAL PATH: Movement of Optical Element	CRYSTAL: Frequency Change or Damage	SERVO AMPLIFIER: Finite Static & Dynamic Gain
SRD MULTIPLIER: Microwave Power		RF CHAIN: Component/Wiring Disturbance
LAMP & CELL OVENS: Thermistor Stress		TEMP CONTROLLERS: Temperature Setpoint

Acceleration: The most significant factors contributing to RFS acceleration sensitivity are shown in Table 6. An RFS does not have an inherent static acceleration sensitivity. It may, however, show frequency change due to static acceleration or orientation because of thermal effects. Frequency change is also possible due to redistribution of molten rubidium in the lamp under high static g forces.

Dynamic acceleration can have a profound effect on the stability and purity of an RFS, as discussed in the Vibration section below. The most significant factors contributing to RFS acceleration sensitivity are shown in Table 6.

TABLE 6 RFS ACCELERATION SENSITIVITIES

PHYSICS PACKAGE	CRYSTAL OSCILLATOR	ELECTRONICS
	CRYSTAL: G–Sensitivity	SERVO AMPLIFIER: Finite Static Servo Gain
RB LAMP/LIGHT PATH: Rb Movement (Light Shift) Movement of Optical Element		SERVO AMPLIFIER: Servo Offset (Δ Gain)
SRD MULTIPLIER: Microwave Power		RF CHAIN: RF Power

Vibration: The most significant factors contributing to RFS vibration sensitivity are shown in Table 7. The stability and purity of an RFS are affected by mechanical vibration primarily because of the acceleration sensitivity of the quartz crystal used in the VCXO. Direct vibrational modulation of the crystal oscillator at vibration frequencies higher than the servo bandwidth affects the RFS phase noise and spectral purity without producing a frequency offset. Spurious components are produced at $\pm f_{vib}$ at a dBc level of $\pounds(f_{vib}) = 20\log_{10}\left[\frac{\gamma\, f_o\, G}{2\, f_{vib}}\right]$, where γ is the crystal acceleration coefficient, f_o is the carrier frequency, and G is the peak acceleration. The Allan deviation frequency stability is degraded to $\sigma_y(\tau) = \gamma\, G\left[\frac{\sin^2(\pi\, f_{vib}\, \tau)}{\pi\, f_{vib}\, \tau}\right]$, where τ is the averaging time. Vibrational modulation of the VCXO at the 2nd harmonic of the servo modulation rate, however, can cause a large frequency offset. Low frequency vibrational modulation of the crystal oscillator can cause a frequency offset due to loss of microwave power. These XO effects are reduced by a high modulation rate, a wide servo bandwidth, and a low crystal g–sensitivity.

RFS stability can also be affected by vibrational modulation of the physics package light beam at or near the servo modulation rate. This problem is reduced by rigid physics package construction. Circuit board and wiring microphonics can also affect RFS stability. The most significant factors contributing to RFS vibration sensitivity are shown in Table 7.

TABLE 7 RFS VIBRATION SENSITIVITIES

PHYSICS PACKAGE	CRYSTAL OSCILLATOR	ELECTRONICS
	CRYSTAL: G–Sensitivity ($2f_{mod}$)	SERVO AMPLIFIER: Interference
SRD MULTIPLIER: Microphonics, AM	OSCILLATOR CIRCUIT: Microphonics ($2f_{mod}$)	RF CHAIN: Microphonics, Carrier Power
RB LAMP: Rb Movement (Light Shift)		SERVO AMPLIFIER: Servo Offset (Δ Gain)
OPTICAL PATH: Lightbeam Motion (f_{mod})		SERVO AMPLIFIER: Interference

Radiation: The radiation sensitivity of an RFS is essentially that of its electronic circuits since the Rb physics package is inherently quite hard.[18] Survivability can be a critical requirement for both transient and total dose radiation environments. RFS radiation hardening is a specialized area that requires specific design techniques, careful analysis, and expert advice.[19]

Under transient radiation, an RFS may be required to "operate through" or to quickly recover frequency accuracy; in all cases it must not suffer latchup, burnout, or other permanent degradation.

Passive "flywheeling" using a high–Q passive circuit is one technique to maintain a continuous output under transient radiation. The most critical parts for latchup are usually CMOS devices; all circuits may require resistors or other means for current limiting.

Total dose radiation hardening requires careful analysis (based on piece part test data). The most critical devices are usually servo amplifier and temperature controller op amps and the C–field voltage reference. The most critical part for neutron fluence is usually the silicon photodetector, which loses output due to lattice damage. The most significant factors contributing to RFS radiation sensitivity are shown in Table 8.

TABLE 8 RFS RADIATION SENSITIVITIES

PHYSICS PACKAGE	CRYSTAL OSCILLATOR	ELECTRONICS
C–FIELD: Magnetic Sensitivity		C–FIELD SOURCE: Volt Ref, Current Source
PHOTODETECTOR: Detectivity Loss	CRYSTAL: Frequency Change	SERVO AMPLIFIER: Servo Offset (Δ Gain) Transient Recovery, Static Error

Electromagnetic Interference: The most significant RFS EMI susceptibility is usually power supply ripple and transients. Ripple susceptibility is generally worst at the RFS servo modulation rate; large frequency offsets are possible due to interference with the servo. RFS radiated susceptibility depends critically on the shielding and filtering of the RFS package and leads. The requirements for reverse and overvoltage transient protection vary depending on the characteristics of the external power supply. RFS turn–on (in–rush current) and turn–off (voltage spike) transients can be a problem for the host system. The most significant factors contributing to RFS EMI sensitivity are shown in Table 9.

TABLE 9 RFS EMI SENSITIVITIES

PHYSICS PACKAGE	CRYSTAL OSCILLATOR	ELECTRONICS
NONE	OSCILLATOR: Spurious Components	LAMP EXCITER: Light Modulation (f_{mod})
		SERVO AMPLIFIER: Interference (f_{mod})
		POWER SUPPLY: Ripple Attenuation

Humidity: RFS moisture sensitivity is most often associated with high impedance servo amplifier synchronous detector/integrator circuits. For an unsealed unit, performance under humidity or salt fog depends on the adequacy of the conformal coating and encapsulating processes used. The capability to withstand immersion is seldom a requirement for an RFS, and requires a sealed case and connectors. The most significant factors contributing to RFS humidity sensitivity are shown in Table 10.

TABLE 10 RFS HUMIDITY SENSITIVITIES

PHYSICS PACKAGE	CRYSTAL OSCILLATOR	ELECTRONICS
NONE	NONE	SERVO AMPLIFIER: Detector/Integrator Leakage
		TEMPERATURE CONTROLLERS: Temperature Setpoint

Supply Voltage: RFS sensitivity to supply voltage can occur due to a large number of factors. The dc input is often used directly as the supply voltage for the oven heaters, and changes associated with the RFS temperature controllers (dc offsets, thermistor self-heating, heater magnetic field, etc.) can cause supply voltage sensitivity. Significant electronic supply sensitivity is also possible in the lamp exciter and rf circuits. An important distinction is between actual voltage sensitivity and thermal effects due to a change in supply voltage. The most significant factors contributing to RFS voltage sensitivity are shown in Table 11.

TABLE 11 RFS VOLTAGE SENSITIVITIES

PHYSICS PACKAGE	CRYSTAL OSCILLATOR	ELECTRONICS
C–FIELD: Residual Oven Heater Field	NONE	TEMP CONTROLLERS: Heater Current Thermistor Self–Heating
		LAMP EXCITER: Lamp Excitation Power
		RF CHAIN: RF Power/ALC
		MOD GENERATOR: Modulation Deviation

Storage: Exposure to wide temperature extremes during storage is generally not a problem for a well–designed RFS. Besides the obvious material considerations, Rb redistribution within the lamp and cells during prolonged hot storage can be a factor for subsequent lamp starting and frequency restabilization. This may worsen lamp starting, lower cavity Q, obstruct the light path, and generally cause a longer restabilization time. Storage within normal operating temperatures does not have any significant effect on subsequent RFS performance. Test data indicates that an RFS "freezes out" during storage, and, when turned on again, quickly assumes the previous frequency and aging. Electronic failure rates are lower during storage, since electrical and thermal stresses are removed, but chemical processes still continue (at a lower rate).

Retrace: A well–designed RFS has an excellent frequency retrace characteristic ($\mathrm{pp}10^{11}$) that is non–accumulative with little dependency on temperature, off time, or restabilization time.[17] Frequency retrace is, by definition, measured by returning the unit to exactly the same operating conditions to exclude other environmental sensitivities.

Relativity: Relativistic effects due to velocity and gravitational potential are ordinarily negligible for Rb clocks except for those in a spacecraft environment.[20] Time dilation causes the frequency of a moving clock to appear to run more slowly by an amount $\frac{\Delta f}{f} \approx -\frac{v^2}{2c^2}$, where v is the clock velocity and c is the velocity of light. For a GPS satellite in a 12–hour circular orbit, the fractional frequency change is $-8.35\mathrm{x}10^{-11}$. Gravitational redshift causes a clock to run more slowly in a stronger gravitational field by an amount $\frac{\Delta f}{f} = \frac{\mu}{c^2}\left(\frac{1}{R} - \frac{1}{r}\right)$, where μ is the Earth's gravitational constant, R is the Earth's radius, and r is the orbital radius. It is about $1\mathrm{pp}10^{16}$/meter at the Earth's surface. For a GPS satellite, the gravitational redshift is $5.28\mathrm{x}10^{-10}$ and the net relativistic frequency change is $+4.45\mathrm{x}10^{-10}$.

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