Selection Criteria for Rubidium Frequency Standards

W.J. Riley
Hamilton Technical Services
Beaufort, SC 29907 USA
bill@wriley.com

• Abstract

This paper covers the criteria for selecting a rubidium frequency standard (RFS) or closely-related CPT and CSAC gas cell atomic clock devices that use either Rb or Cs as their working element. There are several classes of RFS designed for commercial, military and space applications, each with corresponding performance features and limitations, and the specifications for an RFS mainly cover the latter. The primary function of any RFS is to supply a stable frequency regardless of its operating conditions, which include a number of common and application-specific considerations. The paper provides a comprehensive list of those items and describes how they relate to a particular RFS usage. It includes examples of specifications for current commercial, military, and space RFS products from several leading manufacturers.

• Introduction

The primary purpose of a rubidium atomic frequency standard (RFS, RAFS or AFS) is to always produce the same frequency. While its product description may emphasize its special features, the specifications of a typical RFS are mainly a list of its limitations because there are many mechanisms that can cause it to depart somewhat from the objective of producing a perfectly invariant frequency. And, like any real active electronic device, it has finite size and weight, consumes power, costs money, and will eventually stop working.

An RFS design can offer distinctive features such as an adjustable output frequency, multiple outputs, GPS syntonization, etc., but their specifications are nevertheless dominated by factors that limit their frequency stability. Those factors, associated mainly with internal noise, environmental sensitivities, and temporal variations, along with practical considerations regarding their manufacture, are the subject of this paper[1].

While there are many references that describe the physics and design of rubidium frequency standards and related devices (see Reference [1], there are relatively few papers and little technical literature that describe their selection criteria (see References [2], [3], [12] and [13]).

• Frequency Standards, Oscillators, and Clocks

In most contexts, little distinction is paid between the terms frequency standard, oscillator and clock. Rubidium frequency standard is the generally-preferred term; rubidium oscillator is widely used but strictly-speaking incorrect because an RFS is a form of passive atomic frequency standard, not an active oscillator. The word clock implies that the RFS is used, along with counting hardware, to keep time, but again, it is widely used as a shorter term.

RFS units employed as frequency references emphasize absolute frequency calibration, and may include a means such as GPS disciplining. RFS units intended only as a clock source may have relaxed requirements on the phase noise and purity. RFS units used as RF sources often have more demanding requirements for their

---
[1] We use “RFS” herein to include CPT and CSAC atomic frequency standard devices that utilize either Cs or Rb gas cells.

phase noise and spectral purity, which is mainly a function of their internal crystal oscillators.

RFS units intended for dynamic environments that include vibration and rapid temperature change can benefit from a low g sensitivity crystal oscillator and a fast frequency lock servo.

• Types of Rubidium Frequency Standards

Most atomic clocks utilize the ground state hyperfine resonance of an alkali element, either rubidium or cesium, as their frequency reference. The classic RFS uses an Rb lamp for intensity optical pumping of either an Rb-87 absorption cell in a microwave cavity along with a discrete Rb-85 isotopic filter cell, or an integrated resonance cell containing both Rb isotopes. More recently, a somewhat different arrangement employing coherent population trapping (CPT) has become an attractive alternative because it uses a modulated semiconductor laser diode to avoid the need for the filter cell and microwave cavity. CPT is also the basis of chip-scale atomic clocks (CSAC). The CPT devices can use either Cs or Rb as their working element.

As a general statement, one can associate the conventional RFS with a broad range of size, performance and cost, including the highest-stability GPS satellite clocks (see Appendix A), while CPT devices have medium-level performance in small, lower-cost products, and CSAC devices offer much smaller and lower power but somewhat lower performance.

This paper, while emphasizing the classic RFS, also applies to newer CPT and CSAC devices. In fact, most of this material also applies to other atomic clock technologies such as trapped Hg ion devices such as the deep space atomic clock (DSAC).

Distinctions can also be made between RFS units tailored for either commercial, military or space applications. While no sharp lines can be drawn between these classes, commercial units emphasize cost, MIL units emphasize ruggedness, and space units emphasize performance and reliability.

RFS products can also be divided into standard and custom designs, where the latter are associated with a particular set of requirements for a specific application.

Another distinction can be made between modular and more complete RFS products, where the latter are complete instruments with such features as enclosures, mains power, metering and monitoring, frequency adjustment, multiple outputs and frequencies, frequency synthesis, low phase noise, clock circuitry, GPS disciplining, etc.

In all cases, the quality of the crystal oscillator and the bandwidth of the servo that locks it to the atomic reference have an important impact on the RFS performance, particularly with regard to its phase noise.

• Stability Terminology

Let us first clarify some of the terminology used to describe frequency stability (or perhaps more correctly, its instability).

Fractional Frequency Deviation

Ignoring adjustability, an RFS will have a certain nominal output frequency, f_0, and an actual output frequency, f, as measured with adequate precision against a suitable absolute standard via a traceable process. The output frequency is generally denoted by its *fractional frequency deviation*, $\Delta f/f_0 = (f - f_0) / f_0$. For example, for f_0 = 10 MHz, if the actual frequency is f = 10.000001 MHz, the frequency deviation is Δf = 1 μHz, and the fractional frequency offset is 1 ppm, denoted as $1\text{x}10^{-6}$, $1\text{pp}10^{6}$, or 1e-6, which are dimensionless quantities (not Hz) and generally written simply as $\Delta f/f$ and denoted as a function of time by the symbol y(t). This terminology is used for most stability specifications, e.g., a temperature coefficient of $1\text{x}10^{-12}/°\text{C}$. Values like that are used to quantify most RFS stability parameters and environmental sensitivities. Note that the corresponding phase value as a function of time is denoted as x(t) and has units of seconds.

Phase and Frequency Noise

Frequency is the rate of change of phase, and that relationship describes the connection between phase and frequency noise. Phase noise is usually expressed in the frequency domain as a spectral density while frequency noise is expressed in the time domain as a statistical quantity. The most common measure of phase noise is the logarithmic form of the power spectral density (PSD) of the phase fluctuations, the SSB phase noise, £(f), in units of dBc/Hz. It is generally expressed as a plot versus log sideband frequency in Hz.[2] See Reference [7] for more information about these quantities and how they appear in RFS specifications.

Stability Statistics

RFS frequency stability is actually a stochastic (noise) process, and the size of the frequency fluctuations vary as a function of their observation or averaging time as characterized by certain statistics such as the *Allan deviation*[3], ADEV, $\sigma_y(\tau)$, which is usually shown on a log-log plot versus averaging time, τ. The slope of an ADEV plot indicates the type of power law noise; it generally improves with longer averaging time until reaching a minimum (the "flicker floor") after which it increases because of drift and environmental sensitivity. Examples of RFS ADEV plots are show in the Appendices. The ADEV is usually calculated after removal of frequency drift (which is expressed separately). Information about the statistics used for frequency stability analysis will be found in Reference [7].

Initial Accuracy and Temporal Stability

RFS frequency is set to within an initial accuracy specification at the factory before shipment. But the RFS frequency is also a temporal process because it changes over time, an effect called aging when due to internal mechanisms and drift as observed from all causes.

Frequency Measurements

Frequency measurements are always made with respect to some reference source. Frequency accuracy is the degree to which it equals its nominal value, while precision denotes the degree to which the measurements consistently resolve the frequency variations. The measurement system determines that resolution and its scatter is determined by the combined noise of the source, reference and system. Thus it is vital that any such frequency measurements made to verify RFS performance are supported by an appropriate system and reference, and that the RFS under test have proper operating conditions (e.g., thermovac for space clocks). Phase measurements are preferable. Reference [7] shows some commonly-used measuring systems for precision frequency sources. An investment in a suitable clock measuring system mat not be feasible for an RFS user, who will then have to depend on data provided by the clock vendor.

• Time

Although an RFS is often called a clock and is used for timekeeping, it has no intrinsic sense of time, nor does it necessarily have clock hardware. Some RFS units do, however, include settable counting circuits, 1 pps outputs, and other clock features, and their specifications should describe these in detail. After initial synchronization to a specified accuracy, the subsequent time error is a function of the unit's frequency offset and stability, and the elapsed time.

[2] Do not be unduly alarmed if the phase noise plot shows discrete components related to the power mains frequency since those are most often due to the measuring system.

[3] The *Hadamard deviation*, HDEV, is also used to characterize RFS stability because it ignores linear frequency drift. The *Time deviation*, *TDEV,* is another statistic that estimates the time error of the clock caused by its noise.

• Frequency Offset

RFS frequency offset is generally stated as the fractional frequency difference between it and a suitable reference (e.g., a primary frequency standard such as a cesium beam tube device or a GPS-disciplined source). The RFS will normally have some means for performing a frequency calibration (i.e., syntonization) by a mechanical, electrical or digital adjustment. That adjustment will not materially affect its subsequent stability, and may need to be repeated occasionally to compensate for subsequent RFS drift. Any residual frequency offset not only affects the RFS accuracy but integrates to a time error when the unit is used as a clock:

$$\Delta T = \Delta f/f \cdot t$$

For example, a frequency offset of 1×10^{-11} would cause a time error of 0.864 µs over 1 day (86,400 s).

A change in environmental conditions (e.g., temperature) is likely to change the frequency offset, and set a practical limit on syntonization effectiveness.

• Frequency Aging

The frequency of an RFS is not perfectly constant, even ignoring environmental and other external effects, but rather displays frequency change due to internal mechanisms associated with both its Rb physics package and (to a lesser extent) its electronics.

Linear frequency aging causes an initially perfectly syntonized rubidium clock to experience a time error that integrates quadratically as a function of time:

$$\Delta T = \tfrac{1}{2} \cdot [(\Delta f/f)/\Delta t] \cdot t^2$$

For example, if the RFS frequency changes linearly by 1×10^{-12}/day (1.157×10^{-17}/s), that causes a time error of 43.2 ns over 1 day. In the long run this term will dominate the clock error. For example, after 1 month (30 days) the quadratic term becomes 38.88 µs, greater than the 25.92 µs caused by the above frequency offset.

RFS aging is generally specified on a per day basis after a certain period of undisturbed operation, with equivalently lower values expected per month, per year and "forever" because the aging of an RFS typically diminishes as it matures. For a very well-behaved unit with one dominant aging mechanism, it is possible to successfully model its aging by log or diffusion law fits. In general, however, such modeling is problematic. A strategy for dealing with aging is an important consideration in any RFS application, and may require system-level means or periodic recalibration.

• Frequency Drift

RFS frequency drift is the combination of both internal and external effects that cause it to change over time. In a well-controlled environment, aging and drift are equivalent. In fact, the term "frequency drift" is commonly used to denote either.

• Frequency Adjustment

The RFS frequency can be adjusted over a range of a few pp10^9 by means of the internal physics package DC magnetic bias field ("C-field"), or, in many modern designs, by setting an internal synthesizer. The C-field adjustment can be via an RFS control potentiometer and/or an external tuning voltage. The latter can be used in an analog control loop to discipline the RFS frequency with respect to an external reference (e.g., GPS). That can also be accomplished to within a specified resolution via the RFS synthesizer and a digital control interface. In cases where the host system has means for making frequency adjustments (e.g., some GPS satellite payloads), it is desirable to operate the RFS without tuning at a fixed minimum C-field for best stability[4].

[4] Low C-field reduces RFS sensitivity to both internal and external effects but limits its tuning range.

The RFS specifications should include information about the analog (C-field) tuning adjustment, if any (range, sensitivity, etc.) and/or digital tuning interface (protocol, resolution, etc.).

• Environmental Sensitivity

There are quite a few environmental sensitivities that apply to an RFS (e.g., temperature, barometric pressure, etc.) and these are discussed separately below. Information about their physical basis will be found in Reference [6]. Each application determines those factors that are important, and an RFS for a military vehicle can require a very different design than for a laboratory standard. For example, in a benign lab, barometric sensitivity can be a dominate consideration where is doesn't matter for a space clock in vacuum. Fortunately there is little interaction between most RFS environmental specifications, and most are quite consistent for a given design. That being said, temperature sensitivity is often the largest consideration and exhibits significant unit-to-unit variation, probably because it can have multiple contributors of varying sign and magnitude.

RFS environmental sensitivity is often defined in relation to MIL-spec conditions (e.g., those of MIL-STD-202 and MIL-STD-810). See Reference [5] for more details. It is also covered by IEEE Standard 1193, *IEEE Guide for Measurement of Environmental Sensitivities of Standard Frequency Generators* [10]. Similar information for crystal oscillators can be found in MIL-PRF-55310, "Oscillator, crystal controlled, general specification for" [11].

It is the responsibility of the RFS vendor to choose a set of environmental specifications appropriate to the intended product target, or to obtain them from their customer, and to then verify and document compliance with those requirements. It is the responsibility of the RFS user to verify that the vendor-supplied set of environmental specification is appropriate to their application, or to supply them to the RFS vendor, and to confirm satisfactory compliance with them.

Most commercial RFS applications are satisfied by the vendor's catalog environmental specifications, but special cases may need to be negotiated. Military RFS applications often impose a wider range of environmental conditions and/or platform-specific requirements. Space RFS applications almost always have program-specific needs (e.g., launch vibration, radiation) for which the RFS design may need tailoring.

• Noise

All frequency sources have finite signal-to-noise (S/N) ratios and noise-induced phase and frequency fluctuations that are a fundamental limitation to their stability. This is commonly referred to as short-term stability (STS), although its effects can extend out to days. STS is a time-domain measure that is closely related to phase noise in the frequency domain. These noise mechanisms are stochastic processes that are specified with statistical quantities such as the Allan deviation (ADEV). See Reference [7] for more information about frequency stability, phase noise, power-law noise processes and frequency stability analysis

• Crystal Oscillator

All[5] RFS have an internal crystal oscillator to generate their active output that is locked to the Rb atomic resonance by a frequency lock servo, The crystal oscillator generally operates at the RFS output frequency, and it largely determines its phase noise and sub-second short term stability. It also influences RFS behavior under vibration. It is therefore important to understand the characteristics of the RFS crystal oscillator and its influence on the overall unit [9]. For example, the phase noise of the crystal oscillator not only affects the RFS output purity, but it is also an important factor in the quality of the physics package microwave excitation.

The crystal oscillator may be ovenized or temperature compensated, or may simply operate at

[5] I don't know of any exceptions for an RFS product. An RbXO has an external crystal oscillator.

the temperature set by a baseplate temperature controller (BTC, see below).

The RbXO [8] is a form of RFS where the Rb reference operates intermittently to syntonize the crystal oscillator (which has a tuning non-volatile memory), thereby saving energy.

Some low phase noise ("LN") RFS designs have a separate phase-locked (usually ovenized) crystal oscillator that provides the output. Clean-up OCXO products are also available for that purpose.

While the design details related to the crystal oscillator are the responsibility of the RFS vendor, the user must determine his system requirements for phase noise and spectral purity, remembering that subsequent frequency multiplication raises the noise and spurious levels and that vibration can have a profound effect on the signal purity (see Vibration).

• Choice of Output Frequency

Most precision frequency references are distributed at 10 MHz which has proven to be a good general choice and has become the de-facto standard. Use of a non-standard frequency is normally limited to specialized use such as GPS satellite clocks and high-volume embedded applications. For example, some GPS satellite clocks have used the 10.23 MHz pseudo-random code rate, and others have used a 13.40134393 MHz "natural frequency" that minimizes RFS complexity. Binary (e.g., 2.048 MHz) and telecom (e.g., 1.544 MHz) rates are non uncommon. VHF outputs (e.g., 100 MHz) are used occasionally for low phase noise or direct digital synthesizer (DDS) clocking applications. DDS in either the RFS or the host system provides great flexibility. Be aware that special output frequencies can also complicate RFS testing.

An RFS with a 1 PPS pulse output is fairly common, and can be needed for driving clock circuitry and enabling GPS time and frequency receiver disciplining.

• Output Waveform and Power

Most RFS units have a sinusoidal RF output signal, most commonly at 10 MHz, with a power level of the order of +7 dBm (5 mW, 0.5 V rms) into a 50 ohm load. This is adequate to drive most host equipment without compromising stability. Multiple outputs are sometimes provided, and higher output power can be an advantage if it is to be passively split for multiple loads. In the case of multiple RF outputs, inter-channel isolation may be important and should be specified. Most RFS RF outputs have no DC component, can be either AC or DC coupled, and may be isolated from the RFS case. An isolated RF output can help to avoid ground loop interference. It can be important to know all these (and other, see below) details.

Some RFS units have a digital output waveform such as a 5V p-p "TTL" squarewave or differential LVDS. In that case, the waveform should be fully-specified as to level, waveshape, duty cycle, rise and fall times, etc. Such outputs are generally intended for embedded applications where the RFS is connected directly to host system logic. Sinusoidal RF output is preferred for most frequency reference distribution.

• Harmonics

The harmonic content of an RFS RF output is generally specified as below -30 dBc or so, low enough to avoid gross waveform distortion. That can be particularly important when driving a zero-crossing detector since an amplitude change can cause a phase change. Better purity is seldom required but can be obtain with external low-pass filtration if necessary.

• Spurious/Non-Harmonics

Non-harmonic spurious components are present on the RF output of most RFS units and must be specified. A level of at least -80 dBc is typical. These unwanted components can occur either at baseband or as sidebands on the desired RF component or its harmonics. Examples of the former include spurious components from switching power supplies and RF components from the Rb lamp exciter. Examples of the latter include RF output sidebands separated from the carrier by switching power supply and/or oven controller rates and at the frequency lock servo modulation rate. Those spurious components are at well-defined frequencies; it is also possible that there are spurious components at unexpected frequencies (e.g., UHF parasitics).

• RF Output Impedance

While most RFS RF outputs are specified for a 50 ohm load, the RF output source impedance may or not be controlled or specified. It can be important that the VSWR of the RFS RF output be reasonably low (say < 1.5:1) to avoid reflections from a mismatched load, especially in a situation where it results in low or variable amplitude at the load. An RFS RF output impedance specification usually applies only at the carrier frequency.

• Phase versus Temperature

Be aware that any lowpass or bandpass filter (LPF or BPF) at the RFS RF output introduces phase shift whose temperature coefficient results in a pseudo frequency shift when exposed to temperature slew. This is especially important with a narrowband BPF such as a crystal filter. Long coaxial cable lines can also show this effect.

• Humidity/Salt Fog/Immersion

Humidity, especially that resulting in condensation, can affect certain RFS circuits. Exposure to salt fog and other ionic contamination can result in severe corrosion. It can be an advantage, or even essential, that RFS circuit boards are conformally coated and/or the RFS case be sealed against such exposure. A sealed unit may require a means for pressure relief and/or a strong, heavy case. It is rare that an RFS is specified for actual immersion.

• Temperature

The temperature environment is an important consideration for any RFS, both during operation and under storage. An RFS will have specifications for its operational and storage temperature limits. During operation, temperature sensitivity is likely to be the most significant factor affecting its frequency stability.

The upper operating temperature of an RFS is usually determined by the point where the physics package oven with the lowest set-point loses control since performance will deteriorate above that condition. Newer RFS designs with smaller cells generally operate at higher temperatures and thus may be an advantage. There is no specific determinant for RFS maximum storage temperature but, because of the possibility of Rb migration under long-term hot storage, a recommended limit is imposed lower than that where component damage occurs.

The lower operating temperature of an RFS is usually determined by the point where the physics package oven with the least demand power margin goes out of control since performance will deteriorate below that condition. The minimum storage temperature is likely set to an arbitrary -55°C.

There is little actual experience with RFS units undergoing long-term storage at either temperature extreme, and the worst situation is probably the thermal stress caused by rapid RFS warm-up from cold storage.

The operating temperature is usually measured at the RFS case, in particular its baseplate. That, in turn, is determined by either its conductive mounting surface or the ambient air. Conductive heat transfer is mandatory for operation in vacuum. In air, without hard mounting, a convective heat sink is usually required to maintain a reasonable temperature Radiative heat transfer is normally not a significant factor. Obtaining proper heat transfer is particularly important for a unit mounted on a vibration isolator. The use of a baseplate temperature controller to reduce overall RFS temperature sensitivity is discussed below.

RFS temperature sensitivity is usually expressed as a static or steady-state value, and is not necessarily linear, and can display significant unit-to-unit variation, particularly because it is generally the result of multiple internal mechanisms having varying signs, magnitudes and time constants. In a dynamic environment, an RFS can be exposed to temperature slew and/or shock, and the resulting transient response is not necessarily the same as that for slower changes. Some hysteresis and lack of retrace is also possible.

All those factors make RFS temperature coefficient modeling and compensation problematic, but it can nevertheless be effective, especially for steady-state sensitivity, and is increasingly used with RFS units having digital frequency adjustment and microprocessor control.

• Retrace

RFS units generally have excellent frequency retrace when they are turned off and on again under the same environmental conditions. The duration of the off period is not much of a factor. RFS retrace frequency error is normally non-accumulative.

• Barometric Pressure

Barometric pressure is an often-neglected but potentially significant RFS sensitivity factor, particularly for units with large absorption cells. It is mainly caused by drumhead deflection of the glass cell, and perhaps because of thermal effects.

RFS operation under vacuum or in space is not a problem for units intended for that environment, but otherwise it can cause internal overheating for components that are not conductively heat sunk.

A sealed RFS eliminates the effect of barometric pressure change.

• Altitude

Altitude exposes an RFS to a combination of barometric pressure and temperature change, and is generally no different in its effect than those factors individually.

• Supply Voltage

An RFS generally requires a DC supply voltage rather than being designed to operate from AC mains power, and thus is specified to accept a certain DC voltage range and polarity, and to require a certain maximum demand current during warm-up and a steady state current that is a function of temperature. The variation in power consumption is mainly due to its physics package oven(s).

Reverse polarity protection may or may not be included within the RFS and, if not, may be needed from the host system.

DC isolation may be required between the RFS DC return lead and its case ground, in which case a DC/DC converter will likely be needed either inside or external to the RFS itself. In the latter instance, consideration must be paid to how the RFS case is electrically insulated while still providing adequate thermal transfer.

Other supply voltage considerations include the RFS frequency sensitivity to supply voltage, and to noise, transients and ripple on the supply line. Conversely, a DC/DC converter inside the RFS, while providing isolation and/or a wider input voltage range, can cause conducted interference (see EMI below).

RFS voltage sensitivity is a combination of electrical and thermal effects, and is generally small enough so as not to be a major consideration.

• Power Consumption

The power consumption of an RFS depends mainly on its type. Conventional units and the core RFS of a space unit require around 12-15 watts steady-state at room temperature, CPT units 1-2 watts and CSAC units 0.1-0.2 watts. The demand power during oven warm-up is considerably higher and determines the required power supply current rating. Power varies with ambient temperature, especially for a space unit with a baseplate temperature controller (BTC).

• Dynamic Input Impedance

An RFS generally contains filtration on its DC input supply line, and that can have significant impact on the impedance that the RFS presents to its DC source as a function of (audio) frequency. High Q resonances can pose a particular problem when used with a host DC/DC converter.

• Warm-up Time

Depending on the application, RFS warm-up time can be an important consideration. RFS warm-up is to some extent a design tradeoff between speed versus increased demand power and thermal stress, and lockup time can vary from less than 10 seconds to a few minutes. Besides physics package and crystal oscillator oven warm-up, a conventional lamp-pumped RFS requires time for lamp starting. Additional time is also needed for frequency stabilization.

The RFS RF output is generally present immediately upon application of DC power, and that can pose a problem since it will not be locked to the Rb atomic resonance. In fact, it often sweeps back and forth with a large offset until the physics package and crystal oscillator warm up. All RFS units have a monitor signal that indicates lock, and that may have to be utilized by the host system.

In an application where frequent power on-off, warm-up and large external temperature variation is expected, thermal cycling stress can be an important consideration and may require design verification testing to assure adequate endurance.

• Thermal Interface

Consideration must be given to the thermal interface between an RFS and the host system that provides a heat sink or other means for dissipating the RFS power. Common methods include a finned heat sink, perhaps with a fan to dissipate heat via convection or simply a large enough thermal mass to carry away the heat conductively. Ideally, the RFS would be attached to a constant-temperature baseplate. Radiative heat transfer is seldom a factor, even with RFS operation in vacuum.

• Baseplate Temperature Control

Baseplate temperature control is an excellent way to improve RFS temperature stability at the expense of additional size, weight, power and complexity. In its simplest form, it can be a convective heat sink with a temperature-controlled fan. More elaborate arrangements using temperature-controlled heaters have been successfully employed for GPS satellite clocks.

Use of a baseplate temperature controller requires a thermal insulator between the BTC and its mounting surface. Its operating range extends from the lowest mounting surface temperature where it has sufficient demand power to the highest mounting surface temperature where the temperature rise from the RFS dissipation reaches the BTC set point.

• Reliability

An RFS reliability analysis generally follows the procedures for electronic equipment prescribed in either MIL-HDBK-217 or Bellcore/Telecordia SR-332. It is important to use the applicable environment (e.g., Ground Fixed at +40°C) for the analysis. The resulting failure rate is associated mainly with the electronic circuits. The physics package, with the possible exception of the Rb lamp[6], has been generally found to be very reliable (mostly mechanical, the associated electronic parts (photodiode, thermistors, SRD diode, etc.) considered separately). Cell failures are very unusual, practically nonexistent, foil oven heaters likewise. Some concern exists for the semiconductor laser diodes used in some conventional and all CPT/CSAC RFS units.

The most important part of an RFS reliability assessment may be close examination of the thermal and electrical parts stress that is a prerequisite to performing the reliability analysis.

Today's commercial electronic parts, including plastic encapsulated microcircuits have achieved an outstanding level of reliability. Some military and most space RFS products further improve on that with enhanced parts selection and screening. Those activities are generally program-specific and associated with any required radiation hardening.

In practice, it is found that most RFS failures are associated with bad workmanship. Factory temperature cycling and burn-in (Environmental Stress Screening, ESS[7]) has proven to be important for weeding out such defects.

The life of an RFS is typically limited by obsolesce rather than any specific life-limiting factor. RFS products are usually covered by a limited warranty than protects against early failures.

• Monitors

All RFS units have an indicator that shows that its crystal oscillator is locked to the Rb atomic resonance. Most units also have either analog or digital monitor signals that show such parameters as the Rb lamp light level and the XO control voltage. Modern RFS units often have digital interfaces and user software to monitor their operation.

• Storage

There are no significant considerations regarding the storage of an RFS. One should, of course, abide with the unit's storage temperature limits.

• Aging and Drift

Internal aging within the Rb physics package causes its frequency to change[8]. That change, along with other effects associated with its operating conditions, results in frequency drift over time. The aging rate tends to diminish over time, and, after initial stabilization, for classic units, is typically on the order of $\pm1\text{x}10^{-11}$/day, $\pm1\text{x}10^{-10}$/month and $\pm1\text{x}10^{-9}$/year (and not much more than that "forever"). Day-to-day, however, environ-mental disturbances are likely to dominate the aging.

RFS frequency drift can be the largest contributor toward clock error over time. It can also require that the RFS frequency be adjusted to restore it to agreement with an absolute reference.

RFS aging can be caused by several mechanisms of varying sign, magnitude and consistency, and therefore does not follow any set pattern or behavior. It can even flatten, reverse direction and increase again. This makes its modeling and removal problematic. That said, some of the highest-performing space RFS units have shown highly-modelable aging that fits a log or diffusion ($\sqrt{t}$) model.

• Helium Exposure

Atmospheric helium is, to an extent, a "poison gas" for an RFS because it can permeate the absorption cell glass envelope and cause a fre-

[6] Rb lamp life problems have been resolved by lamp design and processing improvements.

[7] ESS is a recipe for applying temperature cycling and mild vibration to a unit to precipitate latent defects.

[8] Several factors can contribute to RFS aging including changes in the Rb lamp intensity/spectrum, chemical/physical effects in the Rb absorption cell, and changes in the physics package oven temperatures.

quency change[9]. This is not a big issue unless the unit is stored or operated in a He-rich environment for a long time.

• Magnetic Field

DC magnetic field sensitivity can be an important RFS factor, but most units have sufficient magnetic shielding that this is not a major concern. This sensitivity is a direct result of the properties of the Rb hyperfine resonance, and is strongest along the axis of the physics package internal DC magnetic field. Several techniques have been developed (e.g., C-field commutation[10], Zeeman sensing[11]) to reduce RFS magnetic field sensitivity, but passive magnetic shielding[12] is generally adequate for most applications.

• Vibration

Vibration can have a profound effect on the stability and even the functioning of an RFS, largely because of its quartz crystal oscillator.

Survival Under Vibration

It is quite remarkable how well properly-designed electronic assemblies can survive severe sinusoidal and random vibration. The key, of course, is "properly designed". Without proper care regarding circuit board and other structural resonances, proper bonding of components, consideration of fastener strength, and many other aspects of the mechanical design, structural and fatigue failures will occur under the stresses encountered under rocket launch, aircraft flight and other such conditions. Correct specification and verification of the requirements is essential.

There are no unique vibration vulnerabilities associated with the Rb physics package, but it is important that the cells and optical elements be ruggedly attached.

Performance Under Vibration

The importance of RFS vibration sensitivity depends very much on its operating environment and the need for spectral purity. In general, an RFS is less affected by vibration than an ordinary crystal oscillator, whose quartz crystal resonator has a typical acceleration sensitivity of $1\text{x}10^{-9}$/g and therefore can exhibit strong discrete PM sidebands under sinusoidal vibration or suffer significant phase noise degradation from random vibration.

But an RFS also has a crystal oscillator (XO) that makes it susceptible to the same mechanism in a more complicated way. For vibration frequencies well above the bandwidth of the RFS frequency lock servo, the effect is essentially the same. Well below that frequency, the servo acts to eliminate the effect (assuming that the Rb physics package itself is immune). The Rb physics package, if ruggedly constructed, indeed has little vibration sensitivity, mainly associated with deflection of its light path.

There's more to the story however. The Rb servo operates by applying deliberate FM to its microwave excitation, using the resultant recovered AC signal, via synchronous detection, to steer the XO. Thus the frequency lock loop is very sensitive to vibrational modulation at that particular rate (for the light beam) or twice the modulation rate for the XO.

Finally, at low vibration frequencies, the resulting XO modulation can even cause a reduction or loss of the physics package microwave excitation.

You can see that this is quite a complicated topic. If your RFS application involves significant operational vibration, vendor consultation is advised. Besides a rugged unit, a low g-sensitivity XO may be required, and/or one with active or

[9] He buffer gas in the absorption cell raises the RFS frequency. In normal operation, it reaches equilibrium with the trace atmospheric He tension. Subsequent operation in a vacuum can result in negative aging.
[10] Periodic C-field reversal reduces the sensitivity to external magnetic field variations to 2nd order.
[11] Interrogation of the field dependent Zeeman hyperfine lines can measure and stabilize the internal C-field.
[12] It also provides radiation shielding.

passive vibration isolation or the entire RFS may need to be mounted on a vibration isolator.

Structural resonance issues have diminished as RFS units have become smaller.

Vibration requirements can apply either under operating or non-operating conditions, and the former is the more stringent since electrical power is applied and the RFS ovens are hot. But there is generally little difference in the severity of those conditions, and, of course, operation is required to assess performance under vibration. It is recommended that RFS vibration testing be performed with the unit operating because that can better expose problems such as intermittent connections.

• Mechanical/Pyro Shock

Mechanical shock survival is a fairly common requirement for all RFS applications. Exposure is generally while non-operating, but can be during operation, especially when associated with a time error limit.

Internally, the main items are concern include damage to quartz crystals and displacement of physics package elements. Dislodgement of heavy electronic components, radiation shields and the like are also concerns, as is actual breakage of mounting feet, etc.

The classic military shock test was to simulate battleship naval gunfire. Other tests simulated railcar coupling. One seldom sees those requirements anymore.

Commercial and military RFS units may include a bench handling shock requirement that simulates the rough treatment it may encounter during servicing. One hopes that space clocks are handled more carefully!

Space RFS units usually include a pyroshock requirement that describes the units exposure to the pyrotechnics associated with rocket stage and payload separation. Those conditions are generally tailored to the particular launch vehicle.

Shock testing can involve actual drops into a sandbox or hard benchtop, or shock waveforms applied by an electrodynamic shaker.

• Acceleration

Static acceleration is hardly ever an issue for an RFS and is seldom specified. That sensitivity of the crystal oscillator is eliminated by its frequency lock servo. One possible RFS concern is movement of molten Rb in the lamp, but that rarely observed.

RFS constant acceleration testing (besides a simple tip-over) is generally done on a large, slow centrifuge under operating conditions, and slip ring noise can be problem for making frequency measurements.

• Acoustic Noise

Acoustic noise is seldom specified as a test condition for an RFS. The effect is similar to that of random vibration but applied as sound waves through the air. It simulated an environment such as a rocket launch or jet aircraft engine. Typically this test would be conducted with the unit operating and frequency and/or phase noise would be measured.

• Other Environmental Tests

Explosive atmosphere is another item seldom specified as a test condition for an RFS, and would not be expected to pose a problem.

Similarly, Rain, Sand and Dust and Fungus tests are rarely if ever required.

• Thermal Cycling Fatigue

An RFS that is operated intermittently is subject to thermal cycling fatigue, especially for a unit that has fast warm-up from a cold soak. This is arguably the worst operating stress that RFS units are routinely exposed to. Thermal cycling endurance (not just on-off cycles) is an important design verification test (DVT) requirement, especially for military applications like tactical aircraft. In mild form, it also can be the basis of environmental stress screening (ESS) applied on an individual basis by the RFS manufacturer to assure a reliable product.

• Orientation

An RFS is, in principle, immune to static g forces and orientation since its crystal oscillator's acceleration sensitivity and "tip-over" effect due to its quartz crystal resonator is locked to the atomic resonance. In practice, there can be some RFS orientation sensitivity caused by thermal effects, but these are generally quite small.

• EMI

Most RFS applications impose electromagnetic interference (EMI) requirements of some sort. These can involve radiated and/or conducted susceptibility or emissions. EMI requirements are often tailored for a particular application.

An RFS has particular susceptibility to conducted interference on its DC power input at audio frequencies associated with its frequency lock loop servo modulation rate and harmonics thereof. Under particular (usually contrived) conditions, large frequency offsets and even unlocking are possible. One needs to set realistic values for the interfering ripple level, its exact frequency and phase relation with the servo modulation, and the amount of allowable frequency disturbance.

An RFS is likely to employ power switching circuits in its power supply and perhaps its oven controllers and those circuits are likely to produce discernable conducted emissions on its DC power line.

An RFS is often permitted to have radiated emissions at its RF output frequency and harmonics thereof, but this usually associated more with its connecting cable than the unit itself. An RFS may also have discernable radiated emissions at frequencies associated with its Rb lamp exciter, and perhaps those involved with its RF chain and physics package excitation. The connecting cables can often have a significant influence on the RFS radiated emissions since they act as antennas.

An RFS is generally not susceptible to radiated fields.

• Nuclear Radiation

Nuclear radiation hardening requirements apply to most space RFS usage, some military RFS applications and a few commercial ones. When it is required, radiation hardening influences all aspects of RFS specification, design, manufacture and test. Expert knowledge is needed to assess the environment, define the threats, analyze and tailor the RFS design, devise overall and spot shielding, select and screen its parts, plan and conduct verification tests, and assure manufacturing compliance.

The radiation environment can be from natural or manmade (e.g., weapons or reactor) sources, and it can include total gamma dose, neutron fluence, proton and other heavy particles, along with transient X-ray exposure, and single event/cosmic ray upsets. Each of these radiation types affects an RFS, mainly its electronic circuits, in specific ways.

RFS response to total dose radiation involves frequency offset and stability degradation (and eventually gross failure).

RFS response to transient radiation involves potential device upset/latchup and either "operate through" output phase continuity[13] with a specified time error limit or functional recovery within a specified time[14]. All RFS ports with cables attached may need hardening against system generated EMP (SGEMP).

Fortunately, RFS radiation hardening is well-understood and can be successfully implemented without unduly affecting its design or performance. If fact, the detailed circuit analyses needed provide valuable information for other aspects of its design. Thus, when applicable, radiation hardening becomes just another item of RFS specification.

• Relativity

Any clock is subject relativistic effects including time dilation and gravitational redshift. The former applies to a rapidly moving clock while the latter applies to one well above ground level, and thus these effects are significant only for space clocks. For example, GPS satellite clocks have a frequency that is about $+4.4 \times 10^{-10}$ higher in their half-synchronous (MEO) orbit. Thus a GPS clock must be adjusted to a slightly lower frequency while on the ground. That RFS specification will depend on its tuning means, if any.

• Phase/Frequency Jumps

Phase and/or frequency jumps can occur with any RFS, although these disturbances are not commonly a problem, and are not routinely specified or tested for.

First of all, it is important to understand the relationship between these effects and how they can be observed. Frequency is the rate of change (the derivative) of phase. Phase is the integral of the instantaneous frequency. RFS stability should preferably be measured as phase because that is the more fundamental parameter from which the frequency can be determined by calculating phase differences divided by the measurement interval. A short measurement interval provides better resolution of any such disturbances.

An RFS uses a frequency lock loop (not a PLL) to lock its crystal oscillator to the atomic resonance. Many mechanisms associated with the Rb physics package and/or the frequency lock servo can cause a frequency fluctuation. Those frequency changes can take the form of short transients or permanent offsets, and the resulting phase change can integrate to a step or a ramp. One such mechanism is a sudden change in the intensity and/or spectrum of the Rb lamp which, via the light shift effect, can cause a frequency jump. Generally speaking, only high-performance RFS units intended for demanding applications (such as GPS satellite clocks) are screened for such problems because they require careful long-term observation.

Phase changes at the RFS output can also occur without an internal frequency change due to such effects as crystal oscillator phase "pops", digital glitches and/or erratic connections. Particular attention should be paid to a phase change equal to an RF carrier period.

• Firmware and Software

Classic analog RFS designs without internal digital processors do not require firmware, but most modern implementations do, and while that is mainly an internal design matter, it introduces additional design review, documentation and configuration control issues.

Externally, an RFS with a digital control and monitor interface requires software for its user interface. That software is generally supplied and documented by the RFS vendor. In the case of a space RFS, it usually interfaces with the spacecraft control and telemetry system, which must then be part of the RFS specifications.

[13] A ringing filter at the RFS output can be used to maintain its output during transient radiation.
[14] Perhaps with time maintained by the host system

• Sources

We will not attempt to comprehensively list or compare sources for rubidium frequency standards and related devices, especially since such information depends on many factors and changes with time.[15] The source of an RFS product can be either the actual RFS manufacturer or another organization that incorporates it into their product. Because of the rather wide range of these products, one likely begins the process of source selection by comparing the specifications available units against the requirements. As usual, the manufacturer's reputation is a major factor, as may be their nationality and the potential need for export licenses, security clearances, etc. It may be necessary to examine the vendor's facilities and verify the experience of their personnel. It is relatively rare for even major RFS users to develop their own in-house RFS designs.

Most commercial RFS requirements are satisfied with standard catalog products, perhaps backed up by a specific SCD. Military RFS requirements may require customization of a commercial design, or even a custom design to a user SCD. But increasingly, because commercial electronic parts are so reliable, and most RFS physics packages are quite rugged, MIL requirements can be satisfied by commercial units with little or no modification. Space RFS requirements may need a custom design unless an existing one can be utilized. Some MIL and most space RFS programs require extensive documentation.

Some of the considerations for RFS vendor selection include:

- Reputation/Past Relationship
- Nationality/Location
- Organizational/Financial Strength
- Product Line/Experience
- Personnel/Expertise
- Manufacturing Capacity
- Support/Warranty
- Security Clearances
- Facilities and Equipment

[15] At the time of this writing, leading U.S. RFS sources are Excelitas, Frequency Electronics, Microsemi, and Stanford Research Systems. In Europe, the Orolia (Spectracom, Spectratime) supplies those devices, and Accubeat does so in Israel.

• Documentation/Data Items

Several types of documentation are associated with RFS specification, design, qualification, manufacture, test, procurement and use.

RFS specifications can take the form of standard product datasheets to custom program-specific source control drawings.

RFS design documentation can take the form of proprietary product information to formal contractual data items. These include program approved parts lists, a drawing package, worst case circuit analyses, reliability/MTBF analyses, radiation hardening analyses, preliminary (PDR), critical (CDR) and manufacturing readiness (MRR), software and firmware code reviews, an interface control drawing, qualification and acceptance test plans and procedures, product user, programming, application notes and service manuals, etc. Certain data items may need review and approval by multiple organizations. Formal product training may be required in some cases.

MIL specs and other such documents should not be listed as applicable to an RFS specification unless they are referred to and their specific conditions provided. If possible, use the same parameter values as given on the standard product data sheet so as to avoid the need for special analysis and test.

• Interface Control Drawing

The RFS documentation should include an Interface Control Drawing (ICD) or equivalent that describes all aspects of the unit's external physical and electrical attributes, including, as applicable, the following:

- Case dimensions
- Weight
- Mounting and heat sinking
- Connector types, mates, pinouts, and functions
- Power requirements
- Output frequency, waveshape and level
- Input signals and functions
- Partial schematics of I/O port circuits
- Monitor/BITE signals
- Control communications protocol

• Hazards

No hazards are uniquely associated with RFS manufacture or usage. The operation of an Rb atomic clock does not depend on radioactivity. These units do not employ high voltages and generally do not contain any hazardous chemicals. No special handing is needed, nor is any special documentation or labeling required.
The Rb-87 isotope is very slightly radioactive, so slightly that its half-life is longer than the age of the universe. We are fond of saying that an RFS has less radioactivity than a bunch of bananas[16], and radioactivity can be excluded from an RFS specification.

• Smart Clock Techniques

Artificial intelligence has not yet been widely applied to frequency references. Some earlier attempts at Modular Intelligent Frequency, Time and Time Interval (MIFTTI) and "Smart Clock" devices were explored but did not catch on. A GPS disciplined clock that not only sets its time and corrects its oscillator frequency but also learns its aging behavior certainly comes close to being a smart clock, particularly if one added the capability to separate out and learn environmental sensitivities like temperature and barometric pressure.

• GPS/GNSS Disciplining

GPS/GNSS disciplining of an RFS is a common application that produces a traceable absolute time and frequency reference at modest cost and complexity. The RFS frequency is steered to bring it into phase and frequency alignment (synchronized and syntonized) with the GPS/GNSS signal with a fairly long time constant that optimizes the overall noise level. In the event of loss of the GPS/GNSS signal, the RFS provides excellent holdover stability, and that, along with the desired phase noise, determines the RFS requirements.

Rb-based GPS disciplined oscillators (GPSDO) are available as complete units or can be quite easily implemented by an RFS having a 1pps input and appropriate firmware.

• Ensembling/Time Scales

An RFS is rarely used as part of a clock ensemble or elaborate time scale since higher-performing clock technologies (e.g., H-masers, Cs or Rb fountains) are used in those applications. Nevertheless, certain applications where very high reliability is needed use multiple RFS units in a phase coherent combiner. The main RFS requirement for such an application would be high-resolution digital tuning.

• Distinguishing Traits

An RFS is nearly always the best choice for a frequency standard that requires better performance than a crystal oscillator. At the borderline between their capabilities where they have similar costs, it is more practical to use the low end of RFS technology rather than the upper end for a frequency standard grade ovenized crystal oscillator.

A GPS/GNSS disciplined Rb oscillator is usually the device of choice for a local time/frequency standard, providing a traceable source of absolute time and frequency at modest cost and complexity.

[16] An RFS contains about a milligram of Rb-87 and its radioactivity is about 20 pCi, about 1/20th of a banana.

An RbXO, or more likely a CPT or CSAC device is the technology of choice when low power is critical, while the CSAC also offers very small size. The performance progression of those choices is in the order given above while the cost varies inversely.

Distinguishing features between RFS designs include:

- Component/module/ instrument packaging
- Stand alone/GPS disciplined
- Crystal oscillator type/low phase noise
- Servo bandwidth/dynamics
- Output frequency/waveform/1 pps
- Special features like user interfaces. frequency synthesis, multiple O/Ps, time codes, 1 pps input

• Design Documentation

Detailed design documentation beyond that included on a product data sheet is generally not provided for a catalog RFS item, but such information (e.g., a reliability analysis) may be available upon request. Complete design documentation is usually part of a custom design or military/space RFS program.

• Qualification Tests

Manufacturer-conducted qualification tests are part of the RFS design process to assure full compliance with its specifications. This entails a major effort because it generally includes such items as a stress-level reliability analysis, mechanical shock and vibration tests, a suite of EMI tests, etc. Details about the QTP procedure and results are generally not provided except for custom designs or military/space programs.

• Acceptance Tests

Manufacturer-conducted acceptance tests are part of every RFS delivery, although the ATP procedure and results may not be included with the unit. The items included in the ATP are generally limited to those that show unit-to-unit variation. Because frequency aging is one of those, and its measurement requires a period of time for initial stabilization and data collection, that also provides for a period of burn-in and screening. Formal ATP processes are a part of military/space RFS procurements. In many cases, the user will conduct his own RFS acceptance tests, likely a subset of the vendor's factory tests.

• Over/Under Specification

System engineers are trained to avoid both over and under specification. The dangers of the latter are obvious, and can result in serious system failures. But over-specification creates problems too. In general, it is best to stick with standard RFS products and their catalog specs. Those exceeding the requirements are fine. Those that are not necessarily will have to be tightened. It may be possible to re-qualify a design to the needed conditions. Also, the user may have some control over the environment that the RFS is exposed to.

• RFS Selection

RFS selection logically begins by considering the application and its requirements. Some attributes may not matter much (e.g., warm-up time for a continuously-running laboratory clock, aging for a GPS-disciplined RFS) while others may be critical (e.g., power for a battery-powered clock, phase noise for a microwave receiver). One can quickly decide on what category of RFS is appropriate (e.g., a commercial unit for low cost, a rugged MIL unit for a tactical aircraft) and zero in on the applicable vendors and their products, with due consideration given to their location and reputation. Even if your application seems to require a custom design, these standard products will give you an idea of what specifications are practical. Some applications (e.g., a GNSS satellite clock) will necessarily require a full-up procurement program and perhaps even a new design. Obviously, vendor consultation is needed in cases like that. Organizations that have frequent, major or unique RFS requirements will probably need to establish in-house expertise regarding RFS devices and a close relationship with their clock vendor(s).

• Acknowledgments

Many people and organizations have contributed to rubidium frequency standard technology for over 50 years. Reference [4] contains information about their work. Progress continues to be made, particularly with smaller, lower power and less expensive CPT and CSAC devices.

• About the Author

Mr. Riley has worked on rubidium frequency standard and related time and frequency technology for most of his professional career. He began as a Development Engineer at General Radio where he pursued that technology including quartz and rubidium frequency standards. In 1980 he became the Engineering Manager of the Rubidium Department at EG&G where he directed the design of rubidium frequency standards, including those used onboard the GPS satellites. His last position before retirement was as Manager of Rubidium Technology at FTS/Datum/Symmetricom. Mr. Riley is also the proprietor of Hamilton Technical Services where he developed and sold software for frequency stability and consults in the time & frequency field. He is the author of three books, numerous papers and reports, and holds several patents. Mr. Riley is an IEEE UFFC Life Fellow. He has served on several IEEE standards committees and the PTTI Advisory Board. He received the 2000 IEEE International Frequency Control Symposium Rabi Award and the 2011 Distinguished PTTI Service Award.

• Acronyms and Abbreviations

ADEV	Allan Deviation
AC	Alternating Current
AFS	Atomic Frequency Standard
ATP	Acceptance Test Procedure
BITE	Built In Test Equipment
BPF	Band Pass Filter
BTC	Baseplate Temperature Controller
CDR	Critical Design Review
COTS	Commercial Off The Shelf
CPT	Coherent Population Trapping
Cs	Cesium
CSAC	Chip Scale Atomic Clock
DC	Direct Current
DDS	Direct Digital Synthesizer
DSP	Digital Signal Processing
DSAC	Deep Space Atomic Clock
DVT	Design Verification Test
EMI	Electromagnetic Interference
ESS	Environmental Stress Screening
FCS	Frequency Control Symposium
FM	Frequency Modulation
FXR	Flash X-Ray
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPSDO	GPS Disciplined Oscillator
HDEV	Hadamard Deviation
He	Helium
Hg	Mercury
ICD	Interface Control Drawing
IEEE	Institute of Electrical and Electronic Engineers
I/O	Input-Output
ION	Institute of Navigation
LPF	Low Pass Filter
LVDS	Low Voltage Differential Signaling
MEMS	Micro Electro-Mechanical System
MEO	Medium Earth Orbit
MIFTTI	Modular Intelligent Frequency Time & Time Interval
MIL	Military
MTBF	Mean Time Between Failures
MRR	Manufacturing Readiness Review
NIST	National Institute of Standards and Technology
OCXO	Oven Controlled Crystal Oscillator
OCVCXO	Oven Controlled Voltage Controlled Crystal Oscillator
PDR	Preliminary Design Review
PLL	Phase Locked Loop
PM	Phase Modulation
PPS	Pulse Per Second
PSD	Power Spectral Density
PTTI	Precise Time and Time Interval
RAFS	Rubidium Atomic Frequency Standard
Rb	Rubidium
RbXO	Rubidium Crystal Oscillator
RF	Radio Frequency
RFS	Rubidium Frequency Standard
SCD	Source Control Document
SGEMP	System Generated Electromagnetic Pulse
SRD	Step Recovery Diode
SSB	Single Sideband
S/N	Signal to Noise
STS	Short Term Stability
S/V	Space Vehicle
SWP	Size, Weight and Power
TC	Temperature Coefficient
TDEV	Time Deviation
T&F	Time and Frequency
TTL	Transistor Transistor Logic
UFFC	Ultrasonics Ferroelectrics and Frequency Control
UHF	Ultra High Frequency
VCXO	Voltage Controlled Crystal Oscillator
VHF	Very High Frequency
VSWR	Voltage Standing Wave Ratio
XO	Crystal Oscillator

• References

1. W.J. Riley, *Rubidium Frequency Standard Primer*, LuLu Press, Inc., ID # 9559425, October 2011. Also available here.
2. W.Weidemann, "Application Critical Parameters for Rubidium Standards", *Proceedings of the 1998 IEEE International Frequency Control Symposium*, pp. 84-87, May 1998. This is one of the few technical papers that describe the selection of an RFS.
3. Ball Corporation, Efratom Time and Frequency Products, Irvine, CA, *Precision Time and Frequency Handbook*, Ninth Edition, 1993. This handbook contains a wealth of still-valuable information about obsolete RFS products and their specifications and applications. Once commonly available, it is now hard to find.
4. W.J. Riley, "A History of the Rubidium Frequency Standard", IEEE UFFC web site, January 2020.
5. T.J. Lynch, W.J. Riley and J.R. Vaccaro, "The Testing of Rubidium Frequency Standards", *Proceedings of the 43rd Annual Symposium on Frequency Control*", pp. 257-262, May 1989.
6. W.J. Riley, "The Physics of the Environmental Sensitivity of Rubidium Frequency Standards", *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*", Vol. 39, No. 2, pp. 232-240, March 1992.
7. W.J. Riley, *Handbook of Frequency Stability Analysis*, NIST Special Publication 1065, July 2008.
8. W.J. Riley and J. R. Vaccaro, "A Rubidium-Crystal Oscillator (RbXO)", *IEEE Transactions on Ultrasonics., Ferroelectrics, and Frequency Control*, Vol. UFFC-34, No. 6, pp. 612-618, November 1987.
9. J.R. Vig, "Introduction to Quartz Frequency Standards", IEEE UFFC web site, October 1992.
10. *IEEE Guide for Measurement of Environmental Sensitivities of Standard Frequency Generators*, IEEE Standard 1193.
11. MIL-PRF-55310, "Oscillator, crystal controlled, general specification for".
12. M.A. Lombardi, "Selecting a Primary Frequency Standard for a Calibration Laboratory", *Cal Lab*, Vol. 15, pp. 33-39, April 2008.
13. ITU Handbook, *Selection and Use of Precise Frequency and Time Systems*, 1997.

Appendix A

Examples of Conventional, CPT and CSAC Commercial Gas Cell Frequency Standard Specifications

These products are current examples of commercial atomic clocks: a Stanford Research Systems PRS-10 conventional rubidium frequency standard, an AccuBeat NAC1 commercial Rb atomic clock using coherent population trapping (CPT), and a Microsemi SA.45s chip-scale atomic clock that uses a miniature Cs gas cell. These datasheets were captured from their respective manufacturer's web sites in January 2020.

Conventional commercial RFS units have 1-second ADEV stabilities on the order of $1x10^{-11}$. The AccuBeat CPT unit has a specified STS of $2x10^{-10}$, an order of magnitude worse than a typical conventional RFS, but it is smaller and has lower power dissipation.

The CSAC unit has a specified 1-second STS of 3x10-10, slightly worse than the AccuBeat CPT unit. It has a much smaller size and power dissipation than a conventional RFS. Lower phase noise and space qualified versions of this CSAC are available.

Information about past conventional RFS units and their specifications can be found by searching the internet for such products as FRK, FRS, LPRO, and X-72.

Note: The examples of gas cell atomic clock specifications in Appendices A-C include current products from most major U.S. and European manufacturers: AccuBeat, Excelitas, Frequency Electronics, Microsemi, Orolia and Stanford Research Systems.

Frequency Standards

PRS10 — Rubidium frequency standard with low phase noise

PRS10 Rubidium Frequency Standard

- ***Low phase noise (<−130 dBc/Hz at 10 Hz)***
- ***Time-tags or phase-locks to a 1 pps input***
- ***72 hour Stratum 1 level holdover***
- ***RS-232 for diagnostics, control and calibration***
- ***20 year lamp life***

- ***PRS10 ... $1495** (U.S. list)*

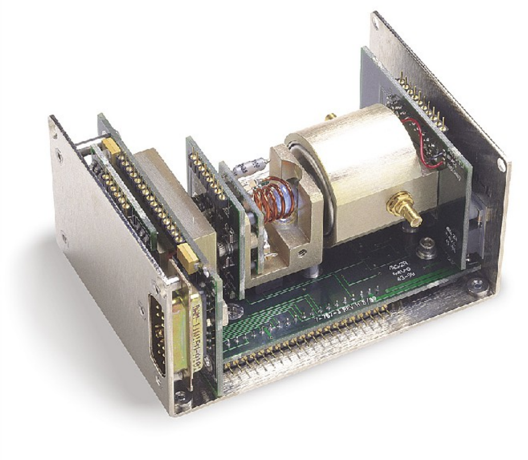
The PRS10 is an ultra-low phase noise, 10 MHz rubidium-disciplined crystal oscillator. The device fulfills a variety of communication, synchronization and instrumentation requirements. The phase noise of the 10 MHz output is low enough to be used as the reference source for synthesizers. The unit's short-term stability and low environmental coefficients make it an ideal component for network synchronization. Its low aging rate makes it an excellent timebase for precision frequency measurements.

The PRS10 can time-tag an external 1 pps input with 1 ns resolution. These values may be reported back via RS-232, or used to phase-lock the unit to an external reference (such as GPS) with time constants of several hours. This feature can provide Stratum 1 performance at a very low cost.

The PRS10 establishes a new level of features and performance in atomic frequency standards. Its design provides the lowest phase noise, greatest versatility, and easiest path to system integration of any rubidium frequency standard available.

PRS10 Operation and Design

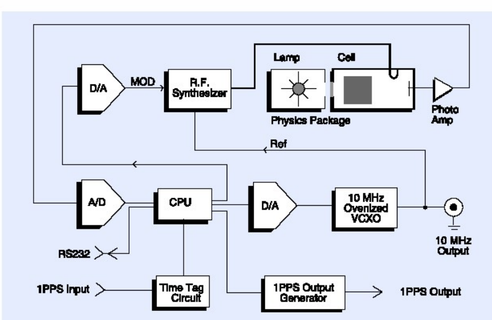
All commercial rubidium frequency standards operate by disciplining a crystal oscillator to the hyperfine transition at 6.834,682,612 GHz in rubidium. The amount of light from a rubidium discharge lamp that reaches a photodetector through a resonance cell will drop by about 0.1 % when the rubidium vapor in the resonance cell is exposed to microwave power near the transition frequency. The crystal oscillator is stabilized to the rubidium transition by detecting the light dip while sweeping an RF frequency synthesizer (referenced to the crystal) through the transition frequency.



PRS10 physics package and lamp assembly

The PRS10 uses a microcontroller, clocked at 10 MHz, to control all aspects of operation and to allow diagnostics, measurement, and closed case calibration via an RS-232 interface. The processor sweeps the RF synthesizer, synchronously detects the optical signal from the physics package, and servos the 10 MHz crystal oscillator to the rubidium transition via a 22-bit DAC and a varactor.

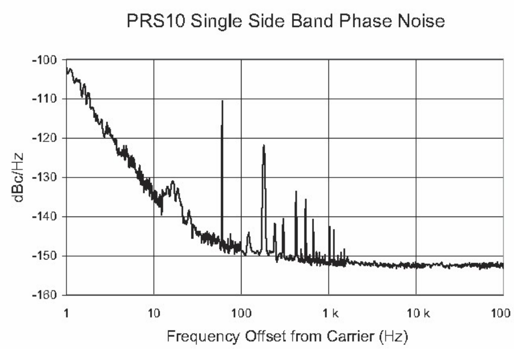
When turned on, the processor applies a voltage to the varactor corresponding to the last locked value. The frequency-lock servo is disabled until a useful resonance signal is detected from the physics package, providing a smooth transition to the final frequency as the unit warms up. In the case of a problem with the physics package, the unit will suspend the frequency servo and hold the varactor voltage at the last locked value.



PRS10 block diagram

Manufacturers of rubidium frequency standards sometimes use a crystal frequency that is an exact sub-multiple of the hyperfine transition frequency in order to simplify the design of the RF frequency synthesizer. Some designs use a DDS synthesizer, clocked by the crystal, to generate the 10 MHz output. Often, the crystal frequency is modulated in order to sweep the synthesizer through the transition frequency. The crystals are usually operated in the fundamental mode and not temperature stabilized. While such approaches are simpler to design, the phase noise, short-term stability, and spur content of their outputs suffer.

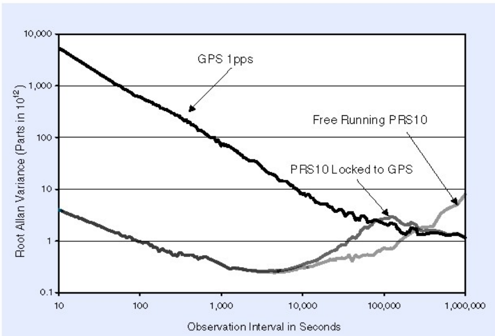
In contrast, the 10 MHz output from a PRS10 comes directly from a 3rd overtone, stress-compensated (SC-cut) crystal oscillator operated in an oven at its plateau temperature. A dual-loop RF synthesizer, with a crystal IF at 22.482 MHz, is used to generate 359.72 MHz and make 6.834 GHz via a step recovery diode. There are several advantages to this approach: the phase noise is very low (<–130 dBc/Hz @ 10 Hz offset), there are no spurious components, and the output will be well behaved should the physics package fail to provide a lock signal. (The aging will be about 5×10^{-10}/day when not locked to rubidium.) The phase noise plot of a PRS10 shows a 42 dB reduction in phase noise at 10 Hz offset from the carrier at 10 MHz when compared to a conventional rubidium standard.



Historically, the lifetime of rubidium frequency standards has been dominated by rubidium depletion in the discharge lamp. To avoid excess flicker noise, manufacturers would load less than 100 µg of rubidium into spherical discharge lamps. The PRS10 uses a lamp with a side arm loaded with 1 mg of rubidium. This design eliminates rubidium depletion as a failure mechanism, and provides better temperature control without excess flicker noise.

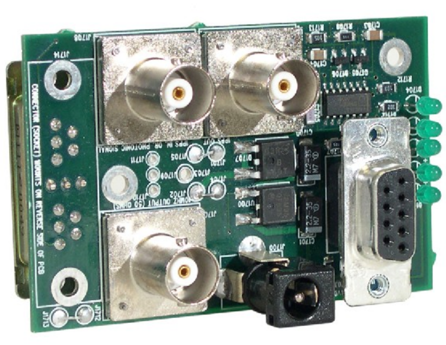
GPS Tracking

Frequency offsets and long-term aging of the PRS10 can be eliminated by phase-locking to a source with better long-term stability, such as the 1 pps from a GPS timing receiver. As shown in the Allan variance plot, the short-term stability of GPS is poor (about $5{,}000 \times 10^{-12}$) compared to the stability of the PRS10 (about 5×10^{-12}). However, over several hours, GPS is more stable, and so the stability can be improved by phase-locking the PRS10 to GPS with a long time constant.



PRS10 Allan variance plot

The PRS10 can time-tag or phase-lock to a 1 pps input, and provides a slewable 1 pps output. The input can be time-tagged with 1 ns resolution, and the result may be read back via the RS-232 interface. When tracking an external input, the time constant can be set from 5 minutes to 18 hours. The 1 pps output may be moved with 1 ns resolution over the range of 0 to 999,999,999 ns via the RS-232 interface.

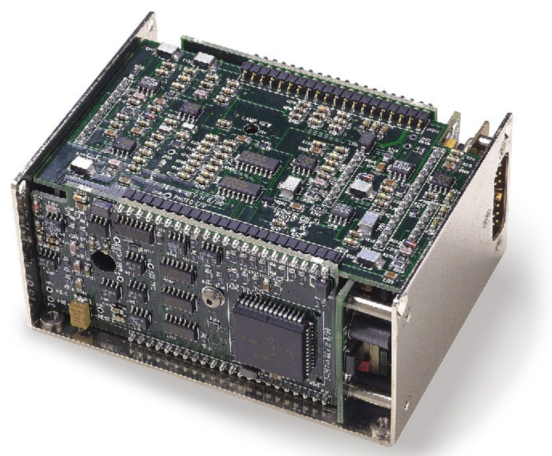


PRBB Breakout Connector Board

When an external 1 pps signal is applied, the PRS10 will verify the integrity of that input and will then align its 1 pps output with the external input. The processor will continue to track the 1 pps output to the 1 pps input by controlling the frequency of the rubidium transition with a small magnetic field adjustment inside the resonance cell.

Standard Interface Connector

The interface connector and device form-factor are compatible with Efratom's Model FRS rubidium frequency standard. In its default configuration, the PRS10 uses pins #4 and #7 for the RS-232 interface to provide a complete set of systems diagnostics and control. Internal hardware jumpers allow these pins to be configured as analog outputs to monitor the lamp intensity and varactor voltage for complete compatibility with the FRS.



Assembled PRS10

Ordering Information

PRS10	10 MHz rubidium oscillator	$1495
Option C	Low monthly aging ($<2.5 \times 10^{-11}$)	$495
PRBB	Breakout connector board	$150
PRPS	24 VDC switching power supply	$150
PRHS	Benchtop heat sink	$100
PRMC	D-type mating connector	$50

PRS10 Specifications

Output

Output frequency	10 MHz sine wave
Amplitude	0.5 Vrms, ±10 %
Phase noise (SSB)	< –130 dBc/Hz (10 Hz)
	< –140 dBc/Hz (100 Hz)
Spurious	< –130 dBc (100 kHz BW)
Harmonic distortion	< –25 dBc
Return loss	>25 dB (at 10 MHz)
Accuracy at shipment	$\pm 5\times10^{-11}$
Aging (after 30 days)	
Monthly	$<5\times10^{-11}$ ($<2.5\times10^{-11}$ with opt. C)
Yearly	$<5\times10^{-10}$
Short-term stability	$<2\times10^{-11}$ (1 s)
(Allan variance)	$<1\times10^{-11}$ (10 s)
	$<2\times10^{-12}$ (100 s)
Holdover	72 hour Stratum 1 level
Frequency retrace	$\pm 5\times10^{-11}$ (72 hrs. off, then 72 hrs. on)
Settability	$<5\times10^{-12}$
Trim range	$\pm 2\times10^{-9}$ (0 to 5 VDC)
	±1 ppm (via RS-232)
Warm-up time	<6 minutes (time to lock)
	<7 minutes (time to 1×10^{-9})
Voltage sensitivity	$<2\times10^{-11}$ (1 VDC supply change)

Electrical

Input voltage	+24 VDC (nom.), +22 VDC (min.), +30 VDC (max.)
Current	2.2 A (warm-up), 0.6 A (steady-state) at 25 °C (Note 1)
Protection	±30 VDC to any pin except rf out
RF protection	100 mA (stable w/ any termination)
Cal reference out	5.00 ± 0.05 VDC
RS-232	9600 baud, 8 bits, no parity, 1 stop bit, 0 to 5 V levels with X-on/X-off protocol
1 pps measurement	±10 ns (accuracy), ±1 ns (resolution)
1 pps output set	±10 ns (accuracy), ±1 ns (resolution)

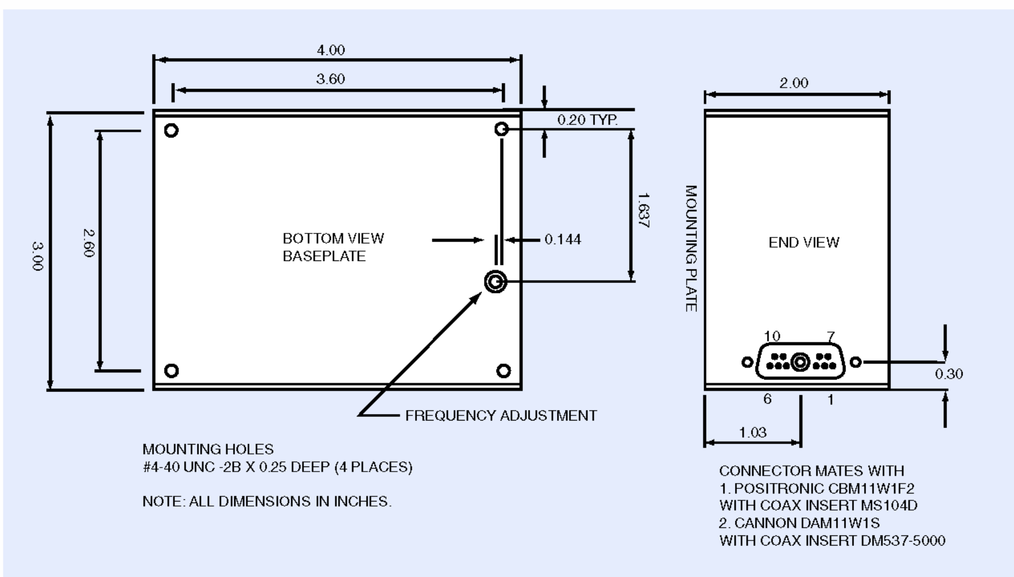
Environmental

Operating temperature	–20 °C to +65 °C (baseplate)
Temperature stability	$\pm 1\times10^{-10}$ (–20 °C to +65 °C baseplate)
Storage temperature	–55 °C to +85 °C
Magnetic field	$<2\times10^{-10}$ for 1 Gauss field reversal
Relative humidity	95 % (non-condensing)

Miscellaneous

Design life[2]	20 yrs.
Size	2.00" × 3.00" × 4.00" (HWD)
Weight	1.32 lbs.
Baseplate threads	4-40 (4 places)
Connector	Mates with ITT/Cannon DAM11W1S series
Warranty	One year parts and labor on defects in materials and workmanship

1. Low power warm-up option is available. Contact factory for details.
2. Lamp lifetime is the dominant consideration in the design life estimate. The estimate is based on the measured reduction of lamp intensity and the elevation of lamp start voltage with time.



PRS10 dimensional drawing

AccuBeat Ltd.
Accurate Frequency & Time

Rubidium Frequency Standard

NAC1 - Nano Atomic Clock

SPECIFICATIONS

Key Features

- *Phase noise (floor): -150dBc / Hz*
- *Power Consumption: < 1.2W*
- *Size: 32cc (41.1mm X 35.8mm X 22 mm)*
- *Aging: <3E-10/month*
- *Temp Stability: ±1E-9 / -20°C to 65°C*
- *Outputs: 10 MHz , 1PPS*
- *Supply voltage: 3.3 VDC*
- *UART interface for monitoring and control*
- *ROHS Compliant*

Description

The NAC1 is the newest and smallest addition to AccuBeat's line of Rubidium Frequency Standards. Incorporating proven traditional glass technology and based on Coherent Population Trapping (CPT), the NAC1 is an extremely small and compact atomic clock that has been designed as a board mounted component. NAC1 provides 10 MHz and 1PPS outputs and short term stability (Allan Deviation) of 2E-11 @ 100 seconds with aging of 3E-10/month at 25°C. The NAC1 has a UART interface for monitoring and control, a Built in Test (BIT) output and a warm-up time of typically 180 seconds. Measuring just 41.1mm X 35.8mm X 22mm and weighing only 75 grams and with a power consumption of less than 1.2 Watts, the new NAC1 is a Rubidium atomic clock especially suitable and designed for a wide range of portable applications.

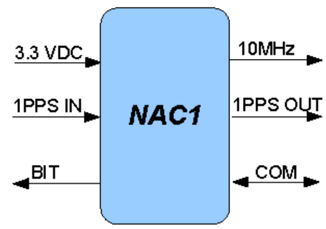
Applications:

The NAC1 is specifically designed for low power applications such as:

- GPS receivers
- UAV's
- Autonomous sensors
- Backpack secure communication radios.

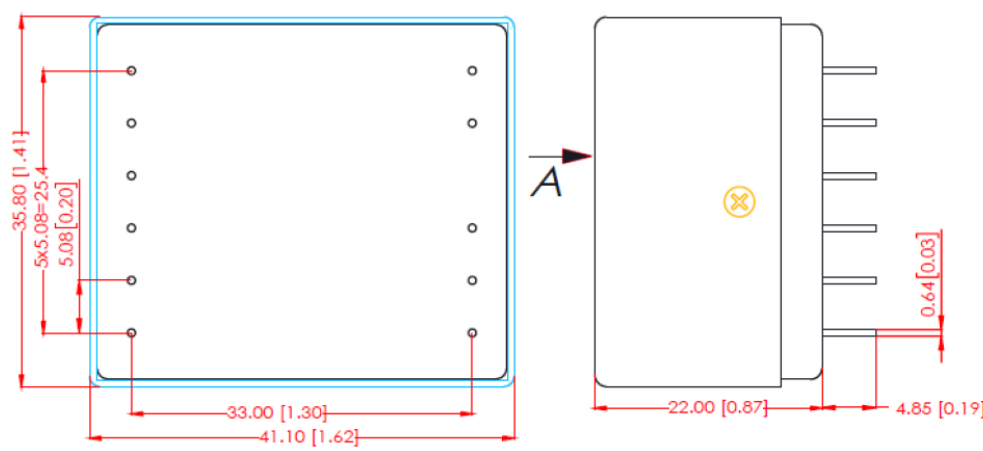
Inputs & Outputs

10MHz Output	CMOS compatible, 3.3V@1MΩ
1PPS Output	CMOS compatible, 3.3V@1MΩ Rise / Fall time: <10 ns, Pulse width: 20 µs
1PPS Input	CMOS, 3.3V@1MΩ
Built in test (BIT)	CMOS compatible, 3.3V@1MΩ '0' = Normal operation, '1' = Alarm
Power input	3.3±0.1 VDC
Serial Comm.	Control and monitor interface
	UART format, CMOS compatible, 3.3V@1MΩ, 115200BPS



Physical Specifications

Size	41.1mm X 35.8mm X 22mm
Weight	<75g



STANDARD PRODUCT SPECIFICATIONS

Performance		
Frequency	Stability (Allan Deviation)	< 2E-10 @ TAU = 1sec < 8E-11 @ TAU = 10sec < 2E-11 @ TAU = 100sec
	Phase Noise	<-86 dBc/Hz @ 10Hz <-120 dBc/Hz @ 100Hz <-138 dBc/Hz @ 1kHz <-143 dBc/Hz @ 10kHz <-148 dBc/Hz @ 100kHz <-150 dBc/Hz @ Floor
	Aging*	< 3E-10 / month < 1E-9 / year
	Maximum frequency change over operating temperature range	±1E-9 (-20°C to 65°C)
	Digital Tuning (Through Serial communication)	Range: ±2E-8 Resolution: 7.6E-13
	Initial offset at shipment	±5E-11
Time Accuracy	1PPS Sync.	±100nsec
Warm-up	Warm-up Time (Time to BIT)	180s (Typ)
Power Consumption	Operation	< 1.2W
	Warm-up	< 2.4W
Storage Temperature		-40°C to +90°C
No damage operating temperature		-40°C to 85°C but the clock is locked at -20°C to 65°C only

*After 30 days of continues operation

All specifications at 25°C, Vcc =3.3VDC unless otherwise specified

SA.45s CSAC and RoHS CSAC Options 001 and 003

Chip-Scale Atomic Clock

Features

- Power consumption <120 mW
- Less than 17 cc volume, 1.6" × 1.39" × 0.45"
- 10 MHz CMOS-compatible output
- 1PPS output and 1PPS input for synchronization
- RS-232 interface for monitoring and control
- Short term stability (Allan Deviation) of 3.0×10^{-10} at τ =1 sec

Applications[1]

- GPS receivers
- Backpack radios
- Anti-IED jamming systems
- Autonomous sensor networks
- Unmanned vehicles
- Underwater sensor systems
- Stability for various other communication and transmission applications
- RoHS-Compliant CSAC
  - RoHS 2 (Directive 2011/65/EU)
  - Wide storage temperature: 100 °C

[1]The CSAC is not tested, qualified, or rated for space applications.

With an extremely low power consumption of <120 mW and a volume of <17 cc, the Microchip SA.45s Chip Scale Atomic Clock (CSAC) brings the accuracy and stability of an atomic clock to portable applications for the first time. The CSAC is also available in a RoHS-compliant form.

The SA.45s provides RF and 1PPS outputs at standard CMOS levels, with short-term stability (Allan Deviation) of 3.0×10^{-10} at τ = 1 sec, typical longterm aging of $<9 \times 10^{-10}$/month, and maximum frequency change of $\pm 5 \times 10^{-10}$ over an operating temperature range of –10 °C to 70 °C.

The SA.45s CSAC accepts a 1PPS input that may be used to synchronize the unit's 1PPS output to an external reference clock with ±100 ns accuracy. It also use the 1PPS input to discipline its phase and frequency to within 1 ns and 1.0×10^{-12}, respectively.

A standard CMOS-level RS-232 serial interface is built in to the SA.45s. This is used to control and calibrate the unit and also to provide a comprehensive set of status monitors. The interface is also used to set and read the CSAC's internal time-of-day clock.

Specifications[1]

Electrical

RF Outputs	
Frequency	10 MHz (option 001) 16.384 MHz (option 003)
Format	CMOS
Amplitude	0 V to V_{CC}
Load Impedance	1 MΩ
Quantity	1
1PPS Output	
Rise/fall Time (10%–90%) at Load Capacitance 10 pF	<10 ns
Pulse Width	100 µs (Option 001) 97.656 µs (Option 003)
Level	0 V to V_{CC}
Logic High (V_{OH}) Min	2.80 V
Logic Low (V_{OL}) Max	0.30 V
Load Impedance	1 MΩ
Quantity	1
1PPS Input	
Format	Rising edge
Low Level	<0.5 V
High Level	2.5 V to V_{CC}
Load Impedance	1 MΩ
Quantity	1
Serial Communications	
Protocol	RS-232
Format	CMOS 0 V to V_{CC}
Tx/Rx Impedance	1 MΩ
Baud Rate	57600
Built-In Test Equipment (BITE) Output	
Format	CMOS 0 V to V_{CC}
Load Impedance	1 MΩ
Logic	0= Normal operation 1= Alarm
Power Input	
Operating	<120 mW
Warmup	<140 mW
Input Voltage (V_{CC})	$3.3 \pm 0.1\ V_{DC}$

[1]At input voltage V_{CC} = 3.3 V_{DC} and ambient temperature = 25 °C, unless otherwise specified.

Environmental

Specification	Details
Operating Temperature	–10 °C to 70 °C
Maximum Frequency Change over Operating Temp Range (Maximum Rate of Change 0.5 °C per Minute)	$\pm 5 \times 10^{-10}$
Frequency Change Over Allowable Input Voltage Range	$\pm 4 \times 10^{-10}$
Magnetic sensitivity (≤2.0 Gauss)	$\pm 9 \times 10^{-11}$/Gauss
Radiated Emissions	Compliant to FCC part 15, Class B, when mounted properly onto host PCB
Vibration	Maintains lock under MIL-STD-810G, Operational, 7.7 g_{rms} per Figure 514.7E-1. Category 24
Humidity	0%–95% RH per MIL-STD-810, Method 507.4
Storage and Transport (Non-operating)	
Temperature	–55 °C to 85 °C
Temperature (RoHS-Compliant)	–55 °C to 100 °C
Vibration	MIL-STD-810G, 7.7 g_{rms} per Figure 514.7E-1. Category 24
Shock	MIL-STD-202-213A, Condition E, 1000 g

Performance Parameters

Specification	Details
Warm-up Time	<180 s
Analog Tuning	Range: $\pm 2.2 \times 10^{-8}$ Resolution: 1×10^{-11} Input: 0 V–2.5 V into 100 kΩ
Digital Tuning	Range: $\pm 1 \times 10^{-6}$ Resolution: 1×10^{-12}

Phase Noise (SSB)

Frequency	Option 001	Option 003
1 Hz	<–50 dBc/Hz	<–46 dBc/Hz
10 Hz	<–70 dBc/Hz	<–66 dBc/Hz
100 Hz	<–113 dBc/Hz	<–104 dBc/Hz
1 kHz	<–128 dBc/Hz	<–128 dBc/Hz
10 kHz	<–135 dBc/Hz	<–135 dBc/Hz
100 kHz	<–140 dBc/Hz	<–140 dBc/Hz
Frequency Accuracy		
Maximum Offset at Shipment	$\pm 5 \times 10^{-11}$	
Maximum Retrace (48 hrs Off)	$\pm 5 \times 10^{-10}$	
1 PPS Sync	±100 ns	

Aging

Type[2]	SA.45s[3]
Monthly	$<9 \times 10^{-10}$
Yearly	$<1 \times 10^{-8}$

[2]After 30 days of continuous operation.

[3]All CSAC units are tested for aging specs as per the datasheet and meet the specs at the time of shipment. However, continuous operation of CSAC over extended period of time may yield unpredictable aging performance, resulting in failure to meet the aging specs and may not be suitable for certain applications.

Short-Term Stability (Allan Deviation)

Type	SA.45s
τ = 1 s	3×10^{-10}
τ = 10 s	1×10^{-10}
τ = 100 s	3×10^{-11}
τ = 1000 s	1×10^{-11}

Physical

Type	SA.45s
Weight	<35 g (<1.23 oz)
Size	1.6" × 1.39" × 0.45"
MTBF	>100,000 hours
RoHS	RoHS 2 (Directive 2011/65/EU)

Solder

Type	Details
Standard	Hand solder using 63/37 tin/lead solder with maximum soldering tip of 329 °C (625 °F)
RoHS-Compliant	Hand solder using 96.5/3/0.5 tin/silver/copper with maximum solder tip temperature of 370 °C (698 °F) and a dwell time of <5 s.

Ordering Information

Part Number	Description	Output Frequency
090-02984-001	Chip-scale atomic clock option 001	10 MHz
090-02984-003	Chip-scale atomic clock option 003	16.384 MHz
090-03240-001	RoHS-compliant chip-scale atomic clock option 001	10 MHz
090-03240-003	RoHS-compliant chip-scale atomic clock option 003	16.384 MHz

Appendix B

Example of a MIL Rubidium Frequency Standard Specification

This example of a current MIL RFS is the Microchip 8200 module for ground tactical, shipboard and airborne applications. Its datasheet was captured from the Microchip web site in January 2020. Distinguishing features include a wide range of environmental hardening and a sealed case. It offers an excellent combination of package, performance and ruggedness.

Information about past MIL RFS units and their specifications can be found by searching the internet for such products as M-100, RFS-10, RFS-100, RFS-3000, TRFS and 8130A.

8200

Ruggedized Rubidium Oscillator

Summary

The 8200 is a ruggedized rubidium osillator designed for ground tactical, shipboard and airborne applications where superior frequency stability under diverse environmental conditions is required. Advanced communications, navigation and targeting systems require precision oscillators that can withstand a wide range of operating environments with minimal degradation in frequency accuracy and stability. The 8200 supports these applications with superior phase noise and excellent short and long term frequency stability.

The 8200 is unique as it combines short and long term frequency stability in a small and low profile package measuring less than one inch high.

The long life rubidium lamp and extended crystal control range of the 8200 helps extend operating periods and minimize maintenance intervals. An alarm signal derived from the basic physics operation indicates if the output frequency is roughly outside 5×10^{-8} of absolute frequency offset. The low temperature coefficient and excellent frequency stability facilitate extended holdover performance.

The height and footprint is ideal for low profile applications. Use of a filtered D-connector for I/O signals minimizes EMI emmissions and susceptibility. For ease of integration, the 8200 only needs one input supply voltage and allow direct plug-in into another circuit board.

The 8200 is designed around proven rubidium technology that has been deployed in numerous airborne, shipboard and ground tactical platforms for over thirty years.

Features

- 10 MHz output
- Hermetically sealed
- Shock or vibration hardened
- Digital monitor and control
- <1.0 inches high

Specifications

Electrical

RF Output	
Frequency	10 MHz
Format	Sinewave
Amplitude	0.7V rms nominal
Load impedence	50Ω at 10 MHz
Output connector	SMA (f)
Quantity	One

Performance

Phase Noise (SSB), £(f)

SB Frequency	10 MHz
1 Hz	<–72 dBc/Hz
10 Hz	<–90 dBc/Hz
100 Hz	<–128 dBc/Hz
1 kHz	<–140 dBc/Hz
10 kHz	<–148 dBc/Hz

Spectral Purity	
Harmonics	<–50 dBc
Non-harmonics	<–70 dBc (<150 MHz) <–80 dBc (>150 MHz)

Short term stability σy (τ) (Allan deviation)

Time	Allan Deviation
1 s	$\leq 3 \times 10^{-11}$
10 s	$\leq 1 \times 10^{-11}$
100 s	$\leq 3 \times 10^{-12}$

Aging	
Monthly*	$\pm 5 \times 10^{-11}$
*After 1 month of operation	

Frequency Characteristics	
Accuracy at shipment	$<\pm 5 \times 10^{-11}$ (25 °C)
Retrace	$<\pm 5 \times 10^{-11}$ (on-off-on: 24 hour, 24 hour, 24 hr at 25°C)
Voltage sensitivity	(10% voltage change from normal 28 Vdc) $<5 \times 10^{-12}$
Tempco	$<3 \times 10^{-10}$ (over operational temperature range)
Orientation sensitivity	$<5 \times 10^{-11}$ for any orientation
Pressure sensitivity	$<1 \times 10^{-13}$/mbar
Magnetic field sensitivity dc	($\leq$2 Gauss) $\leq \pm 4 \times 10^{-11}$ Gauss

Frequency Control	
With analog input (optional)	$\pm 6.5 \times 10^{-9}$, 0–5V into 5 kΩ
With digital input	$\pm 1 \times 10^{-8}$ (with resolution $\pm 1 \times 10^{-12}$)

Warm-up Time	
Time to lock	<8 min (–40°C)
Time to $<1 \times 10^{-9}$	<10 min (–40°C)

Input Power	
Warm-up	<20 W (28V, –40°C baseplate)
Operating	<16 W (28V, –40°C baseplate) <12 W (28V, 25°C baseplate) <8 W (28V, 80°C baseplate)
Input voltage range	15 Vdc to 32 Vdc

Health Monitoring	
Lock status (BITE)	
TTL low	Lock
TTL high	Unlock
RS-232 control/monitor interface. Provides ID, status/monitor information, and frequency/operating parameter adjustments. Protocol: 9600, 8, 1, none, no flow control	

Environmental and Physical

Relative humidity (operating)	0 to 95% RH per MIL-STD-810, Method 507.4
Salt fog	MIL-STD-810, Method 509.4
Operating Temperature	–40°C to 80°C baseplate
Storage Temperature	–55°C to 95°C
Thermal shock (non-operating)	MIL-STD-202, Method 107, Test condition A, 10 cycles –55°C to 85°C
Operating Altitude	Sea level to 40,000' (12,192 m)
Non-operating Altitude	Sea level to 80,000' (24,384 m)
Operating Vibration MIL-STD-810, Method 514.5, Procedure I	Category 24, Minimum Integrity, 7.7 grms at 0.04 g2/Hz 20 Hz 1 kHz, 15 min/axis (maintain lock)
Non-operating Vibration MIL-STD-810, Method 514.5, Procedure I	Category 24, Minimum Integrity, 15.4 grms at 0.16 g2/Hz 20 Hz 1 kHz, 30 min/axis
Operating Shock MIL-STD-202, Method 213	30 g, 11 ms, half-sine (maintain lock)
Non-operating Shock MIL-STD-202, Method 213	50 g, 11 ms, half-sine
Emissions MIL-STD-461	CE102, RE102
Susceptibility MIL-STD-461	CS101, CS114, RS103
MTBF Reliability	MIL-HDBK-217F, 76000 hours. Ground fixed at 40°C baseplate
On-Off cycling endurance Reliability	5000 cycles at 10°C baseplate
Input Connector DB-15-pin	Input power, monitoring and I/O
Height	0.95"
Width	4"
Depth	4.63"
Volume	17.6 in^3
Weight	<1.5 lbs

Connector Designation

Connector	Pin	Function
	1	Power In
	2	Power In
	3	D_OUT (RS232)
	4	GND
	5	GND
	6	NC
	7	Lock
	8	GND
	9	NC
	10	D_In (RS232)
	11	Freq Ctrl (Optional)
	12	GND
	13	NC
	14	Service
	15	GND
J2 SMA plug MIL-PRF-39012	RF Out	

Part Number

Part Number	Description
16052-101	8200 Rb Oscillator, 10 MHz

For More Information

www.microsemi.com

 900-00669-000 rev B DS00003065A

www.microchip.com

Appendix C

Examples of High-Performance Space-Qualified Rubidium Clock Specifications

These Rubidium Atomic Frequency Standard Data Sheets from Excelitas, Frequency Electronics, and Spectratime/Orolia were captured in January 2020 from their respective web sites. These units are representative of the Rb clocks used on-board the GPS and Galileo navigation satellites.

Space RFS designs tend to emphasize performance and reliability, and, of course, must to radiation hardened. Otherwise, space is a relatively benign environment for a Rb clock. Most current space RFS applications are for GNSS systems like GPS and Galileo, and their generic datasheet specifications are usually superseded by program-specific SCDs.

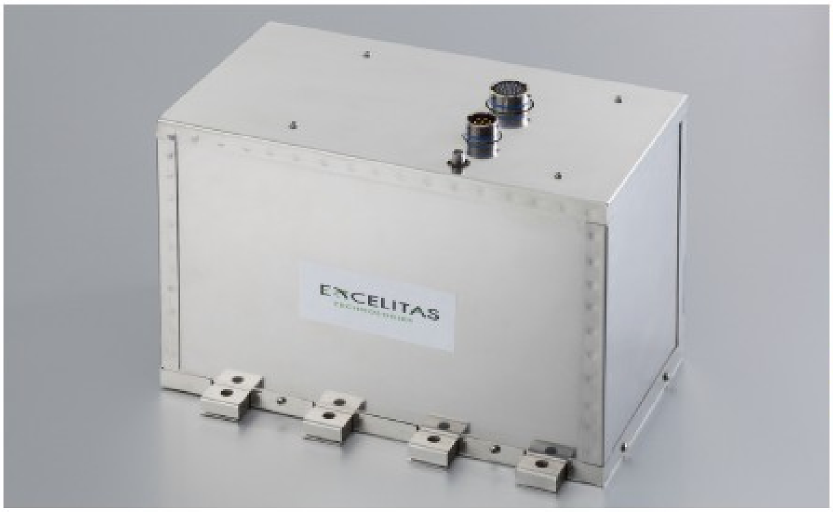
GNSS systems generally involve close control of their onboard clocks and supply daily updates, thereby emphasizing their 1-day stabilities. An RAFS having a pure white FM noise characteristic at a $1x10^{-12}\tau^{-1/2}$ level would have a 24-hour rime deviation (TDEV) of only about 0.1 ns corresponding to a clock-induced navigation error of about 0.03 m, typically small compared with other factors.

GNSS Rb clocks commonly include integral baseplate temperature controllers to reduce their temperature sensitivity to negligibility. That also allows their performance and testing to emphasize that thermal operating condition.

GPS clock stability is commonly expressed using the Hadamard deviation (HDEV) because it ignores the effect of linear frequency drift that is largely removed by the system. RFS drift tends to diminish over time, and its early stabilization is often well modeled by a diffusion (√ time) fit. The HDEV stability plot shown for an actual Excelitas GPS III RAFS was from a 1-month factory ATP run where that model was used to remove its early aging.

DATASHEET
Frequency Standards

High-Performance Space-Qualified
Rubidium Atomic Frequency Standard (RAFS)



Key Features

- High-Stability: 2×10^{-12} at $\tau = 1$ second
- Low Power: ≤ 14 watts
- Low Drift: ≤ 5x10-14/day
- High-Reliability: 700,000 Hr MTBF
- Fully Space-Qualified
- Radiation Hardened
- Negligible Environmental Sensitivities
- Small Size: 5.0" x 8.5" x 6.0"
- Low Weight: < 14 lbs.

Applications

- Global Navigation Satellite Systems (GNSS)

The Excelitas Rubidium Atomic Frequency Standard (RAFS) is an exceptionally High-Performance and High-Reliability Space-Qualified rubidium (Rb) clock developed for Global Navigational Satellite Systems. It is the highest performance device of this type currently available, combining exceptional stability and low drift with negligible environmental sensitivity, while offering the low size, weight and power advantages of a rubidium frequency standard. The design has been fully documented and qualified for all space requirements, including radiation. The RAFS offers exceptional performance as a precise time and frequency reference for demanding applications.

The RAFS employs classical rubidium gas cell atomic frequency standard principles. It utilizes a physics package with a discrete isotopic filter cell for best stability. The relatively large, cool absorption cell and thin film spectral filter provide exceptionally high signal-to-noise ratio and excellent short term stability. Calorimetric Rb lamp process control and screening assures long life. The "natural frequency" output of 13.4 MHz permits the use of a low complexity, single loop design for improved reliability. Operation at low fixed magnetic bias field improves stability and reduces magnetic and radiation sensitivity. An integral baseplate temperature controller greatly reduces the overall temperature sensitivity by utilizing a thermal insulator that can be tailored to meet various panel operating temperatures. While the RAFS may be operated in air, operating in a vacuum environment that eliminates barometric sensitivity, the extremely low temperature, magnetic, radiation and voltage sensitivities mean that the unit has extremely low sensitivity to all environmental effects, providing a very low flicker floor. The low aging rate of $<5 \times 10^{-14}$/day is exceptionally smooth and modelable using either a log or diffusion fit to the data.

A crystal oscillator at nominal 13.4 MHz produces the output signal via an output amplifier. This RF output path is hardened against transient radiation. The 13.4 MHz crystal oscillator also excites the Rb physics package via a phase modulator and frequency multiplier chain. This produces a discriminator signal that is processed by a servo amplifier to lock the crystal oscillator to the Rb atomic resonance. Temperature controllers, a lamp exciter and a precision C-field source support the operation of the physics package, while a dc/dc converter and linear regulators provide power for the RAFS circuits. An integral controller stabilizes the RAFS baseplate temperature and several analog monitors are available to assess the operation of the unit.

EXCELITAS
TECHNOLOGIES

Rubidium Atomic Frequency Standard

TABLE 1 Specifications

Input Power	28.0 VDC ± 4.0 VDC
	≤ 39 W total steady-state with BTC
	≤ 14W basic clock at +45°C baseplate
	≤ 65 W during warm-up
Warm-up	≤ 1 hour to ± $2x10^{-10}$
Monitors	0 to +5 VDC, 5kΩ source impedance

TABLE 2 Baseplate Temperature Controller (BTC)

Set-Point	+45°C ± 1°C
Stabilization Factor	integral controller
Thermal Insulator	0.7 W/°C
Heater Demand Power	≤ 28 W

TABLE 3 Outputs

RF Output	13.40134393 MHz Sinewave
	+18 dBm ± 1.5 dB
	All harmonics ≤ 50 dBc
	All spurious ≤ -85 dBc ($f_0 \le f \le 2f_0$)
	≤ -50 dBc ($2f_0 \le f \le 3f_0$)
Analog Monitors	Lock, Light, Signal, VCXO, Baseplate Temperature (2)
	Ovens (3), Power Supplies (4), ALC, C-Field, BTC

TABLE 4 Frequency

Nominal Frequency	13.40134393 MHz
Accuracy	± $1x10^{-9}$ at shipment
Trim Range	None (Fixed C-Field)
Stability $\sigma y(\tau)$	≤ $2x10^{-12}\ \tau^{-1/2} + 2x10^{-14}$ ($1 \le \tau \le 10^5$ seconds, drift removed)
Drift	≤ $1x10^{-13}$/day at BOL operation
	≤ $5x10^{-14}$/day after 1 year of continuous operation
Phase Noise, f(f)	≤ -95 dBc/Hz at f = 1 Hz, decreasing at -10 dB/decade to f = 100 kHz
Temperature Sensitivity	≤ $2x10^{-13}$/°C typical w/o BTC, below noise level for ± 1.5°C with BTC
Voltage Sensitivity	≤ $3x10^{-12}$ for 25.5 VDC to 28.0 VDC
Magnetic Sensitivity	≤ $1x10^{-12}$/Gauss
Barometric Sensitivity	≤ $1x10^{-13}$/mbar typical
Retrace	≤ $5x10^{-12}$ (to same environmental conditions)

TABLE 5 Environmental Specifications

Operating Temperature	Full performance with BTC range between -4°C and +21°C panel temperature.
	Functional between -20°C to +45°C panel temperature.
Storage Temperature	-34°C to +71°C
Altitude	Sea level to vacuum
Vibration	12.4g rms, 20 Hz to 2 kHz
Pyroshock	1500 g max to 10 kHz
Thermal Cycling	-34°C to +71°C
Acceleration	20 g
Radiation	Hardened to withstand natural and manmade space environments, including phase-continuous operation through transient radiation
EMI	Per MIL-STD-461E
EMP / SGEMP	Hardened to withstand
On-Off cycling endurance	≥ 1000 cycles

FIGURE 1 Typical Performance

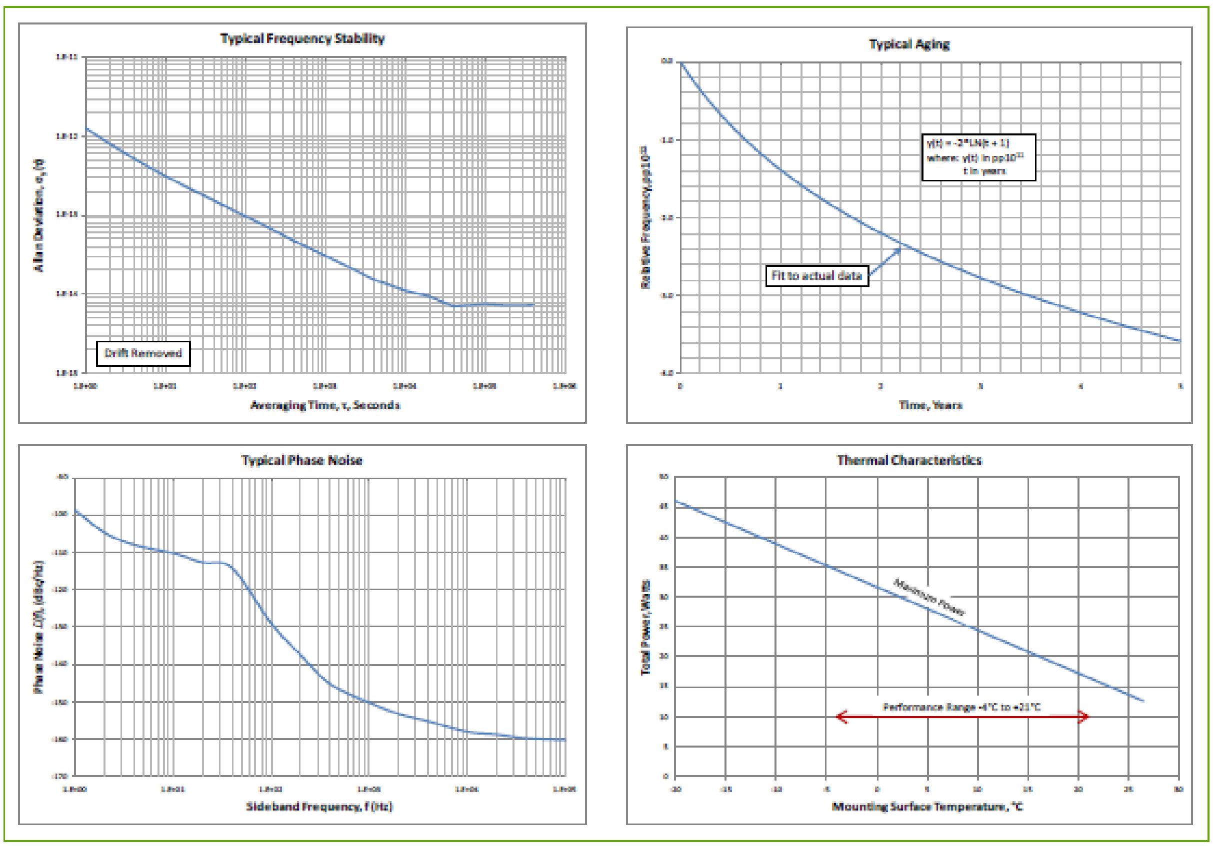
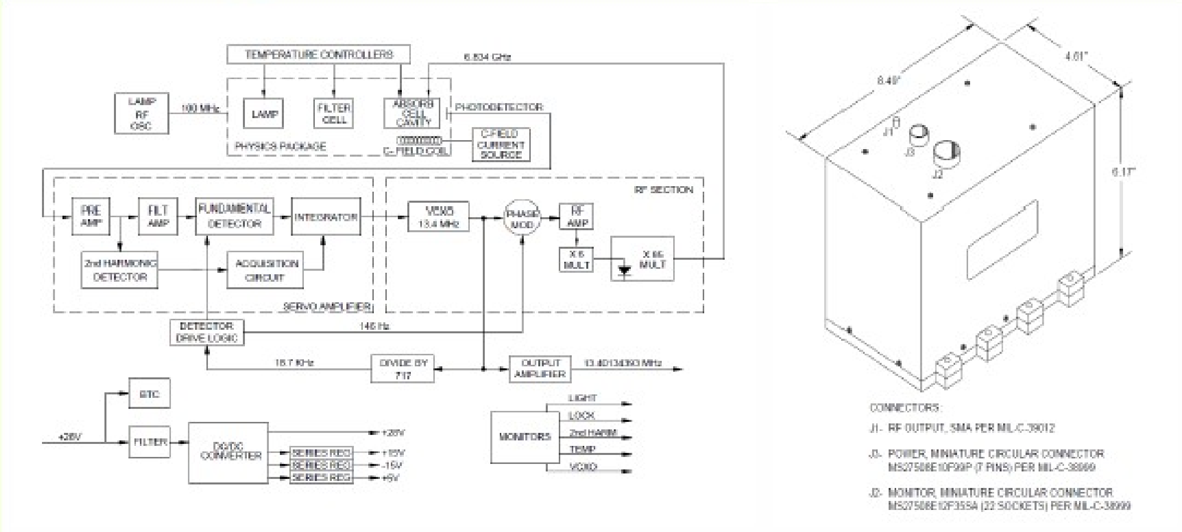


FIGURE 2 Block Diagram/Mechanical



About Excelitas Technologies

Excelitas Technologies is a global technology leader focused on delivering innovative, customized solutions to meet the lighting, detection, energetic, frequency standards and high-reliability power needs of OEM customers.

From aerospace and defense applications to industrial, safety and security, medical lighting, analytical instrumentation, and clinical diagnostics, Excelitas Technologies is committed to enabling our customers' success in their specialty end-markets. Excelitas Technologies has approximately 3,000 employees in North America, Europe and Asia, serving customers across the world.

defense@excelitas.com
www.excelitas.com/Defense

Excelitas Technologies
Energetic Systems
1100 Vanguard Blvd.
Miamisburg, Ohio 45432
USA
Telephone: (+1) 937.865.3800
Toll Free: (+1) 866.539.5916
Fax: (+1) 937.865.5170

Excelitas Technologies
Power Supplies
1330 East Cypress Street
Covina, California 91724 USA
Telephone: (+1) 626.967.6021
Toll Free: (+1) 800.363.2095
Fax: (+1) 626.967.3151

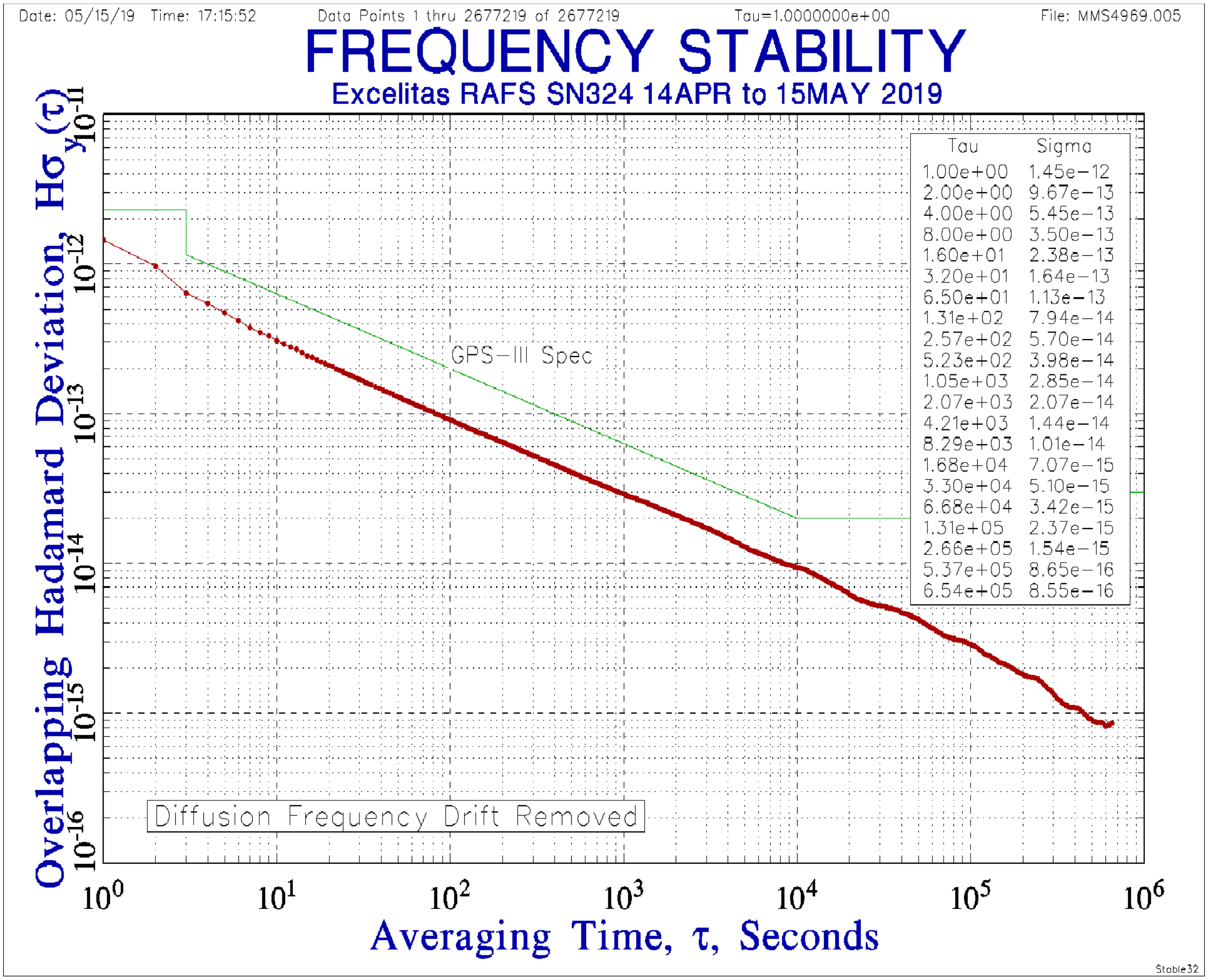
Excelitas Technologies
Frequency Standards
& Switching
35 Congress Street
Salem Massachusetts 01970
USA
Telephone: (+1) 978.745.3200
Toll Free: (+1) 800.950.3441
Fax: (+1) 978.745.0894

Excelitas Technologies
Lighting & Radiant Sources
44370 Christy Street
Fremont, California 94538-3180
USA
Telephone: (+1) 510.979.6500
Toll Free: (+1) 800.775.6786
Fax: (+1) 510.687.1140

Excelitas Technologies
Sensors
22001 Dumberry Road
Vaudreuil-Dorion, Quebec
Canada J7V 8P7
Telephone: (+1) 450.424.3300
Toll Free: (+1) 800.775.6786
Fax: (+1) 450.424.3345

Excelitas Technologies
International Sales Office
Bat HTDS BP 246, 91882
Massy Cedex, France
Telephone: +33 (1) 6486 2824

For a complete listing of our global offices, visit www.excelitas.com/ContactUs



Date: 05/15/19 Time: 17:15:52
Data Points 1 thru 2677219 of 2677219
Tau=1.0000000e+00
File: MMS4969.005
FREQUENCY STABILITY
Excelitas RAFS SN324 14APR to 15MAY 2019
Overlapping Hadamard Deviation, Hσy(τ)
Averaging Time, τ, Seconds
GPS−III Spec
Diffusion Frequency Drift Removed
Tau Sigma
1.00e+00 1.45e−12
2.00e+00 9.67e−13
4.00e+00 5.45e−13
8.00e+00 3.50e−13
1.60e+01 2.38e−13
3.20e+01 1.64e−13
6.50e+01 1.13e−13
1.31e+02 7.94e−14
2.57e+02 5.70e−14
5.23e+02 3.98e−14
1.05e+03 2.85e−14
2.07e+03 2.07e−14
4.21e+03 1.44e−14
8.29e+03 1.01e−14
1.68e+04 7.07e−15
3.30e+04 5.10e−15
6.68e+04 3.42e−15
1.31e+05 2.37e−15
2.66e+05 1.54e−15
5.37e+05 8.65e−16
6.54e+05 8.55e−16
Stable32

1.0 INTRODUCTION

Frequency Electronics, Inc. (FEI) has developed a rubidium atomic frequency standard (RAFS) for precision time-keeping and stable frequency generation for global navigation satellite systems (GNSS). FEI has leveraged its experience from rubidium standards provided to the Milstar constellation and to the Advanced Extremely High Frequency (AEHF) satellite program. A total quantity of 19 rubidium standards were delivered for Milstar and launched starting in 1995. For AEHF 12 rubidium standards have been provided with an additional 9 on order. The first AEHF satellite was launched in August 2010, the second was launched in May 2012 and the third is scheduled for launch in fourth quarter of 2013.

2.0 BLOCK DIAGRAM

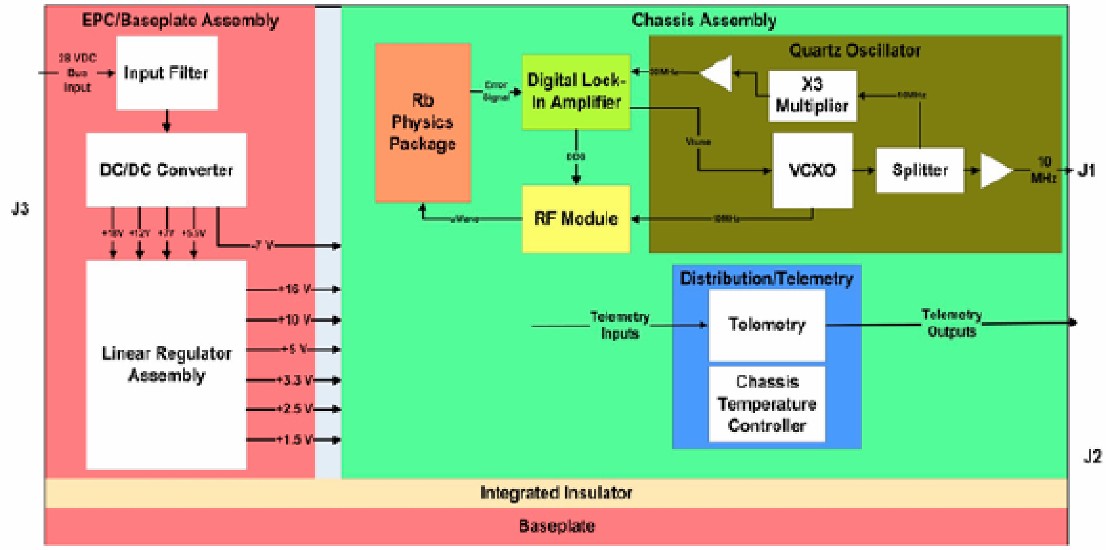
» The RAFS is built in a modular fashion as shown in the below block diagram. The two Major modules are:

- The EPC/ Baseplate Assembly
- The Chassis Assembly

» Both assemblies are mounted within a temperature controlled environment that is thermally isolated from the RAFS baseplate by an integrated insulator. The baseplate temperature controller (BTC) maintains an environment of ±1°C from -34°C to +25°C. In addition, the physics package, VCXO, RF module, and digital lock-in amplifier are designed, built and tested as separate, connectorized modules. This allows for an easy upgrade path to accommodate design changes necessitated by obsolete parts or to incorporate future design improvements.

» Other aspects of the RAFS include:

- Ease of alignment and test
- Optional digital frequency tuning in steps of 10^{-14}



RAFS Block Diagram

3.0 SPECIFICATIONS

RF Output	10.0 MHz or 10.23 MHz Sinewave (other frequencies can be provided) + 18 dBm ± 1.5 dB Harmonics ≤ -50 dBc Spurious ≤ -85 dBc
Analog Monitors	Lock, Light , Signal, VCXO, Baseplate Temperature, Ovens, Power Supplies , ALC, C-Field, BTC
Accuracy	± 1 x 10^{-9} at shipment
Trim Range	None (Fixed C-Field)
Stability σy(τ)	6 x 10^{-13} $\tau^{-½}$ 2 x 10^{-14} (1≤τ ≤ 105 seconds, drift removed)
Drift	≤ 1 x 10^{-13}/day at BOL operation ≤ 3 x 10^{-14}/day after 1 year of continuous operation
Phase Noise, f(f)	-110 dBc/Hz at 1 Hz offset from carrier -138 dBc/Hz at 10 Hz -148 dBc/Hz at 100 Hz -158 dBc/Hz at 1 KHz -160 dBc/Hz floor
Temperature Sensitivity	≤ 2 x 10^{-13}/°C typical w/o BTC, below noise level for ± 1.5°C with BTC
Voltage Sensitivity	≤ 3 x 10^{-12}
Magnetic Sensitivity	≤ 1 x 10^{-12}/Gauss
Barometric Sensitivity	≤ 1 x 10^{-13}/mbar typical
Retrace	≤ 5 x 10^{-12}
Input Power	28.0 VDC ± 4.0 VDC (Available with other bus voltages from 28 to 100 V)
	≤ 39 W total steady-state with BTC (-4 to + 21C)
	≤ 20 W basic clock at +45° C baseplate
	≤ 65 W during warm-up
Warm-up	≤ 1 hour to ± 2 x 10^{-10}
Size (L x W x H)	11.2 x 4.6 x 5.8 in 285 x 117 x 147 mm
Mass	16.5 lbs/7.5 kg
Operating Temperature	Full performance with BTC range between -4°C and +25°C panel temperature. Functional between -20°C to +45°C panel temperature.
Storage Temperature	-34°C to + 71°C
Altitude	Sea level to vacuum
Vibration	12.4g rms, 20 Hz to 2 kHz
Pyroshock	1500 g max to 10 kHz
Acceleration	20 g
Radiation	100 K Rad
EMI	Per MIL-STD-461E
SEE (Single Event Effect)	1 in 1,000 Years
On-Off cycling endurance	≥1000 cycles

4.0 RADIATION HARDENING

» Rad Hard Parts

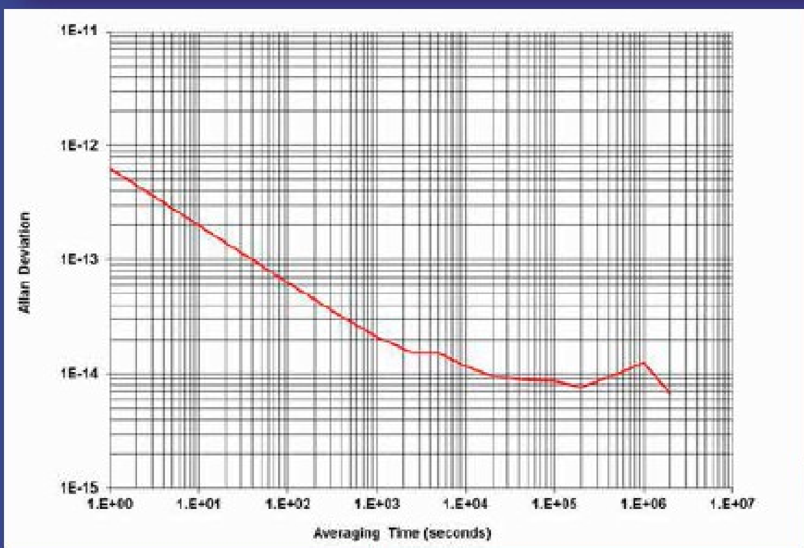
» FPGA

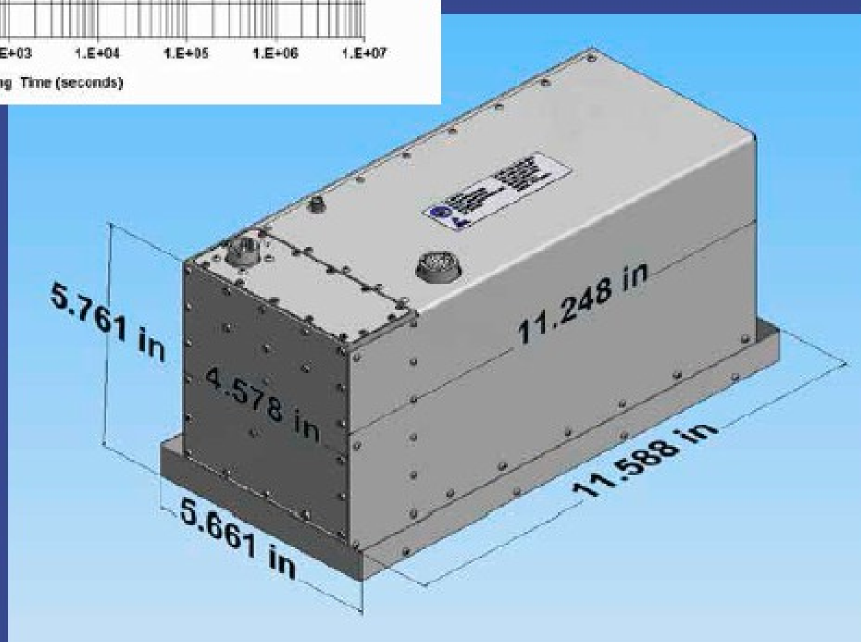
- Frequency setting stored on select resistors connected to input pins (no use of upsetabble memory)
- Fuse programmed (write once)
- Hardware triple redundant logic, with three way voting to minimize single event effects
- Software triple redundant logic with 3 way voting of critical values (digital output to DAC (quartz oscillator control voltage)

» Radiation shields

- Spot shields for critical components

5.0 ALLAN DEVIATION IN VACUUM



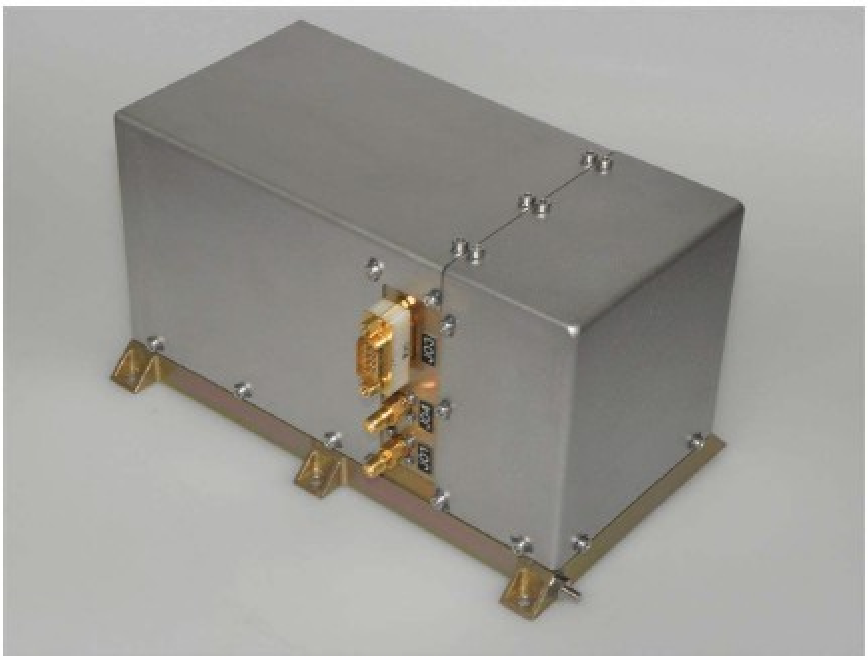


iSpace+™ Space-Qualified RAFS Spec

November 2016 / Rev 3.0

Rubidium Atomic Frequency Standard (RAFS)

High Precision & Performance Source



Applications:

Navigation and Science | Space

sales@spectratime.com
www.spectratime.com

Switzerland Headquarter
+41.32.732.16.66

North America Sales Offices
+1.512.470.3980

Specifications are subject to change without prior notice

An Orolia Group Business

Product Characteristics:

- Volume 2.5 liters
- Thermal sensitivity: -10°C to +15°C : < 2E-14 / °C typical
- Stability < 3E-14 / 10'000sec typical
- Long term stability < $1x10^{-10}$ / year
- Power supply range compatible with 28V or 50V power bus
- Output frequency 10MHz

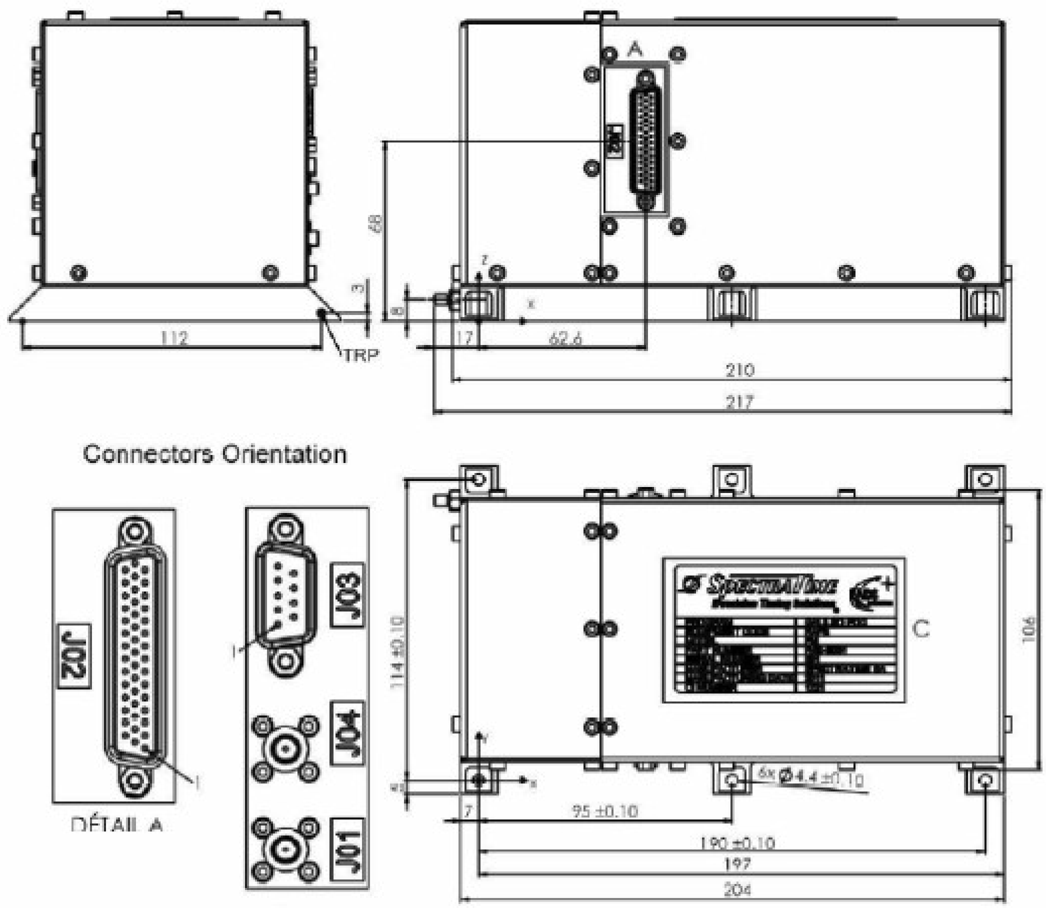
Main Features:

- Very low temperature sensitivity
- Excellent short term stability
- Small volume
- Rb lamp extended life expectancy (>20 years)

Main Applications:

- Navigation satellites
- Space scientific missions
- Military communication satellites
- Tracking and guidance control
- Advanced low orbit digital communication sat.

Package: (all dimensions in millimeters)



Parameter	value	Unit
I/P Main Bus Voltage	0-5	V
Main Bus Current	0-5	V
TCB Temperature	NTC	
EPC Temperature	NTC	
STRUCTURAL & MECHANICAL INTERFACES		
Surface Finish-Flatness		
Overall contact area	< 0.2	mm
Local flatness	< 0.1/100	mm/mm
Roughness	< 3.2	µm
Interconnections		
RF outputs	SMA (J01 + J04)	
TM/TC Interface	SUB-HD 44 (J02)	
Power Interface	SUB-D 09 (J03)	
ENVIRONMENTAL & THERMAL INTERFACE		
Interface Heat Flux	< 0.3	W/cm^2
Power dissipation		
During warm-up	< 60	W
During nominal operation	< 35	W
Temperature limits		
Operating	-5 to +10	°C
Short-term variation	<= ± 1	°C
Acceptance	-10 to +15	°C
Qualification	-15 to + 20	°C
Cold start	-21	°C
Non-operating	-15 to + 70	°C
PRODUCT ASSURANCE		
Reliability figure (MEO)	< 1200	FIT
IN ORBIT ENVIRONMENTS		
Vacuum level	10^{-5}	mbar
Magnetic field	< ± 0.5	Gauss
Radiation Environment.	LEO/MEO/GEO orbits	

RAFS Description

The Rubidium Atomic Frequency Standard (RAFS) is a state-of-the-art ultra-stable atomic clock able to deliver a frequency stability of about 2×10^{-14} over averaging intervals of 10'000 s.

The RAFS unit is composed of two main parts. The clock it-self named "RAFS core" and the Electronic Power Conditioning name "EPC" which includes the DC/DC converter and the electrical interface to the satellite.

The EPC design could be adapted to the satellite need.

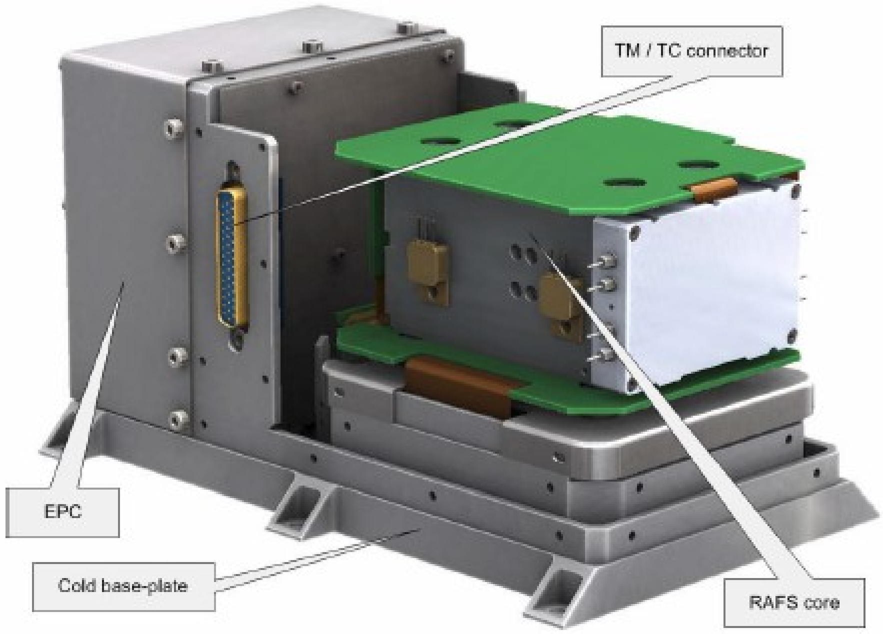


Figure 1: RAFS unit

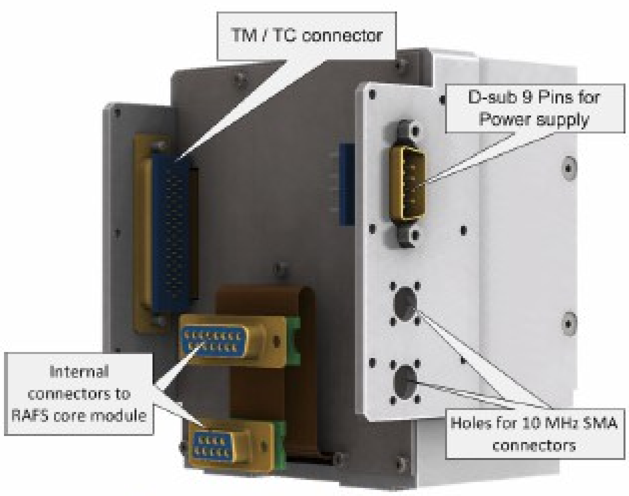


Figure 2: EPC Module housing

RAFS general function and diagram

The RAFS is a Rb clock. The Rb clock essentially consists of a voltage-controlled crystal oscillator (VCXO) which is locked to a highly stable atomic transition in the ground state of the Rb87 isotope. While the frequency of the VCXO is at the convenient standard frequency of 10 MHz, the Rb clock frequency is at 6.834 GHz in the microwave range. The link between the two frequencies is done through a phase-stabilized frequency multiplication scheme whereby a synthesized frequency is admixed to enable exact matching.

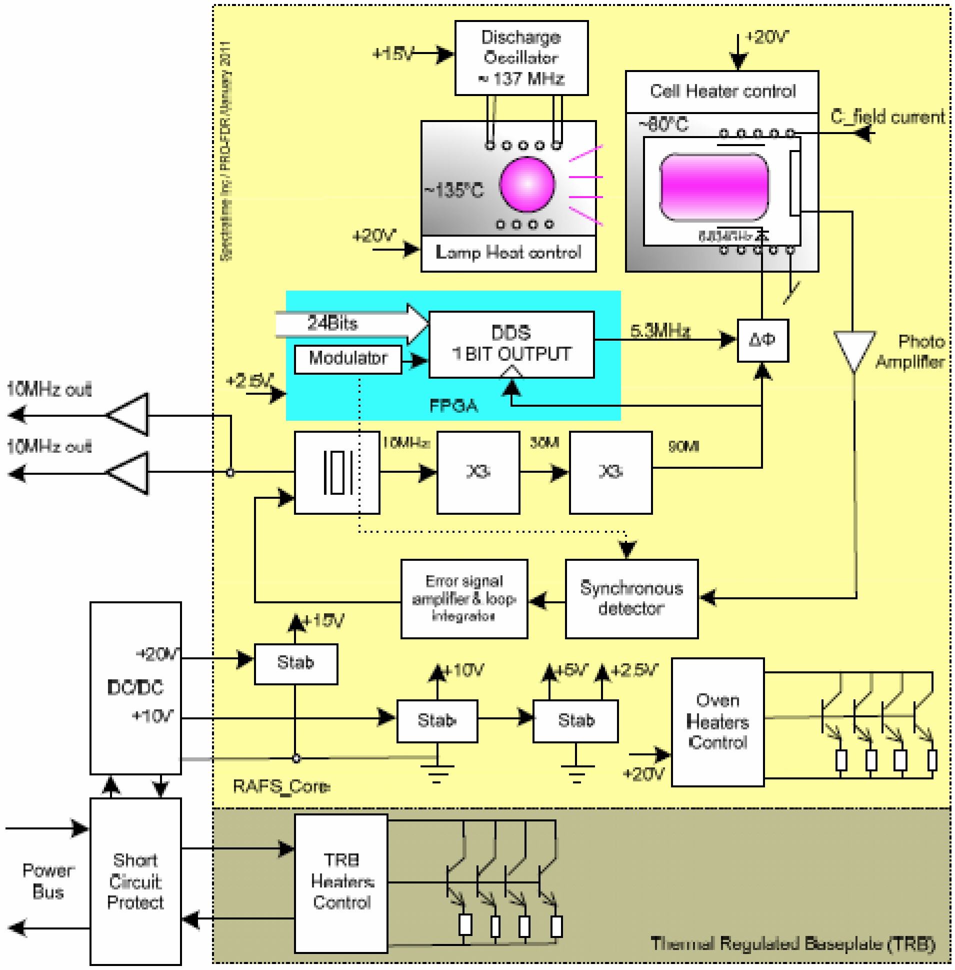
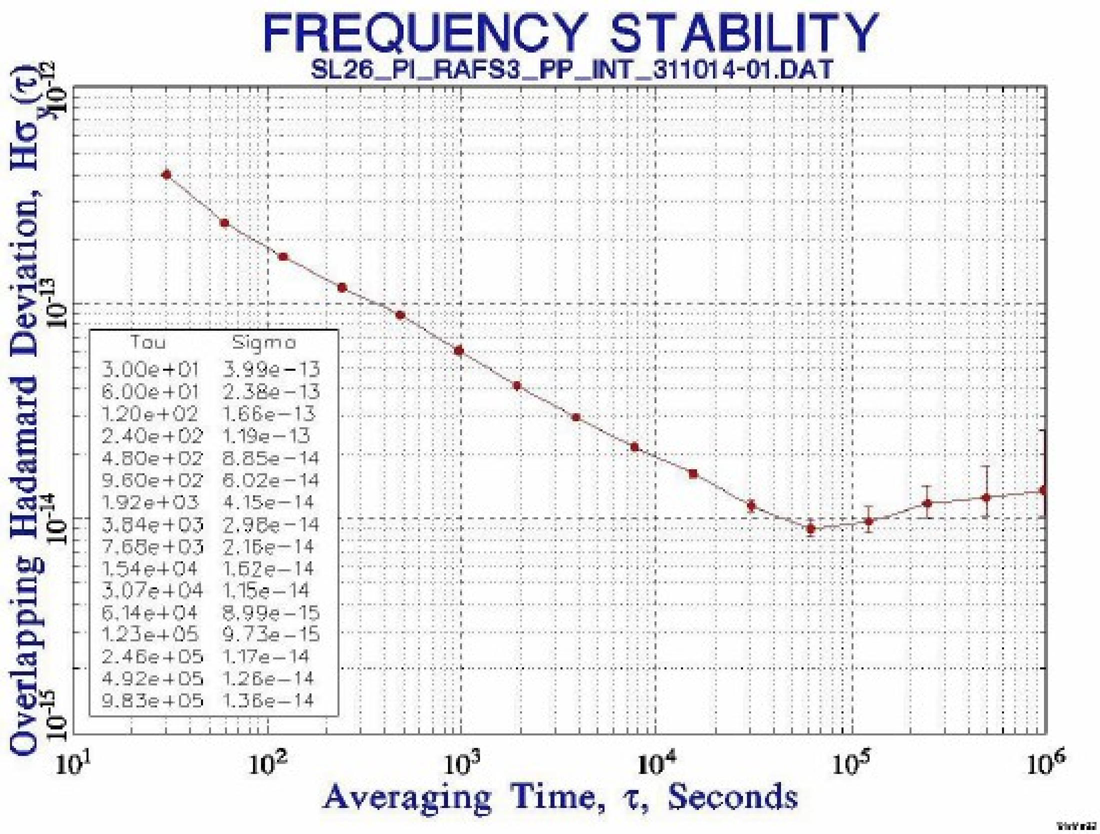


Figure 3: **Overall electrical block diagram**

RAFS typical stability:



File: Selection Criteria for Rubidium Frequency Standards.doc
W.J Riley
Hamilton Technical Services
January 23, 2020