Rubidium Atomic Frequency Standards for GPS Block IIR

William J. Riley
EG&G

BIOGRAPHY

William J. Riley is the Engineering Manager for Rubidium Products at EG&G, Inc. in Salem, MA. His work includes the development and test of rubidium frequency standards and related frequency control products.

Mr. Riley received the BSEE degree from Cornell University in 1962, and the MSEE degree from Northeastern University in 1966. He is a member of the Precise Time and Time Interval Advisory Board, and is a senior member of the IEEE.

ABSTRACT

EG&G, Inc. has been selected to provide the Rubidium Atomic Frequency Standards (RAFS) for the GPS Block IIR NAVSTAR satellites. These satellites will replenish and upgrade the space segment of the Global Positioning System in the mid 1990s. The EG&G GPS RAFS is the latest generation of these high-performance rubidium frequency standards. They offer an aging rate in the low $pp10^{14}$/day range and a drift-corrected 1-day stability in the low $pp10^{14}$ range. The Block IIR version of these devices will have improved performance, higher reliability, smaller size, and greater radiation hardness.

The GPS Block IIR atomic clocks have a "natural frequency" configuration whereby they output a frequency of about 13.4 MHz that is a submultiple of the atomic resonance. The RAFS operates at a low, fixed C-field for increased stability. The unit has been repackaged into a smaller 4.6" x 8.5" x 5.8" outline, but is somewhat heavier (12 lbs.) because of additional radiation shielding. Elimination of the ground tuning logic and the secondary loop synthesizer (with its ovenized crystal oscillator) has reduced the RAFS complexity and improved its reliability to 0.80 for the 7.5-year mission. The RAFS power consumption is only 13 W at +20°C in vacuum.

This paper describes the GPS Block IIR RAFS design, including the changes and improvements made, the test results obtained, and the progress being made as this program enters the production phase.

INTRODUCTION

The GPS Block IIR NAVSTAR satellites will replenish the Rockwell Block II satellites currently being deployed. General Electric Astro Space Division is the prime USAF contractor for this program, ITT Aerospace/Communications Division is the navigation payload subcontractor, and EG&G has been selected to supply the rubidium atomic frequency standards. A major new feature of the Block IIR satellites is crosslink ranging that can be used to exchange clock correction data between satellites without ground segment control, thus providing a high degree of autonomy. Information regarding the EG&G GPS RFS design and performance has been previously reported[1,2,3,4]. This paper updates that information with the Block IIR changes and recent test results[7].

REQUIREMENTS

The requirements for the GPS Block IIR Atomic Frequency Standards are given in the USAF Space Division Technical Requirements Document[5] and the ITT Specification[6]. A summary of those requirements is shown in Table 1. The navigation performance of the GPS system depends critically on the stability of the atomic clocks on board the NAVSTAR satellites. The rubidium frequency standard chosen for the GPS Block IIR application is the high performance unit developed at EG&G especially for this application. This clock has the highest stability of any available device, while also having the practical size, weight, power, reliability, and life advantages of an RFS.

The stability requirements for the Block IIR atomic clocks are shown in Table 2, along with the range error predicted from the measured frequency stability of the EG&G GPS RFS. This high-performance rubidium clock is able to meet the stringent 1- and 14-day autonomous timing requirements.

BLOCK DIAGRAM

The most important new design feature of the Block IIR RAFS is the "natural frequency" approach to integrating the clock and secondary loop synthesizer into a Total Navigation Package. The same synthesis hardware that provides frequency adjustments and selec-

tive availability also converts the Cs or Rb AFS frequency to 10.23 MHz for the navigation payload. This concept eliminates the RFS secondary loop and ground tuning sections, reducing size, weight, power, and complexity, while improving performance, radiation hardness, and reliability.

A block diagram of the RAFS is shown in Figure 1. A voltage controlled crystal oscillator (VCXO) provides the output via an amplifier and crystal filter. The VCXO also excites the Rb physics package via an rf multiplier chain. A servo amplifier processes the discriminator signal from the physics package to lock the VCXO to the Rb resonance. A lamp exciter, C-field source, and temperature controllers support the physics package operation. A power supply operates the unit, while monitor signals indicate the RAFS status. This arrangement is a simplified "natural frequency" configuration that eliminates the secondary loop synthesizer and ground tuning interface by operating the unit at fixed, low C-field and outputting an exact submultiple of the Rb atomic frequency.

PHYSICS PACKAGE

The GPS Block IIR RAFS physics package design is based on classical rubidium gas cell frequency standard principles. This approach gives the highest performance consistent with allowable size. The discrete isotopic filter cell gives zero light shift (ZLS) over a range of light intensity and a high S/N ratio. This permits operation at a relatively low light level, thus reducing temperature and rf power dependencies. The characteristics of the lamp, filter, and absorption cells are described in Reference 1. The lamp operates in the Kr-Rb mixed mode and is excited with 0.45 W of rf power at 105 MHz. The lamp output is free from self-reversal. Lamp life is assured by tight heat sinking, alkali resistant glass, high vacuum processing, small envelope surface area, and calorimetric measurement of rubidium fill.

The filter cell operates in a separate oven whose temperature is adjusted for ZLS. The filter cell buffer gas and pressure are chosen to give optimum signal and lowest temperature coefficient (TC).

The absorption cell buffer gases are chosen for narrow linewidth and low TC. The mix ratio is adjusted for a slightly positive TC to partially compensate for the filter cell TC. The nominal fill pressure is determined by the 13.40134393 MHz output frequency, and is sufficient to reduce the wall relaxation rate without excessive buffer gas collisional broadening. The absorption cell length is optimized for maximum signal at the chosen light intensity and temperature, the latter being the coolest practical for operation at a baseplate temperature of $+50°C$.

A cross-sectional view of the GPS Block IIR RAFS physics package is shown in Figure 2. The three ovens are supported by a fiberglass structure that makes effective use of the vacuum environment for thermal insulation. The low thermal conductivity mounting and leads, and low emissivity ovens, reduce heat losses so that the entire physics package requires only 1.8 W of oven power under normal operating conditions.

A lens is used to collimate the lamp output and provide a uniform light distribution. A two-section C-field coil configuration is used to provide a uniform magnetic bias field. The absorption cell is well-bonded to its oven to avoid temperature gradients, and sapphire oven windows are used for high thermal conductivity. These features help to ensure a homogeneous absorption line. Precisely registered, thin, double-layer foil oven heaters are used to provide a low residual magnetic field.

The microwave cavity is excited with an E-probe and has slotted end covers that support the desired TE_{111} mode while allowing light transmission without significant microwave leakage. The SRD multiplier is mounted against the cavity and shares its stabilized thermal environment. The physics package includes two 0.025 inch Hipernom cylindrical magnetic shields.

ELECTRONICS

The RAFS electronic circuits determine, to a large extent, the overall frequency stability that is achieved.

Temperature Controllers: The temperature controllers are dc thermistor bridges and dissipative regulators, with static thermal gains of about 2000. The oven demand power is determined by the 1-hour warmup requirement. Vacuum conditions not only reduce oven losses, but also raise the thermal gains and servo stability margins.

Lamp Exciter: The lamp exciter is a Clapp rf power oscillator with the Rb lamp located inside the series-tuned coil. The lamp network presents a range of loads as a function of lamp mode, and the circuit has been characterized under these various conditions to ensure proper operation. Starting may require the exciter to redistribute condensed rubidium inside the lamp by rf induction heating. Ignition takes place when sufficient voltage exists across the lamp coil. The running condition is stabilized against environmental changes and supply ripple by a current regulator circuit.

Preamplifier: The photodetector preamplifier is a one-stage configuration with dc and ac transimpedances of 100 kΩ and 5 MΩ, respectively. The ac gain is broadly peaked at the fundamental modulation frequency. The signal-to-noise ratio (S/N) and stability of the RAFS are determined primarily by the strength

of the Rb discriminator signal and the level of white frequency noise. The latter is predominantly due to shot noise at the photodetector, and VCXO phase noise at twice the servo modulation frequency (see below). The dominant source of preamplifier noise is op amp input voltage noise flowing through the shunt resistance of the photodetector, and, because of the low leakage of the EG&G photodiode, this noise contribution is small.

S/N data for the GPS Block IIR RAFS are as follows:

DC Photocurrent	100 μA
Shot Noise	5.7 pA/$\sqrt{\text{Hz}}$
Op Amp Noise	0.9 pA/$\sqrt{\text{Hz}}$
Total Preamp Noise	5.8 pA/$\sqrt{\text{Hz}}$
Preamp Noise PSD	5.8×10^{-24}Hz^{-1}
VCXO Noise PSD	5.8×10^{-24}Hz^{-1}
Discriminator Signal	240 pA per 1×10^{-10}
Predicted Stability	$2.4 \times 10^{-12}\tau^{-1/2}$
Measured Stability	$2.8 \times 10^{-12}\tau^{-1/2}$
(Including reference noise)	

Magnetic Bias Supply: The magnetic bias supply is an active current source that operates the Rb physics package at a low, fixed C-field to minimize its magnetic dependence. The reference voltage for the C-field supply is derived from a precision low-TC, rad-hard zener diode.

RF Chain: The rf multiplier chain consists of a 13.40134393 MHz VCXO, a phase modulator, a diode tripler, a push-push doubler, and a x85 step recovery diode (SRD) multiplier. The low noise of the Rb reference permits a tight lock loop that allows the use of a low-complexity, nonovenized crystal oscillator. An ALC loop is used to maintain constant drive to the SRD multiplier. This approach gives high stability and spectral purity with minimum complexity. Particular care is taken to avoid frequency offsets caused by AM and PM modulation distortion. A pure modulation waveform is generated by passive integration of a precision squarewave, and highly linear phase modulation is obtained by applying small excursions to a hyperabrupt varactor diode in an all-pass phase modulator configuration.

VCXO phase noise at $2 \cdot f_{mod}$ from the carrier (where f_{mod} is the servo modulation frequency), 146 Hz, can degrade the overall RAFS stability[8]. The measured value of the VCXO phase noise, $\mathcal{L}(292\text{Hz}) = -142$ dBc/Hz contributes a non-negligible but tolerable $1.2 \times 10^{-12}\tau^{-1/2}$ to the RAFS instability.

A new feature of the Block IIR design is the inclusion of a high-Q helical resonator rf bandpass filter ahead of the SRD multiplier. This greatly improves the spectral purity and helps to avoid frequency offsets due to spurious components on the microwave spectrum. The SRD multiplier uses a low capacitance diode in a shunt mode with an external dc bias resistor that is used to adjust the microwave power level to the optimum value.

RF Output Amplifier: The rf output amplifier must not only provide the +18 dBm, low-distortion RAFS output, but must also maintain a phase-continuous output under transient radiation. During transient radiation, the active devices of the VCXO and output amplifier are subject to upset. Short-term (≤ 1 μsec) flywheeling is provided by the LC output tank. Medium-term (≤ 100 μsec) flywheeling is provided by a crystal bandpass filter ahead of the output stage. The output stage recovers before the energy in its tank is dissipated. The VCXO crystal resonator itself keeps vibrating during the radiation, and the VCXO circuit recovers within the ringing interval of the crystal filter.

Power Supply: The power supply consists of an input filter, a dc/dc converter, and three linear regulators. The dc/dc converter uses a single-ended flyback configuration that provides both dc isolation and regulation. The +28 V output is used directly as the heater supply while the +5 and ± 15 V supplies are further stabilized by precision linear regulators before supplying the logic and analog circuits. Under normal operating conditions in vacuum, the RAFS circuits consume under 10 W. The total dc input is 33 W demand during warmup and 13 W steady-state at +20°C baseplate.

MECHANICAL PACKAGING

The RAFS outline is shown in Figure 3. The height was reduced by about one inch by eliminating the secondary loop and ground tuning circuitry, and particularly by the removal of the large ovenized secondary loop crystal oscillator. The length and width were increased slightly because of the addition of tantalum covers on the four sides for radiation shielding. The number of mounting feet was increased from four to eight, and the command/monitor connector was changed to a smaller size.

Packaging Layout: The RAFS packaging is shown in Figure 4. The outer magnetic enclosure and the side and top covers have been removed in the right photograph to expose the electronic boards and other subassemblies in cavities of the chassis. The primary objectives in this packaging design are ruggedness, thermal transfer, access for assembly and inspection, EMI shielding, radiation shielding, and light weight.

The main chassis provides the thermal and structural interface for the various assemblies and printed circuit boards (PCBs). It is a one-piece, machined aluminum box-like structure with a solid baseplate and

four vertical walls. The walls have integral stiffening ribs/partitions that form compartments on the outer surfaces. There are ten PCBs mounted in these compartments. The boards are located around the structure to minimize the length of wiring runs and crosstalk. The partitions between the compartments stiffen the wall, provide EMI shielding between the PCBs and provide a mounting surface for heat sinks for components with high power dissipation.

The four walls of the chassis form a central cavity that contains several assemblies. The physics package is mounted at the bottom on the baseplate of the structure. The lamp exciter and helical resonator assemblies are attached to the physics package before installation into the structure. The electrical connections are made with nonmagnetic semi-rigid coaxial cables. The rf output connector is located on the structure wall so that it protrudes directly into the output amplifier compartment.

Filter boxes are mounted at the power and monitor connectors to eliminate radiation to or from exposed leads. EMI gaskets are used under the connector flanges. All leads pass through feedthrough filter capacitors, and the assembly is located near the power supply to minimize exposed lead length. There are also feedthrough filter capacitors in partitions in the chassis where needed for EMI suppression. The electronic compartments have aluminum covers fastened against the chassis with closely spaced screws for containment of electromagnetic radiation. The four sides and the top also have covers of tantalum for nuclear radiation shielding. An outer magnetic enclosure is used to provide additional magnetic shielding.

RADIATION HARDENING

Radiation hardening is a critical aspect of the GPS Block IIR RAFS requirements, and one that has received much attention during the design effort. The RAFS design has undergone detailed radiation hardening analysis by GE, with the assistance of EG&G, GE, ITT, and JAYCOR. Critical parts and subassemblies have also been subjected to radiation testing. In particular, the Rb physics package has been subjected to total gamma dose testing, and the complete RAFS has been subjected to transient radiation testing. The analysis of the RAFS response to transient radiation used the Kenschaft model for the Rb physics package[9]. This analysis and test have shown that the design can meet the stringent clock performance requirements under both the natural and manmade radiation environments.

RELIABILITY

The predicted MTBF of the overall GPS Block IIR RAFS is 298,000 hours, and 348,000 hours excluding those components (such as monitors) that do not contribute to a mission failure. This corresponds to reliability values of 0.80 and 0.83, respectively, for a single Rb clock over the 7.5-year mission duration. Each satellite is expected to have one active and one hot-standby rubidium clock, and one cesium clock as a cold-standby unit.

TEST RESULTS

Two more GPS RFS prototype units (S/Ns 3 and 4) were built as part of the GE proposal effort. These units have the original mechanical configuration, but incorporate the changes associated with the 13.4 MHz "natural frequency" approach. In addition, a Brass-board model of the Block IIR design (see Figure 4) was built and subjected to qualification-level testing. All the EG&G GPS RFS/RAFS units show excellent performance that exceeds the Block IIR requirements.

Stability: All of these RFS units have consistently shown drift-corrected Allan variance stabilities at or below $\sigma_y(\tau) = 3 \times 10^{-12} \tau^{-1/2} + 1.5 \times 10^{-14}$ when measured against the NRL hydrogen maser. One-day stabilities in the high 10^{-15} range are typical. An example of a recent NRL 107-day stability run at constant temperature for S/N 3 is shown in Figures 5–7[10]. The stability is about 10^{-14} between 10^5 and 10^6 seconds. The higher level of white FM at shorter averaging times is due to the measuring system.

Aging: The GPS RFS units have shown aging $\leq 5 \times 10^{-14}$/day. The aging is always negative, tends to decrease gradually with undisturbed operating time, and is consistently smooth and highly modelable.

Temperature Stability: The average TCs of S/Ns 3 and 4 were measured at EG&G to be about -0.7×10^{-13}/°C and $+0.4 \times 10^{-13}$/°C, respectively, over a baseplate temperature range from +20°C to +45°C. S/N 4 was then re-optimized for operation from +15°C to +20°C, where it displayed an average TC of about $+0.6 \times 10^{-13}$/°C. The RAFS Brassboard unit has a TC of -0.8×10^{-13}/°C. The steady-state TC is always smooth, hysteresis-free, and quite modelable.

A test was conducted to measure the clock error caused by orbital temperature variations. S/N 4 was subjected to a +15°C to +20°C triangular temperature profile having a 12-hour period. The resulting time error was about ±2 nsec, well within the operational requirements.

Power: The steady-state power versus temperature characteristic of EG&G GPS RFS S/N 4 was measured as a function of baseplate temperature from −15°C to +35°C. The power was 12.6 W at +20°C and varied by about −50 mW/°C.

Retrace: A series of power on/off retrace tests were

conducted on S/N 1 at NRL. This 58-day test included 4 retrace cycles, with off periods from about 2 to 10 days. This retrace record is unique because it is the only such record known for an RFS of such high stability against such a high stability reference. The measurement noise is therefore very low, even in relation to the low retrace values. The retrace record is also interesting in that the RFS frequency seems to "freeze" during the off period. This indicates that the dominant aging mechanism depends on elevated internal operating temperature. The most likely such mechanism is redistribution of rubidium within the lamp. This process would indeed literally "freeze" while the unit was off.

The retrace behavior of the unit was excellent, ranging from essentially zero (for 2 days off) to about 3×10^{-13} (for 10 days off). These results are consistent with similar retraces conducted on GPS RFS S/N 2 as part of a total gamma dose physics package radiation test (see below). This RAFS design easily complies with the 5×10^{-12} retrace requirement, and the warm-up time required to achieve this retrace is less than the 3 days specified.

Qualification Tests: A series of qualification-level tests, including shock, random vibration, temperature, temperature cycling and EMI, were successfully conducted on the RAFS brassboard unit. All requirements were met[11].

Radiation: A total gamma dose radiation test was conducted on the RAFS physics package. The objective of the test, conducted jointly by EG&G Frequency Products and GE Astro Space, was to determine the effects of total dose gamma radiation on the frequency, photodetector current, and other characteristics of the high-performance Rb physics package. Most of all, the test was run to rule out any unexpected effects. Measurements were made before and after doses of 7, 21, and 70 krads(Si) of gamma radiation from a Co^{60} cell. No significant frequency shifts or other changes in performance were observed within the limit of about 1×10^{-11} set by the drift and retrace effects (primarily due to the disassembly and reassembly of the RAFS before and after each irradiation). Since these exposures represent x1, x3, and x10 of the total dose expected from natural radiation during the 7.5-year life of the GPS satellite, during which the RAFS can be expected to have a total frequency shift of about 1×10^{-10}, this test has confirmed that the effect of the radiation on the Rb physics package is negligible.

The Block IIR RAFS brassboard unit was subjected to a series of transient radiation tests at the GE Flash X-Ray (FXR) facility. The silicon photodiode in the Rb physics package is a sensitive radiation detector which, when exposed to a transient radiation pulse, can over-load the servo amplifier circuits and cause a large disturbance to the VCXO. This behavior can be simulated by exposing the photodetector to a light pulse from a xenon flashlamp. A means was devised to disable the servo circuits until they recovered, thus avoiding any significant time error. The wide servo bandwidth (≈ 45 Hz) assures rapid correction of the VCXO frequency error. Excellent agreement was obtained between the analysis, flashlamp simulations, and the actual FXR tests.

BASEPLATE TEMPERATURE CONTROL

It is likely that a Baseplate Temperature Controller (BTC) will be added to the RAFS design to further enhance its performance. The RAFS temperature coefficient, although low ($\leq 2 \times 10^{-13}/^\circ C$), when combined with the expected S/V orbital temperature variations (2-3°C) results in a significant reduction in clock stability. A simple, single-setpoint BTC can be added within the present RAFS outline dimensions (plus a thin thermal insulator between the clock and S/V panel). This BTC can stabilize the RAFS baseplate temperature by a factor of about 100, thus reducing the effects of S/V temperature variations to below the noise. A BTC having a setpoint of +45°C and an insulator with a thermal conductance of 0.7W/°C can stabilize the RAFS over a 0°C to +25°C range with a maximum additional power dissipation of 18 Watts.

PROGRAM STATUS

The development phase of the GPS Block IIR RAFS program is complete, and the program is entering its production phase. Brassboard testing is complete, and fabrication of an Engineering Development Model is underway. Work is also underway on the design of the baseplate temperature controller. GPS Block IIR Rb clock deliveries are scheduled to begin in July 1993.

ACKNOWLEDGMENTS

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TABLE 1   KEY REQUIREMENTS
GPS BLOCK IIR RUBIDIUM ATOMIC FREQUENCY STANDARD (RAFS)

PARAMETER	REQUIREMENT
Frequency	13.40134393 MHz (Nominal)
Frequency Offset	$\pm 1 \times 10^{-9}$ (Initial Tolerance Limits)
Frequency Adjustment	None (Fixed C-Field)
Frequency Drift	$\pm 5 \times 10^{-14}$/Day (Maximum after 30 Days)
Frequency Stability	$3 \times 10^{-12} \tau^{-1/2} + 5 \times 10^{-14}$ (Maximum Sigma)
Temperature Stability	$\pm 2 \times 10^{-13}$/°C (Average over 0 to +25°C)
Output Power	+18 dBm ±1.5 dB
Harmonics	−50 dBc
Phase Noise	$\mathcal{L}(1 \ \text{Hz}) = -85$ dBc/Hz
	$\mathcal{L}(1 \ \text{kHz}) = -90$ dBc/Hz
DC Power	50 Watts (Maximum during Warmup)
	14 Watts (Maximum SS at +20°C in Vacuum)
Size	5.0″ x 8.5″ x 7.0″ (Maximum)
Weight	12 lbs. (Maximum)
Reliability	0.755 for 7.5 years (Minimum)
Life	7.5 years (Minimum)
Survivability	± 2 nsec (Maximum Prompt Time Error)
	−2 dB (Maximum Prompt Output Level Change)
	2.6 meters (Maximum URE for 24 Hours)
	36.3 meters (Maximum URE for 14 Days)

Note: The detailed requirements for the GPS Block IIR RAFS
are given in ITT A/CD Dwg. No. 1527179.

TABLE 2   GPS BLOCK IIR CLOCK STABILITY REQUIREMENTS

INTERVAL	CLOCK ERROR, nsec	
Days	REQUIREMENT	PREDICTED
1	8.7	2.5
14	121.0	33.0
180	8.7	Dependent On Crosslink Ranging

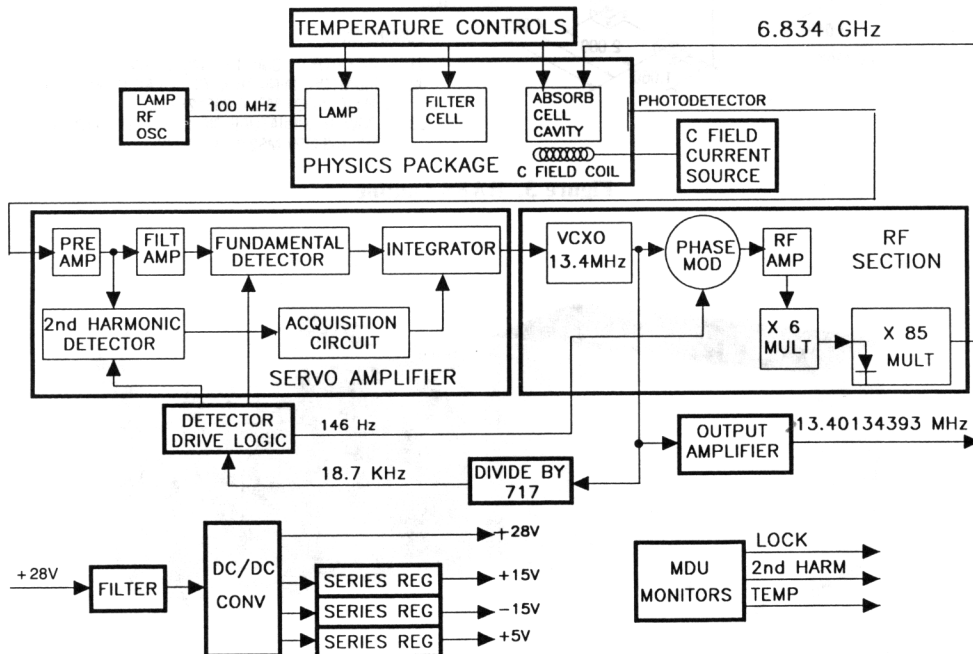Note: Predicted time error based on measured drift-corrected RAFS stability

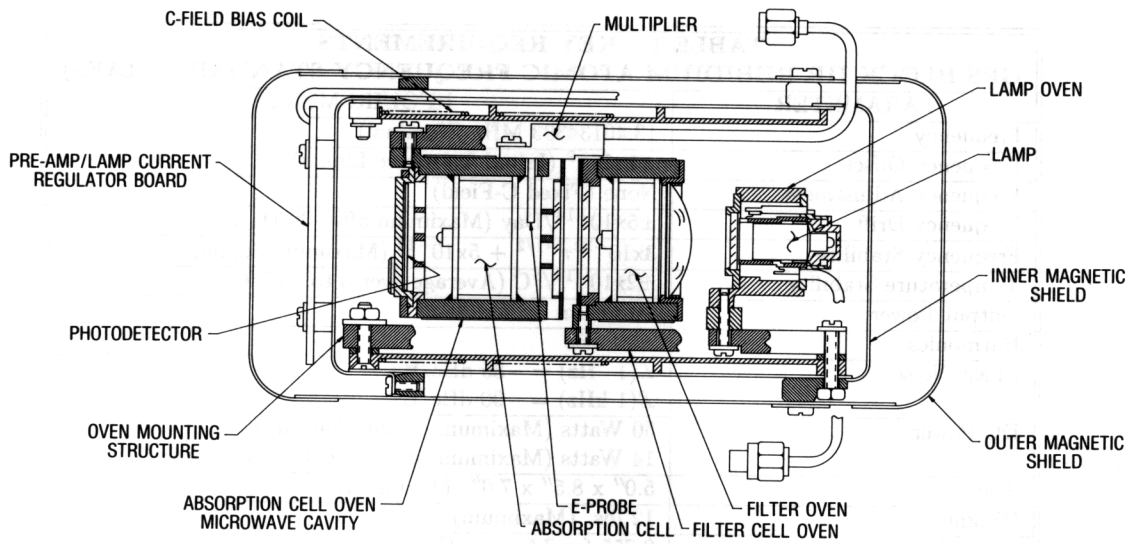Figure 1. Block Diagram of GPS Block IIR RAFS.
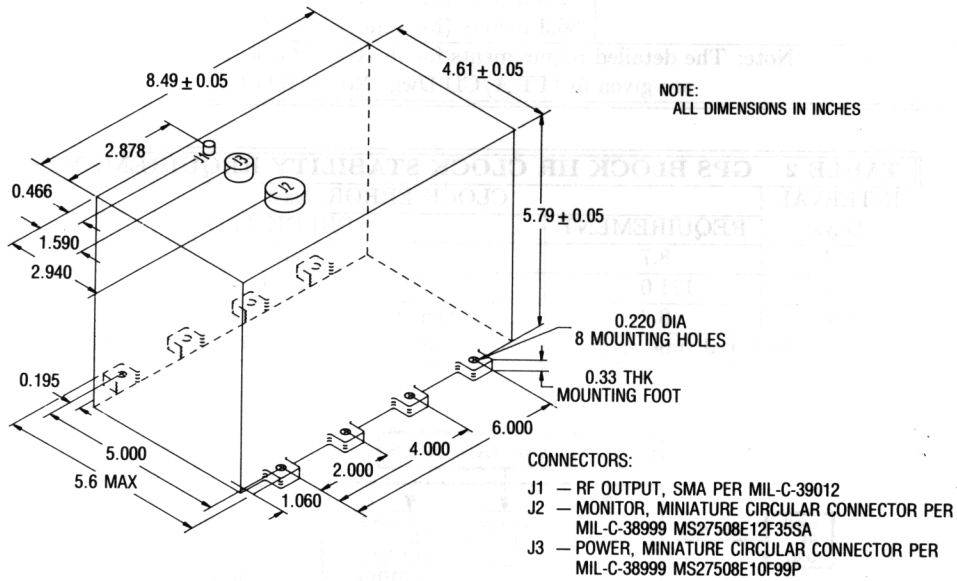
Figure 2. Physics Package Cross-Section.

C-FIELD BIAS COIL
MULTIPLIER
LAMP OVEN
LAMP
PRE-AMP/LAMP CURRENT REGULATOR BOARD
INNER MAGNETIC SHIELD
PHOTODETECTOR
OVEN MOUNTING STRUCTURE
OUTER MAGNETIC SHIELD
ABSORPTION CELL OVEN MICROWAVE CAVITY
E-PROBE
ABSORPTION CELL
FILTER OVEN
FILTER CELL OVEN

NOTE: ALL DIMENSIONS IN INCHES

8.49 ± 0.05
4.61 ± 0.05
2.878
0.466
5.79 ± 0.05
1.590
2.940
0.220 DIA 8 MOUNTING HOLES
0.33 THK MOUNTING FOOT
0.195
6.000
5.000
4.000
5.6 MAX
2.000
1.060

CONNECTORS:
J1 — RF OUTPUT, SMA PER MIL-C-39012
J2 — MONITOR, MINIATURE CIRCULAR CONNECTOR PER MIL-C-38999 MS27508E12F35SA
J3 — POWER, MINIATURE CIRCULAR CONNECTOR PER MIL-C-38999 MS27508E10F99P

Figure 3. RAFS Outline.

Figure 4. Photographs of GPS Block IIR RAFS.

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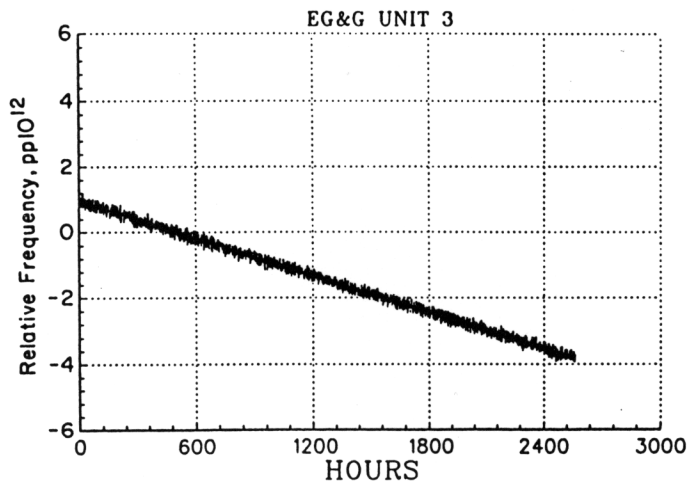
FREQUENCY DATA

Figure 5. S/N 3 Frequency Record.
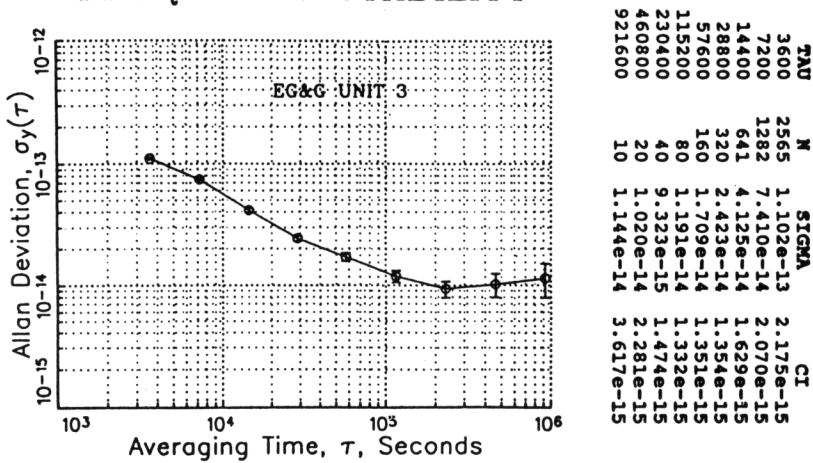
FREQUENCY STABILITY

TAU	N	SIGMA	CI
3600	2565	1.102e-13	2.175e-15
7200	1282	7.410e-14	2.070e-15
14400	641	4.125e-14	1.629e-15
28800	320	2.423e-14	1.354e-15
57600	160	1.709e-14	1.351e-15
115200	80	1.191e-14	1.332e-15
230400	40	9.323e-15	1.474e-15
460800	20	1.020e-14	2.281e-15
921600	10	1.144e-14	3.617e-15

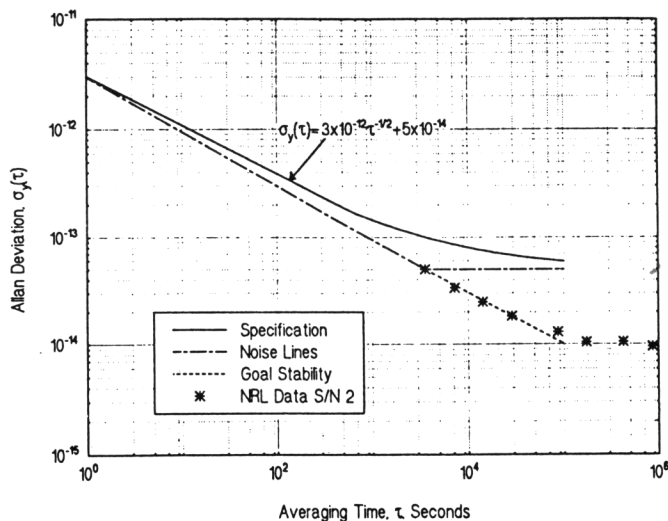**Figure 6. S/N 3 Stability.**

$$\sigma_y(\tau) = 3\times10^{-12}\tau^{-1/2} + 5\times10^{-14}$$

Figure 7. RAFS Stability Requirements.