RUBIDIUM FREQUENCY STANDARD FOR THE GPS IIF PROGRAM AND MODIFICATIONS FOR THE RAFSMOD PROGRAM

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Abstract

PerkinElmer provides the Rubidium Frequency Standards (RFS) for the Boeing Block IIF GPS navigation satellites. The PerkinElmer RFS-IIF is the latest generation of its high performance rubidium clocks which have performed very successfully on board the Block IIR GPS space vehicles for more than 10 years.

The RFS-IIF output is the traditional 10.23 MHz rather than the ≈13.4 MHz "natural frequency" utilized for Block IIR. This necessitated the addition of a secondary phase lock loop (PLL) synthesizer to convert the Rb natural frequency to 10.23 MHz. One main design challenge was to add this new section with a minimum impact on size, weight, power, performance, radiation hardness, reliability and design heritage.

The second major change in the RFS-IIF was to make a significant improvement in the medium to long term stability by using Xenon lamp buffer gas and a thin-film spectral filter in the physics package to reduce shot noise and improve the signal-to-noise ratio (S/N). This has lowered the white FM noise level to below $1x10^{-12}\tau^{-1/2}$.

This paper describes the RFS-IIF design, the changes and improvements made, and the test results obtained. It also discusses the recent redesign activities to eliminate obsolete parts in the RFS-IIF as well as improvements and updates to the PerkinElmer test facility funded by the USAF GPS Wing (GPSW) under the Rubidium Atomic Frequency Standard Modification (RAFSMOD) Program.

Introduction

The Lockheed Martin GPS Block IIR and IIR-M replenishment satellites are approaching full deployment. PerkinElmer built 66 RAFS-IIR units for the Block IIR program [1, 2, 3], which uses that single type of atomic clock. The PerkinElmer RAFS-IIRs are quickly approaching a total of 80 years of on-orbit operation with one clock approaching 11 years of continuous operation.

The GPS Block IIF satellites will follow [4]. Boeing is the prime USAF contractor for the IIF Program. The Block IIF GPS satellites are expected to use a mix of rubidium and cesium standards. The current plan is to fly two (2) PerkinElmer rubidium standards and one (1) cesium standard. A PerkinElmer RFS is expected to be selected as the primary operating standard due to its high performance and proven reliability.

Requirements

Except for the 10.23 MHz output frequency, the requirements for the RFS-IIF are nearly identical to those of Block IIR. The PerkinElmer high performance rubidium clock is able to meet the stringent stability requirements with a margin of nearly an order-of-magnitude over most of the specification range.

Block Diagram

A block diagram of the RFS-IIF is shown in Figure 1. The most important changes are the inclusions of the secondary loop synthesizer and the Xenon lamp and thin film spectral filter in the physics package. The secondary loop synthesizer was not required for the PerkinElmer design used on Block IIR satellites. The RFS-IIF is, however, similar to the original PerkinElmer, Block I RFS described in Reference [5] which never went into production.

Physics Package

The Rb physics package of the RFS-IIF (see Figure 2) is essentially unchanged from its IIR heritage except for the use of a Xe lamp buffer gas and the inclusion of a thin-film optical interference filter. This filter passes both Rb D-lines while blocking essentially all of the buffer gas emissions. This change (from an unfiltered Kr lamp) provides a significant improvement in stability by both raising the rubidium error signal and lowering the shot noise. PerkinElmer has used this technique in its line of tactical rubidium frequency standards for many years, and it is, therefore, based on proven theoretical and experimental grounds. In the GPS physics package, the underlying white FM noise level was reduced from slightly above $2x10^{-12}\tau^{-1/2}$ to below $1x10^{-12}\tau^{-1/2}$. In an operating clock this stability improvement extends from averaging times of 100 seconds to about one (1) day, an interval of prime importance to the GPS system. An improvement at short averaging times, one (1) second to approximately 100 seconds, is not realized because it is obscured by the PLL required to synthesize the 10.23MHz output frequency.

The improved physics package will also be used in the 13.4MHz output frequency version of the PerkinElmer RAFS which is referred to as an Enhanced RAFS or ERAFS.

Electronics

The primary loop electronic design of the RFS-IIF is nearly identical to the IIR unit, as described in Reference [1].

Primary Loop Servo

The RFS-IIF (or ERAFS) physics package produces a significantly stronger discriminator signal than the IIR physics package design. This affects the gain of the primary frequency lock loop and impacts the primary loop servo design. An analysis of the servo was performed including the effects of the switching synchronous detector. The results agreed very well with the actual observed loop dynamics. The lag-lead post-integration filter was revised to maintain stability with the higher discriminator signal produced by the physics package.

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Secondary Loop Synthesizer

The RFS-IIF includes a new secondary loop synthesizer comprised of a pair of frequency dividers and a phase locked crystal oscillator, as shown in the block diagram of Figure 3.

The main objective of the synthesizer design was to provide the 10.23MHz output while maintaining the primary loop stability to the greatest extent possible. This is not a "clean-up" loop, but one having the widest possible bandwidth and fastest response to preserve the primary loop stability to the greatest extent possible and recover quickly from transient radiation.

The synthesizer uses a pair of dividers (÷3051 and ÷2329) to scale the primary and secondary loop VCXO frequencies to a common submultiple of about 4.39 kHz (which is further divided to the 137 Hz servo modulation rate). These numbers give a primary loop frequency and absorption cell frequency (fill pressure) that is very close to that used in the Block IIR RAFS.

Considerable effort went into the design and modeling of the digital phase-frequency detector. While similar circuits are widely used, they are not so widely understood. The dependence of the transfer function on static phase error was of particular interest. This effect is caused by the variation in the sampling time, and is particularly important when a static phase error is deliberately added to avoid the phase detector dead zone.

Mechanical Packaging

The RFS-IIF is packaged identically to its Block IIR predecessor except for the addition of a 2.4-inch section at the center to house the new secondary loop synthesizer. An outline drawing of the RFS-IIF is shown in Figure 4. A photograph displaying the RAFS-IIR and RFS-IIF is shown in Figure 5.

Baseplate Temperature Controller

The RFS-IIF design, like its Block IIR predecessor, includes an integral baseplate temperature controller (BTC) to stabilize its entire chassis temperature at +45°C. A thermal insulator placed between the mounting surface of the RFS and the space vehicle limits and optimizes the heater power required. Experience has shown that there are several important advantages to including baseplate temperature control in a space clock design. Not only is the thermal stability improved, but the known operating temperature allows performance optimization and testing to be concentrated at this one condition. The RFS-IIF has a temperature coefficient of $\leq 2 \times 10^{-13}$/°C without the benefit of the BTC. The BTC improves the temperature coefficient by a factor of better than 50.

Radiation Hardening

The radiation hardening effort on the RFS-IIF was centered on the new secondary loop synthesizer, which cannot upset during transient radiation. In particular, it is essential that the two synthesizer dividers maintain their state in order to avoid a large phase discontinuity. The most critical aspect of that requirement was to ensure that no transitions were added or lost at the output of the comparators that convert the primary and secondary loop signals into digital form. This was accomplished, in part, by using additional devices for photocurrent compensation in these discrete differential amplifiers.

Reliability

The RFS-IIF is slightly more complex because of the addition of the secondary loop synthesizer. Nevertheless, differences in the ground rules for the reliability prediction per MIL-HDBK-217F Notice 1 more than make up for the increased complexity. The predicted MTBF of the RFS-IIF is 677,457 hours, which corresponds to a reliability of 0.824 for the 15-year mission duration.

Test Results

As a family, the RFS-IIF has displayed a significant improvement in stability. There has also been a significant decrease in sudden shifts in frequency, often referred to as "frequency jumps" that were an issue for some earlier IIR clocks.

It has proved challenging to measure the performance of this latest family of PerkinElmer standards. To observe the high performance of the PerkinElmer RFS-IIF, stability measurements must be made under vacuum conditions. The drift removed, long term stability of these standards rivals the performance of a hydrogen maser, and requires the highest performance measurement facility.

Drift removal is a critical aspect when determining the underlying stability of the PerkinElmer standards. Clocks measured at the factory are "young" and still exhibit relatively high drift. The accuracy of the drift removal is critical to determine the stability of young clocks. As the clocks "age", the drift approaches linear and a Hadamard Analysis can be performed.

The best long term stability measurement results at PerkinElmer have been achieved by measuring one PerkinElmer standard against another. This is likely due to environmental effects on the reference H-Maser and synthesizers in the measurement chain. An update to the PerkinElmer facility (discussed later) has now alleviated this complication.

Figure 6 presents the test results for PerkinElmer RAFS-IIR clocks and Figure 7 presents results for PerkinElmer RFS-IIF clocks using two (2) different references. The poorer than expected stability at long averaging times is most likely due to some combination of poor thermal control of the H-Maser reference and synthesizers in the measurement chain, and poor drift fit and drift removal for these young clocks. Figure 7 also includes several RFS-IIF clocks using a second PerkinElmer rubidium clock under very well controlled environmental conditions as a reference. This eliminates potential effects from poor thermal control of the H-Maser and synthesizers. No correction ($1/\sqrt{2}$) was made for the added noise due to the rubidium reference clock. The improvement in performance of the RFS-IIF compared to the RAFS-IIR is most apparent at the medium term stability, approximately 100 to 10,000 seconds.

A typical frequency plot of an RFS-IIF is shown in Figure 8.

Program Status

The RFS-IIF program at PerkinElmer is approaching completion. Manufacture of twenty-nine (29) RFS-IIF flight units is complete. A few more units may be produced depending on program needs. The number of Flight GPS Units (IIR & IIF) produced by PerkinElmer is approaching 100. The inventory of flight qualified electronic components procured in the mid to late 1990's is nearly exhausted.

RAFSMOD Program

The USAF GPS Wing initiated the RAFSMOD program in 2005 in order to maintain the capability to produce these high performance GPS standards. The RAFSMOD Program is focused on eliminating obsolete components with redesign where required, as well as updating GPS clock measuring and monitoring equipment at PerkinElmer.

The first stage of the RAFSMOD program was to conduct a study to identify obsolete components. This was accomplished in May of 2005 and resulted in a report submitted to the GPS Program Office.

Approximately twelve (12) types of electrical components were identified as obsolete. The part types included resistors, capacitors, MSI Logic devices, FETs, varactor and step recovery diodes, RF transformers and crystal resonators. Forty-eight components were replaced compared to the IIF design.

Fortunately, there was very little impact on the design. Most of the replacement components were drop in replacements, usually from new suppliers, with equivalent or better performance than the original components. Several minor circuit board layout updates were required to accommodate devices that were in new or different packages compared to original components.

The updates accomplished during the RAFSMOD program are equally applicable to the 13.4MHz output ERAFS.

The RAFSMOD Program is complete through the Engineering Development Unit (EDU) phase. The EDU has performed as expected with typical performance compared to the IIF design. A frequency plot using a second PerkinElmer rubidium standard as the reference is shown in Figure 9. Drift removed stability results using a second PerkinElmer rubidium as the reference as well as using a hydrogen maser reference are shown in Figure 10. No correction was made for the added noise of the rubidium reference clock. The data is very well behaved and a strong case can be made to correct the measured stability by $1/\sqrt{2}$ when using the second PerkinElmer rubidium clock as the reference. The performance of the EDU is excellent with stability approaching 1×10^{-15} at 1,000,000 seconds (11.5 days).

New statistical methods are in development [6] to allow higher confidence stability estimates at large averaging factors. Figure 10 also presents the results of a Thêo1 analysis of the RAFSMOD EDU using a second PerkinElmer rubidium clock as the reference.

The RAFSMOD Program also includes the production of three (3) flight units of the updated design. One (1) of these units will be subjected to a full qualification test. The other two (2) units are intended for life test.

The requirement to produce three (3) flight units, has the effect of exercising nearly all of PerkinElmer's suppliers of qualified electronic components, setting the stage for continued availability of this high performing standard for the USAF GPS III Program.

The RAFSMOD Program has also included an update of clock measuring and monitoring equipment at PerkinElmer. The equipment used throughout the IIR and IIF Programs is now approximately fifteen (15) years old, failing, and unserviceable. A new frequency measuring facility including specialized equipment such as a Symmetricom MHM 2010 Active Hydrogen Maser and Symmetricom (formerly Timing Solutions) TSC 12030 Series clock measuring system was installed as part of the RAFSMOD Program. Updated clock telemetry monitoring equipment was also installed.

As a result of the RAFSMOD Program, PerkinElmer is well positioned to continue to support the manufacture and test of GPS standards for the foreseeable future.

Acknowledgments

Many people and organizations have contributed to the success of the GPS rubidium clock programs at PerkinElmer (formerly EG&G) over the last 25 years. Bill Riley, who managed the clock group for many years, is retired and continues to consult for PerkinElmer. Kenneth Lyon served as a design engineer on this product for many years. The latest effort has been no exception, with technical and financial support from Boeing, ITT, Lockheed Martin, NRL, SAIC, Aerospace, and the USAF GPS Wing.

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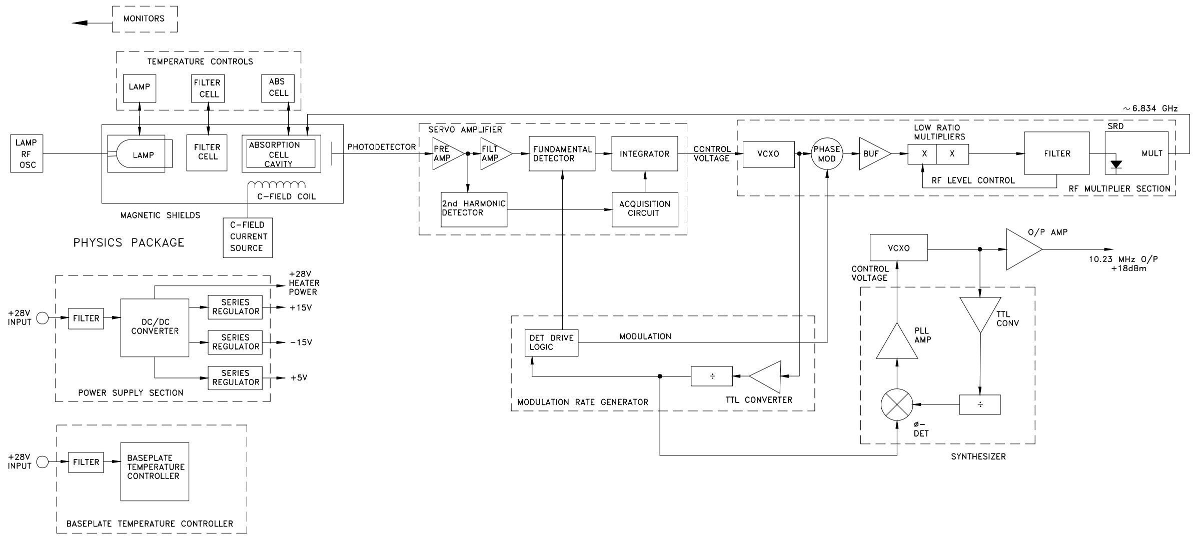
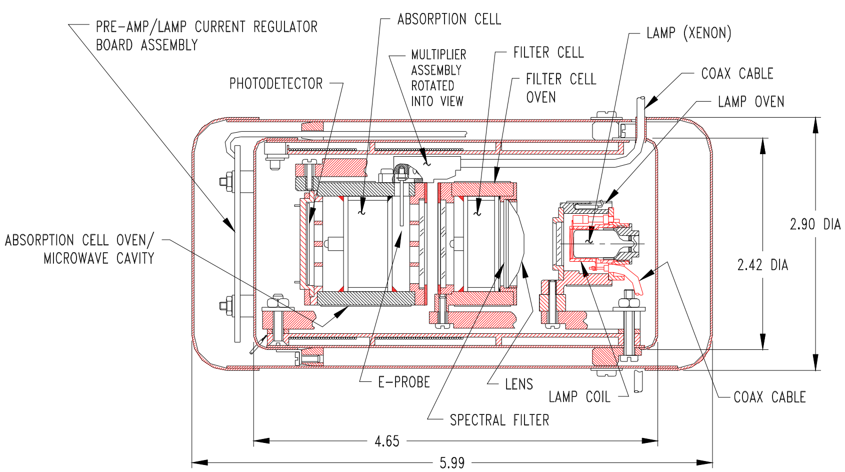


Figure 1. Block Diagram of GPS Block IIF Rubidium Frequency Standard



GPS PHYSICS PACKAGE WITH SPECTRAL FILTER

Figure 2. Physics Package Cross-Section

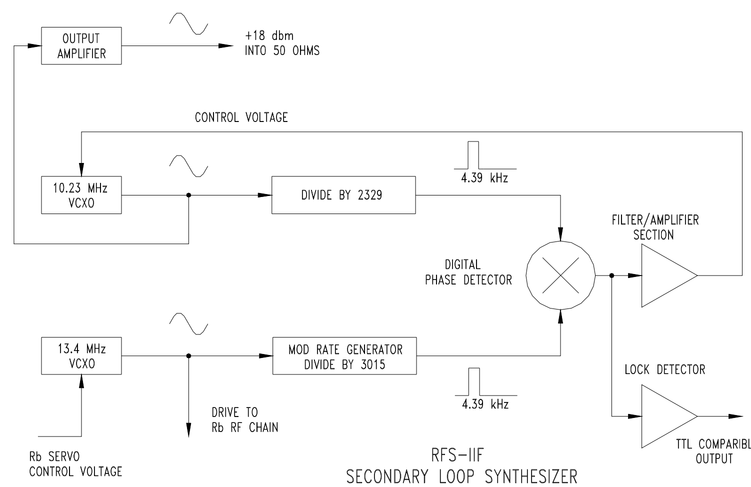


Figure 3. Synthesizer Block Diagram

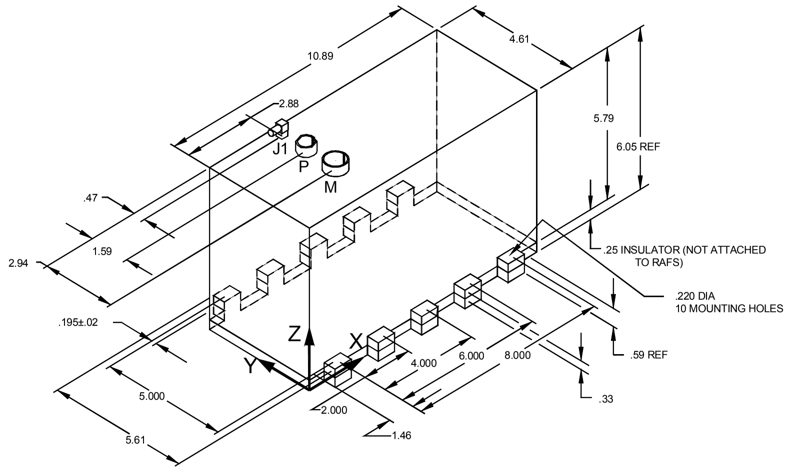


Figure 4. RFS-IIF Outline

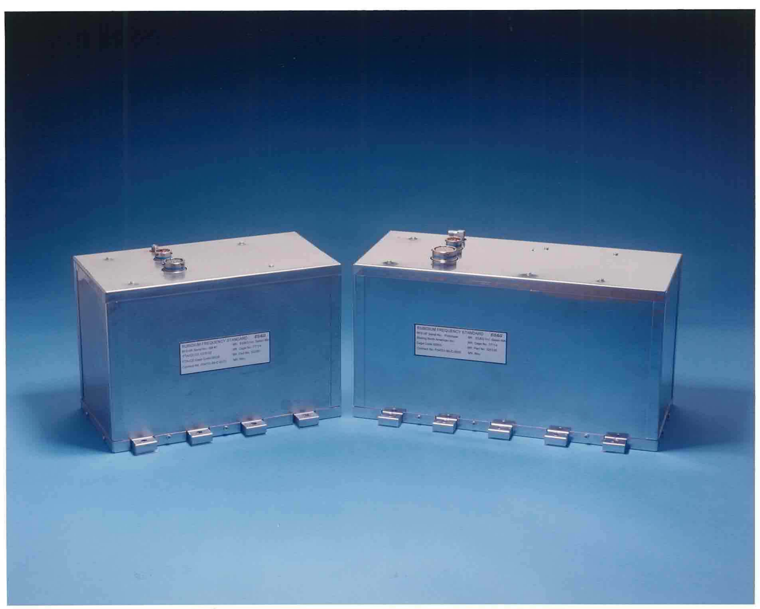


Figure 5. Photograph of RAFS-IIR (Left) & RFS-IIF (Right)

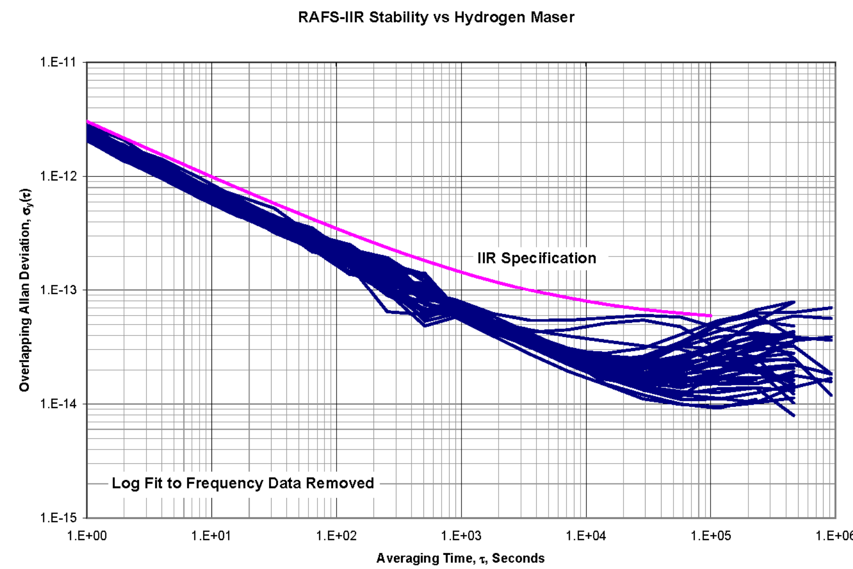


Figure 6. RAFS-IIR Stability Plot

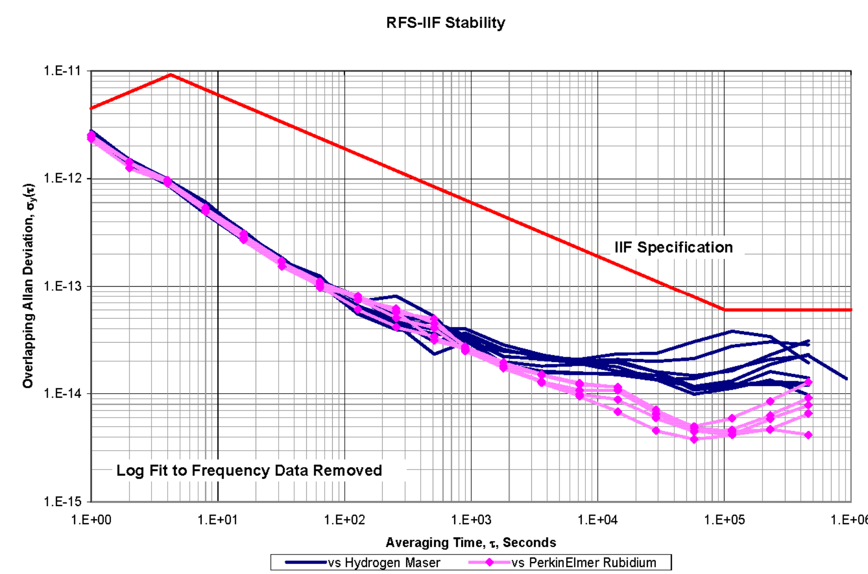


Figure 7. RFS-IIF Stability Plot

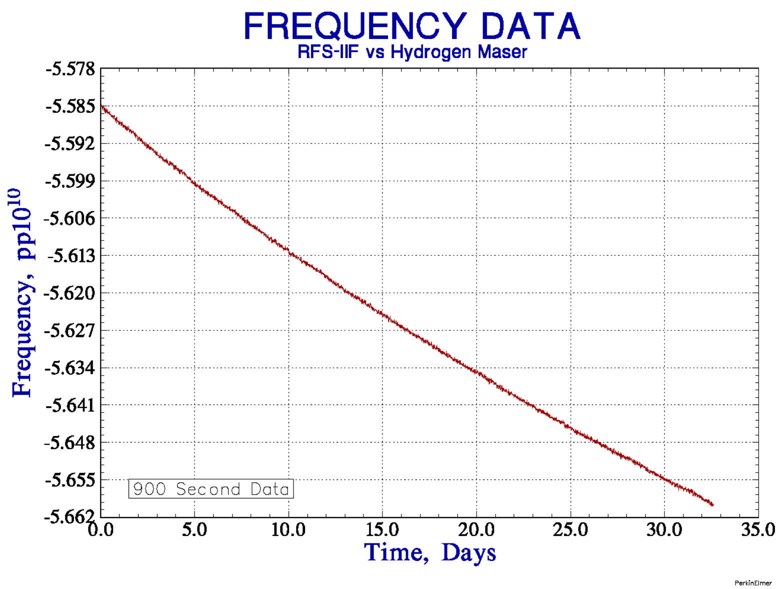


Figure 8. RFS-IIF Frequency Plot

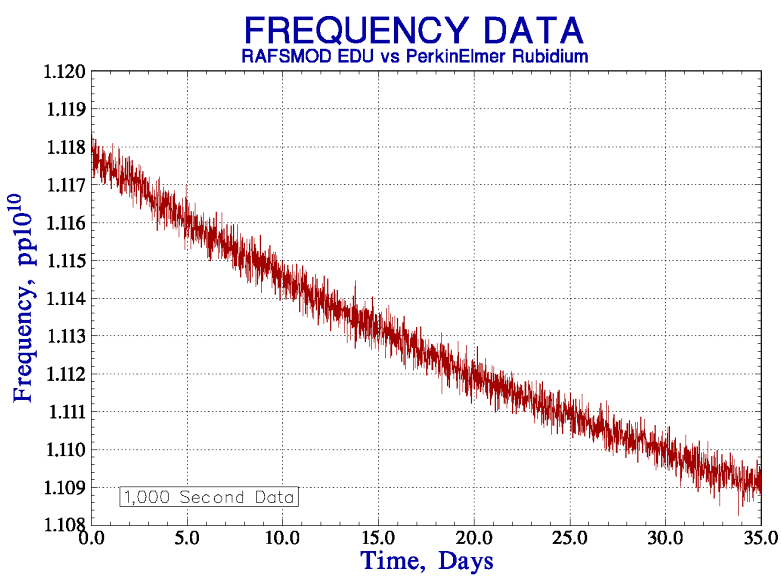


Figure 9. RAFSMOD Frequency Plot

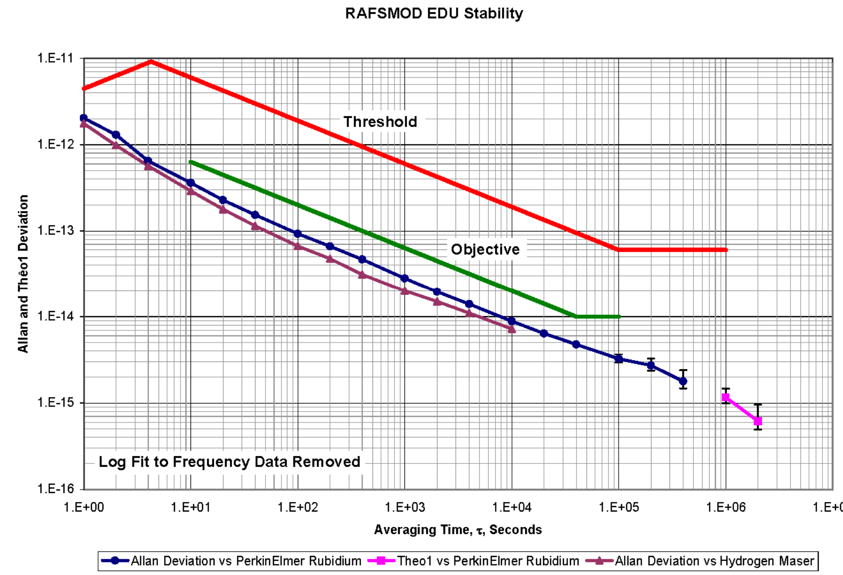


Figure 10. RAFSMOD Stability Plot