

## CAFS—A CESIUM ATOMIC FREQUENCY STANDARD FOR GPS BLOCK IIR

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### Abstract

*Kernco, Inc. was selected to design the Cesium Atomic Frequency Standards (CAFS) for the GPS Block IIR NAVSTAR satellites. These spacecraft are scheduled to be launched in the mid-1990s to replenish and upgrade the existing constellation of Global Positioning System satellites. The Block IIR CAFS output frequency is 13.4003378 MHz, the 686th submultiple of the cesium atomic resonance frequency. Using an integer submultiple simplifies the design of the atomic frequency standard's rf multiplier circuits, eliminating the secondary frequency synthesizer needed in previous designs.*

*This paper describes the GPS Block IIR CAFS design, particularly the improvements made on our earlier Block II design. Test results are included.*

## INTRODUCTION

The GPS NAVSTAR Block IIR satellites will replenish and work with the Block II satellites. Cesium atomic frequency standards will provide highly stable timing references for the satellite navigation system.

Kernco was a second source cesium clock supplier to the current generation of Rockwell built Block II satellites. The first of these satellites carrying a Kernco cesium standard is scheduled for launch in December 1992. The Block II design served as a baseline for the current CAFS unit.

General Electric Astro Space Division is the prime USAF contractor for the Block IIR satellites and the ITT Aerospace/Communications Division is the subcontractor for the GPS navigation system. Kernco is the designer of the cesium atomic frequency standards (CAFS) for this program.

Two complete prototype CAFS have been built and subjected to many qualification level tests, including Flash X-ray test on both units. The full spectrum of qualification tests will be run on a production unit.

## TECHNICAL REQUIREMENTS

The key performance and environmental/survivability requirements are summarized in Table 1.

**TABLE 1 — FUNCTIONAL REQUIREMENTS  
GPS BLOCK IIR CESIUM ATOMIC FREQUENCY STANDARD (CAFS)**

ITEM	SPECIFICATION VALUE
Frequency	13.4003378571 MHz
Frequency Offset	-0, $+1 \times 10^{-9}$ df/f
Frequency Drift	$5 \times 10^{-14}$ df/f per day (after 30 days)
Frequency Repeatability	Less than $5 \times 10^{-12}$ df/f
Temperature Stability	Less than $2E-13$ per degree C (0 to 256°C)
User Output	50 ohms, +18 dBm +/- 1.5 dB
Phase Noise (maximums)	L(1 Hz): -85 dBc/Hz L(1 kHz): -90 dBc/Hz
Harmonic Output	-50 dBc maximum
Input Power (maximums)	28vdc; 26 watts maximum operating 50 watts maximum warmup (1 hr.)
Size	16.5 x 5.25 x 4.75 inches
Weight	17 lbs. (without radiation shielding)
Life	7.5 years
Reliability	0.755 for 7.5 years (minimum)
Survivability	$\pm 10$ nanoseconds (max prompt error) -10 dB max prompt output level change 2.6 meters (maximum 24 hour URE) 36.3 meters (maximum 14 day URE)

SOURCE: ITT A/CD Specification 30072-134L

Orbital stability requirements for the CAFS are shown by the "spec line" in Figure 1. The Figure also shows the frequency stability performance achieved on one of the prototype units.

## CHANGES AND IMPROVEMENTS

**Reduced Size, Weight and Power (See Figure 2)** Denser electronic packaging resulted in reducing the size of the Block IIR CAFS by 35%. Reducing the size of mechanical structures lowered the unit's base weight to 17 pounds from the previous Block II weight of 26 pounds. Adding 4 pounds of nuclear radiation shielding brings the total flight weight to 21 pounds. Power consumption was reduced 14% to less than 23 watts.

**Automatic Start-up** Cold turn-on of the previous (Block II) cesium atomic frequency standards needed ground control uploading of a tuning voltage word to set the unit's VCXO frequency. This initial tuning was needed so that the cesium beam excitation frequency, derived from the VCXO by a combination of multiplication and frequency synthesis, was within 500 Hz of cesium resonance (9.192667... GHz). A preset tuning voltage could not accomplish this because orbital aging and radiation effects during the 7.5 year mission life could cause the VCXO to drift as much as 2 Hz from its initial ground value.

Since the Block IIR satellites provide no control signals to the CAFS beyond turning on 28 Volt spacecraft power, the CAFS has an automatic system to obtain the proper initial setting for the

VCXO control voltage, and automatically achieves cesium locked operation about 20 minutes after power is applied. Frequency is within  $1 \times 10^{-11}$  df/f of final value one hour after a cold turn-on.

## **BLOCK DIAGRAM**

A block diagram of the CAFS is shown in Figure 3. The circuitry follows traditional cesium standard design, using 102 Hz square wave frequency modulation of the 9.192 GHz cesium excitation to sense frequency error.

An analog/digital servo system processes the cesium beam tube's output signal to lock the VCXO to the cesium resonance. The servo's loop time constant is 13 seconds, allowing the VCXO's short time performance to dominate the frequency stability profile for averaging times below about 50 seconds.

User output at 13.4 MHz is derived from a 6.7 MHz VCXO after frequency doubling and buffering. The VCXO frequency is multiplied directly to produce the 9.192 GHz cesium excitation frequency.

The cesium beam physics package is supported by a cesium oven controller, C-field source, hot wire ionizer current supply, electron multiplier power supply, and an integral ion pump/power supply.

Two telemetry outputs to the satellite's navigation system are derived from the servo system. These are a loop lock status monitor and a linear level monitor of second harmonic modulation (204 Hz) present at the output of the beam signal preamplifier. Signals from two temperature sensing thermistors attached to the bottom of the CAFS are also provided to telemetry.

## **PHYSICS PACKAGE**

The cesium beam tube employs single beam dipole deflection optics. Minor outline changes were made to the long-lived design which had been used in the Kernco Block II cesium units. Some electrical feedthroughs were relocated on the tube shell to optimize lead lengths. Sufficient cesium charge and graphite gettering capacity insures an operating life of at least 20 years. Three units on Accelerated Life tests since 1983 confirm lifetimes in excess of the nominal twenty (20) years.

## **ELECTRONICS**

### **VCXO**

The VCXO uses a 6.7 MHz fifth overtone AT cut swept synthetic quartz resonator in a modified Clapp oscillator circuit. The VCXO is thermally insulated and ovenized, servoed to a fixed temperature near 85 °C. The specific operating temperature of each oscillator is factory set to the zero slope inflection point of its df/dt characteristic.

### **User RF Output Circuit**

The 13.4 MHz user output, a 50 ohm source at +18 dBm, is provided by a push-push doubler and a power amplifier. This part of the CAFS circuitry also supplies buffered 13.4 MHz to the rf

multiplier as well as 6.7 MHz to the servo section; for clocking digital circuits.

## RF Multiplier

Square wave FM modulation at 102 Hz produces a servo error signal when the 9 GHz cesium excitation is not precisely at cesium resonance. Modulation takes place at 13.4 MHz in a linear phase modulator driven by a precise triangular waveform.

The 9192.667 GHz cesium excitation frequency is the 686th multiple of the VCXO output. Multiplication is achieved with 36X integer multiplication using doublers and triplers, followed by a step recovery diode harmonic generator. The multiplication factors used are:

$$13.4003 \dots \text{MHz} \times ((2 \times 3 \times 3 \times 2 \times 19) + 2) = 9192.6 \dots \text{MHz}.$$

Where the final addition of  $(2 \times 13.4003 \dots)$  is accomplished by mixing action in the SRD multiplier. The upper sideband of the 19th harmonic is selected by a high-Q cavity filter tuned to the cesium resonance frequency.

## Beam Tube Support Systems

The cesium beam tube needs several power sources to support its operation:

- Cesium oven heater supply (temperature controlled)
- C-field current source
- Hot-wire ionizer current supply
- Mass spectrometer accelerating voltage
- Electron multiplier voltage supply
- Ion pump high voltage supply

The function of these supplies is traditional in cesium atomic clocks and will not be discussed in detail here.

## Servo Circuits

This is the most complex portion of the CAFS' electronics, containing analog and digital circuits which together control a tuning voltage to keep the VCXO frequency locked to cesium resonance. The servo section also provides several secondary functions including generating the lock indicator and second harmonic level telemetry output signals.

## Automatic Starting System (Autostart)

The automatic start-up establishes an initial value in the digital storage register controlling the "coarse" VCXO tuning voltage. After cesium lock is established, this digital register (a 10 bit up-down counter) is incremented or decremented by the servo system to offset VCXO drift.

The cesium oven heater control system is used as a "timer" to initiate the autostart sequence. Autostart begins when the cesium oven regulator comes out of saturation and begins linear tem-

perature control. This occurs about 20 minutes after power is applied to a "cold" CAFS. The VCXO's warm-up is fast enough so that cesium locked frequency is within its tuning range by the time the oven heater circuit comes out of saturation.

The Autostart operates by turning off modulation, zeroing the digital counter/storage register, and clocking 1024 "up" pulses into this register. This sweeps the VCXO through its full tuning range. The maximum value of the cesium beam current signal occurring during the sweep is stored in an analog peak holding circuit. (Maximum beam current occurs when the multiplied VCXO frequency hits the central peak of the field independent transition Ramsey response.) The VCXO is swept a second time and stopped by a comparator circuit when the beam current signal reaches 95% of the stored value. This leaves the digital storage register very close to its cesium locked value. Modulation is switched on, and the servo loop begins steering the VCXO.

## **Power Supplies**

The CAFS runs on 28 vdc spacecraft power and draws 22.5 watts at a temperature of 256°C in vacuum. Power consumption during warm-up is less than 50 watts.

The power supply system uses a single ended flyback switching supply which isolates the CAFS from the input power source. This supply feeds three linear regulators to produce the +15v, -15v and +5v buses which power most of the circuits. The main switching supply also provides power to several secondary supplies with specialized requirements. Examples of these are the 2 kv regulated electron multiplier voltage supply and the hot wire ionizer supply, a downconverting switching supply which sources 2.5 amps to a low impedance (1/3 ohm) load. All power supplies in the CAFS are short circuit tolerant.

Input power filters provide EMI filtering and protect the CAFS power supply from surges and transients.

## **MECHANICAL DESIGN**

Figure 4 shows the CAFS with its outer cover removed.

The cesium beam tube is the largest and heaviest assembly in the CAFS. It measures 13-3/4 x 3 x 3 inches and weighs 9 pounds. The packaging approach placed the electronics against the bottom and sides of the beam tube, so that all beam tube support circuits are close to their respective interfaces with the tube.

Figure 5 is an exploded view identifying the major assemblies. The Base Plate is a machined aluminum part providing the thermal interface with the spacecraft. This assembly contains the main power supply, the input power filter, and the power and telemetry connector filter boxes. The 6.7 MHz VCXO mounts to this assembly.

The Tube Support is a compartmented machined aluminum part housing the rf chain, the user rf output circuits, and the beam tube electron multiplier high voltage power supply. Circuit compartments are fitted with tight covers to prevent rf leakage. The cesium beam tube is rigidly attached to the top of the unit through its central mounting foot.

Printed circuit assemblies containing the servo circuits, cesium oven heater control, and the ionizer power supply are mounted on both sides of the cesium beam tube. Mounting pads on the cesium beam tube shell support these assemblies. The beam tube's ion pump high voltage power supply is mounted in end of the tube, immediately adjacent to the ion pump. All high voltage leads are completely potted to insure corona-free operation.

End panels and covers complete the mechanical assembly and provide additional support and radiation shielding for the printed circuit assemblies mounted on the sides of the cesium beam tube.

## **RELIABILITY**

The CAFS was required to have a 7.5 year mission life, and up to 3 years of pre-launch operation. The predicted MTBF of the CAFS is 601,754 hours, giving a reliability of 0.89657 for the mission life. Several atomic frequency standards are carried on each Block IIR satellite, and can be switched in or out of service by ground commands or on-board computer control.

## **RADIATION CONSIDERATIONS**

A new radiation effects analysis was required because of the tightened autonomous URE specifications. The CAFS circuit designs have been subjected to scrutiny by GE and Jaycor. The critical output circuits were subjected to numerous transient radiation tests at the GE flash X-Ray facility during their development. Both CAFS prototypes were also tested at GE. These analysis and tests have established the shielding and parts screening requirements which enable the CAFS to satisfy the specified radiation requirements.

## **PERFORMANCE DATA**

### **Stability**

Figure 6 shows the SSB phase noise of the CAFS. This plot shows performance well below the spec line with the exception of a power line (60 Hz) spur resulting from imperfect shielding of the measuring setup.

Frequency stability, measured using an HP 5061-004 cesium standard as a reference is shown in Figure 1. Further long-term measurements against a hydrogen maser are anticipated now that developmental performance tests have been completed.

### **Temperature Stability**

The average temperature coefficient of the prototype model measured over 0 to 35°C was less than  $1 \times 10^{-13}$  df/f per degree.

### **Magnetic Field Sensitivity**

The CAFS was subjected to a 3-axis magnetic field sensitivity test, using applied fields of plus and minus two gauss in each axis. A deviation of  $7.25 \times 10^{-13}$  df/f per gauss was measured in the

most sensitive axis.

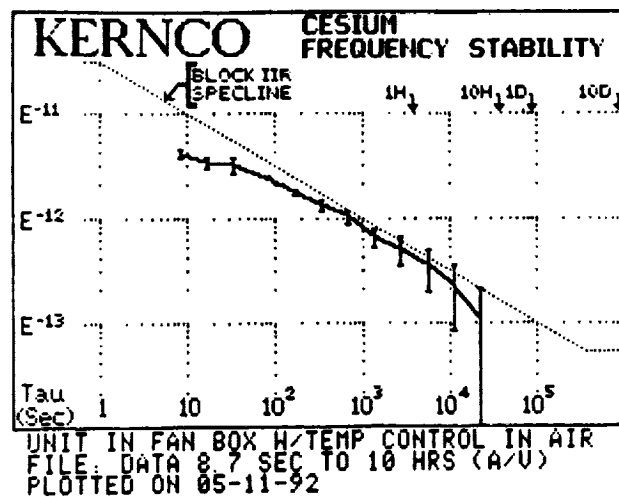
## **FUTURE POSSIBILITIES**

The Block IIR CAFS design has wrung most of what is available from traditional "unintelligent" cesium atomic standard architecture. We expect that future Kernco Satellite clocks will use microprocessor controlled self-checking techniques to compensate and correct for environmental and aging effects. This technology, now demonstrated in ground-based cesium standards, is the next logical step to achieve further performance improvements in spacecraft clocks.

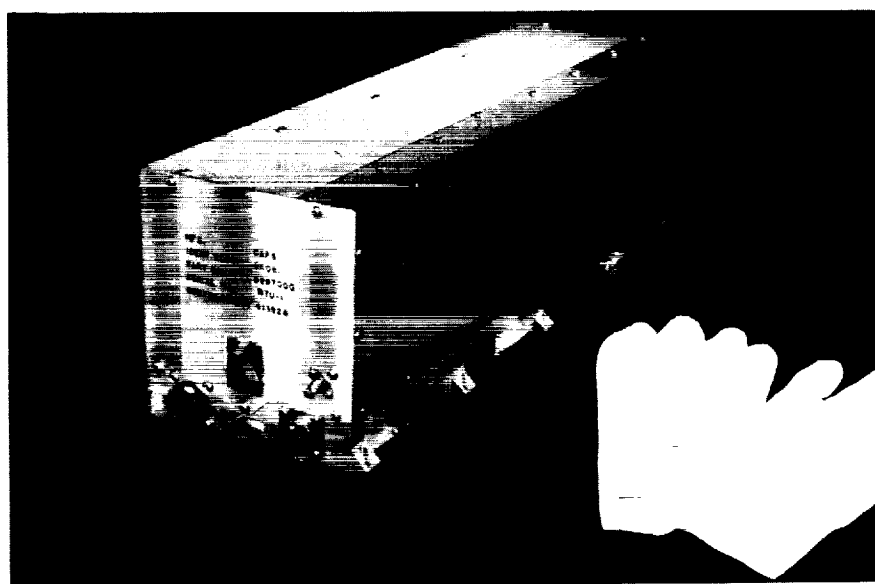
## **ACKNOWLEDGEMENTS**

The author wishes to acknowledge the contributions of others at Kernco, without whom the Block IIR CAFS development could not have been accomplished. Principal contributors were Tom Hoffman, Michael Delaney and Dan Janssen.

The work described was supported by the United States Air Force via ITT A/CD Subcontracts No. 413928 and No. 414741.



**Figure 1. CAFS Frequency Stability**



**Figure 2. GPS-CAFS Unit**



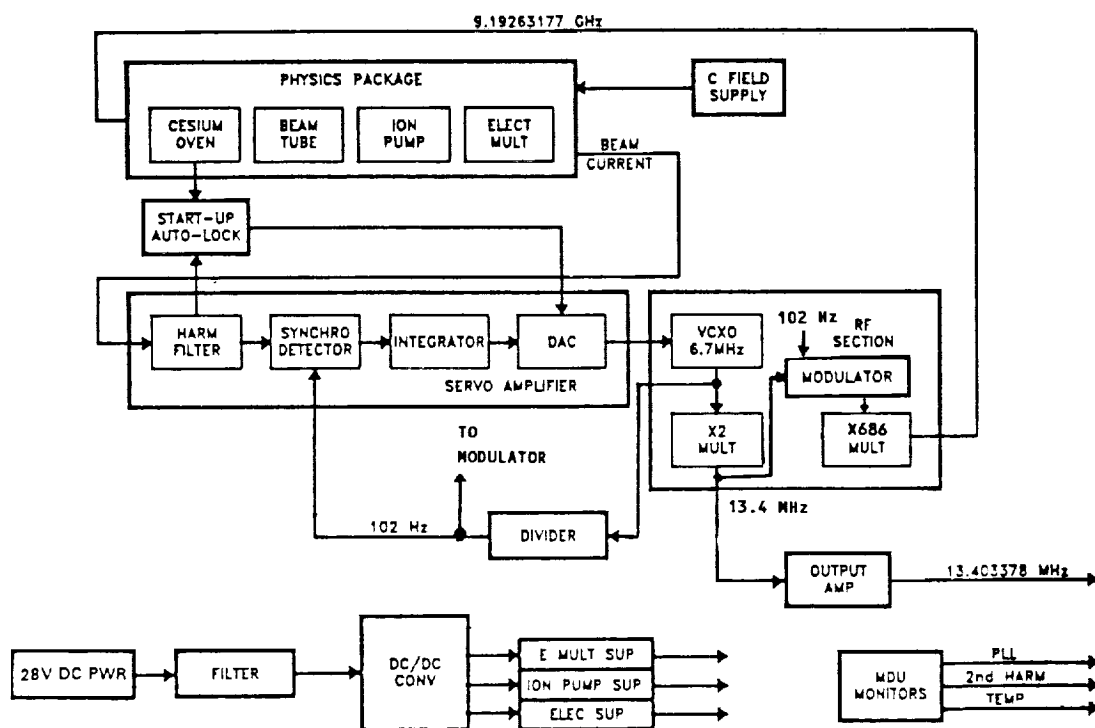


Figure 3. *CAFS Block Diagram*

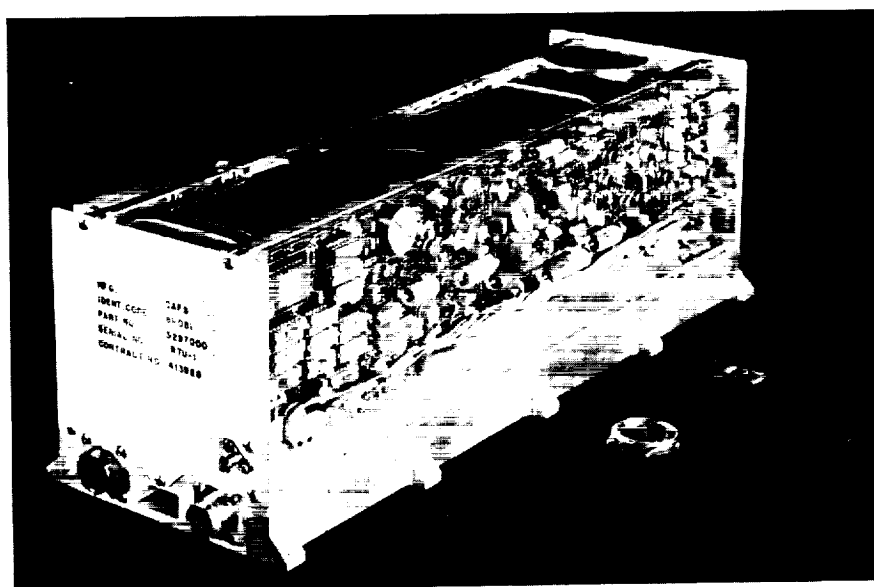
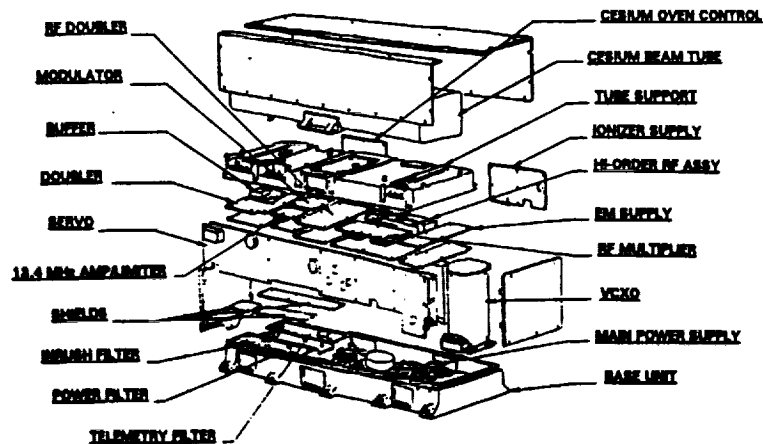
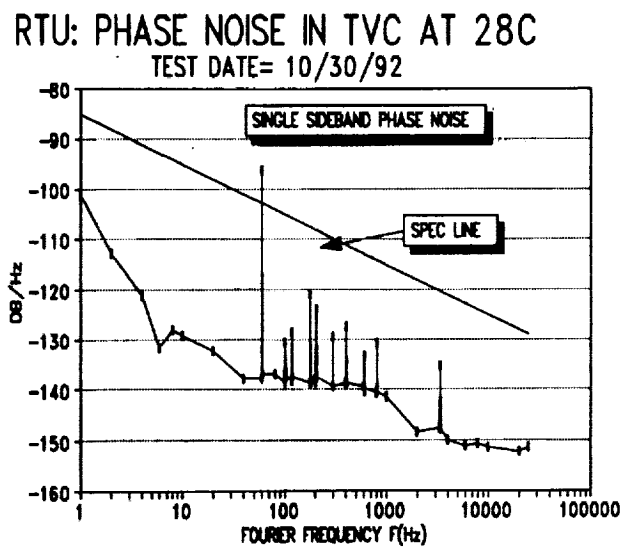


Figure 4. *GPS-CAFS Showing Servo Electronics*



**Figure 5. CAFS - Construction**



**Figure 6. CAFS - Phase Noise**