

## A RUBIDIUM CLOCK FOR SEEK-TALK

William J. Riley  
EG&G, Inc., Frequency and Time Department  
Salem, Massachusetts

### ABSTRACT

The work at EG&G, Inc., on a miniature rubidium frequency standard for the SEEK-TALK program has now reached the prototype stage. This paper describes the design objectives and approach, the more important design features, and the results obtained thus far.

### INTRODUCTION

EG&G, Inc., with support from the U.S. Air Force Electronic Systems Division, has developed a tactical rubidium frequency standard (TRFS) for the SEEK-TALK program. This effort, which is now entering the prototype stage, is directed toward the establishment of a production capability for miniature rubidium clocks of medium stability capable of fast warmup and extreme ruggedness for military avionics applications. The overall unit will consist of an ultra-miniature physics package and four plug-in circuit boards inside a 2½-inch square by 4-inch box. This size is achieved without the extensive use of hybrid microcircuitry, yet is believed to be the smallest atomic frequency standard yet developed. A mockup of the unit is shown in Figure 1.

The physics package is about the size and shape of a "D" flashlight battery. It combines the best features of the integrated and discrete filter cell approaches by using separate filter and absorption cells, both of which are inside the microwave cavity. Small size is achieved by dielectric loading of the cavity and by a unique electric field mode of lamp excitation. Performance is enhanced by excellent line homogeneity made possible by an optical design giving uniform light distribution, separate hyperfine filtration, and a uniform C-field. Low net temperature coefficient is achieved by cancellation of the individual filter and absorption cell coefficients. The discrete filter cell also allows zero light shift to be conveniently obtained by adjusting cavity temperature. The overall physics package assembly includes a low-noise photo-detector and microwave multiplier, as well as lamp exciter and VCXO circuits and a second magnetic shield.

The TRFS electronic block diagram has a single frequency lock loop that contains a wide bandwidth A/B PLL synthesizer as a subloop. A particularly simple rf chain is used that has no mixing and a few tuned circuits. The servo amplifier is a low-complexity cascade detector configuration and the power supply and temperature controller sections use efficient high frequency switching techniques.

# Report Documentation Page

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Figure 1. Photograph of TRFS Mockup Unit.

## SPECIFICATIONS

The specifications for the TRFS are shown in Table 1 and are based on the general requirements of the SEEK-TALK program.

Table 1. TRFS condensed specifications.

|                                        |                               |
|----------------------------------------|-------------------------------|
| Output Frequency, MHz                  | 10                            |
| Output Level, V rms into 50 ohms       | 0.5                           |
| Harmonics, dBc                         | -30                           |
| Spurious components, dBc               | -80                           |
| Phase Noise $\mathcal{L}(f)$ , dBc/Hz  |                               |
| f = 1 Hz                               | -80                           |
| f = 100 Hz                             | -120                          |
| f = 1 kHz                              | -135                          |
| DC Power, watts                        |                               |
| Steady State at 25°C                   | <13                           |
| Warmup                                 | <70                           |
| DC Input Voltage, volts                | 22-32                         |
| Warmup, minutes                        |                               |
| from 25°C                              | 1.5                           |
| from -55°C                             | 4                             |
| Drift                                  |                               |
| per month                              | <5 x 10 <sup>-11</sup>        |
| per year                               | <5 x 10 <sup>-10</sup>        |
| Short Term Frequency Stability         |                               |
| 1 sec                                  | <4 x 10 <sup>-11</sup>        |
| 10 sec                                 | <1 x 10 <sup>-11</sup>        |
| 100 sec                                | <4 x 10 <sup>-12</sup>        |
| Trim Range                             | ≥3 x 10 <sup>-9</sup>         |
| Voltage Coefficient                    | <1 x 10 <sup>-11</sup> /10%   |
| Temperature Coefficient, -54 to +71°C  | <3 x 10 <sup>-10</sup>        |
| Retrace                                | ≤3 x 10 <sup>-11</sup>        |
| Storage Temperature, °C                | -62 to +85°C                  |
| Magnetic Susceptibility, (worst axis)  | <2 x 10 <sup>-11</sup> /Gauss |
| Altitude from SL to 50,000 feet        | <1 x 10 <sup>-13</sup> /mbar  |
| Humidity, %                            | 100                           |
| Shock                                  | 30 g peak                     |
| Acceleration                           | <4 x 10 <sup>-11</sup> /10 g  |
| Sinusoidal Vibration                   | 4 g peak                      |
| Random Vibration                       | 0.04 g <sup>2</sup> /Hz       |
| Reliability, airborne inhabited, hours | ≥20,000                       |
| Size, inches                           | 2½ x 2½ x 4                   |
| Weight, pounds                         | <2.0                          |

## BLOCK DIAGRAM

A block diagram of the TRFS is shown in Figure 2. This block diagram combines high performance, simplicity, and manufacturability. The major sections are:

- a. The physics package which acts as a frequency discriminator to produce an error signal which indicates the magnitude and sense of the difference in frequency between the applied rf excitation and the rubidium atomic resonance.
- b. A servo amplifier which processes the error signal to produce a control voltage for a voltage controlled crystal oscillator (VCXO).
- c. A VCXO section which contains the locked crystal oscillator, circuits to produce the desired (5 or 10 MHz) output, and one divider portion of the synthesizer.
- d. A VHF section which contains the rest of the synthesizer that converts the standard output frequency into a direct submultiple of the rubidium resonance.
- e. A power section which provides supply voltages to the circuitry and has temperature controllers for the two physics package ovens.

## PHYSICS PACKAGE

The heart of the TRFS unit is, of course, the physics package. EG&G began this project with the internally sponsored development of a rubidium physics package that combines good performance with ultra-miniature size. The features include a new concept in lamp excitation and a dielectrically loaded cavity that contains separate filter and absorption cells. The basic physics package structure is shown in Figure 3.

Extreme miniaturization of the lamp assembly was accomplished by eliminating the usual rf coil surrounding the rubidium lamp. An electric field structure was developed for starting and maintaining the lamp plasma. Fabry-Perot studies confirmed the proper spectral output from this structure, which is approximately half the overall diameter of an equivalent coil arrangement since no spacing is required between the lamp and oven wall. The lamp is excited by a conventional Colpitts rf power oscillator which will be located inside the physics package.

Miniaturization of the microwave cavity was obtained, paradoxically, by putting more into it. It was decided to use a discrete filter cell for best performance. This allows independent nulling of the light shift and gives good spatial homogeneity in the absorption cell that results in a low rf power coefficient. It was further decided to locate the filter cell inside the cavity to avoid the volume of an additional oven. The common thermal environment also allows cancellation of the filter cell temperature coefficient by that of the absorption cell, since the latter is adjustable by its binary buffer gas mix ratio. The

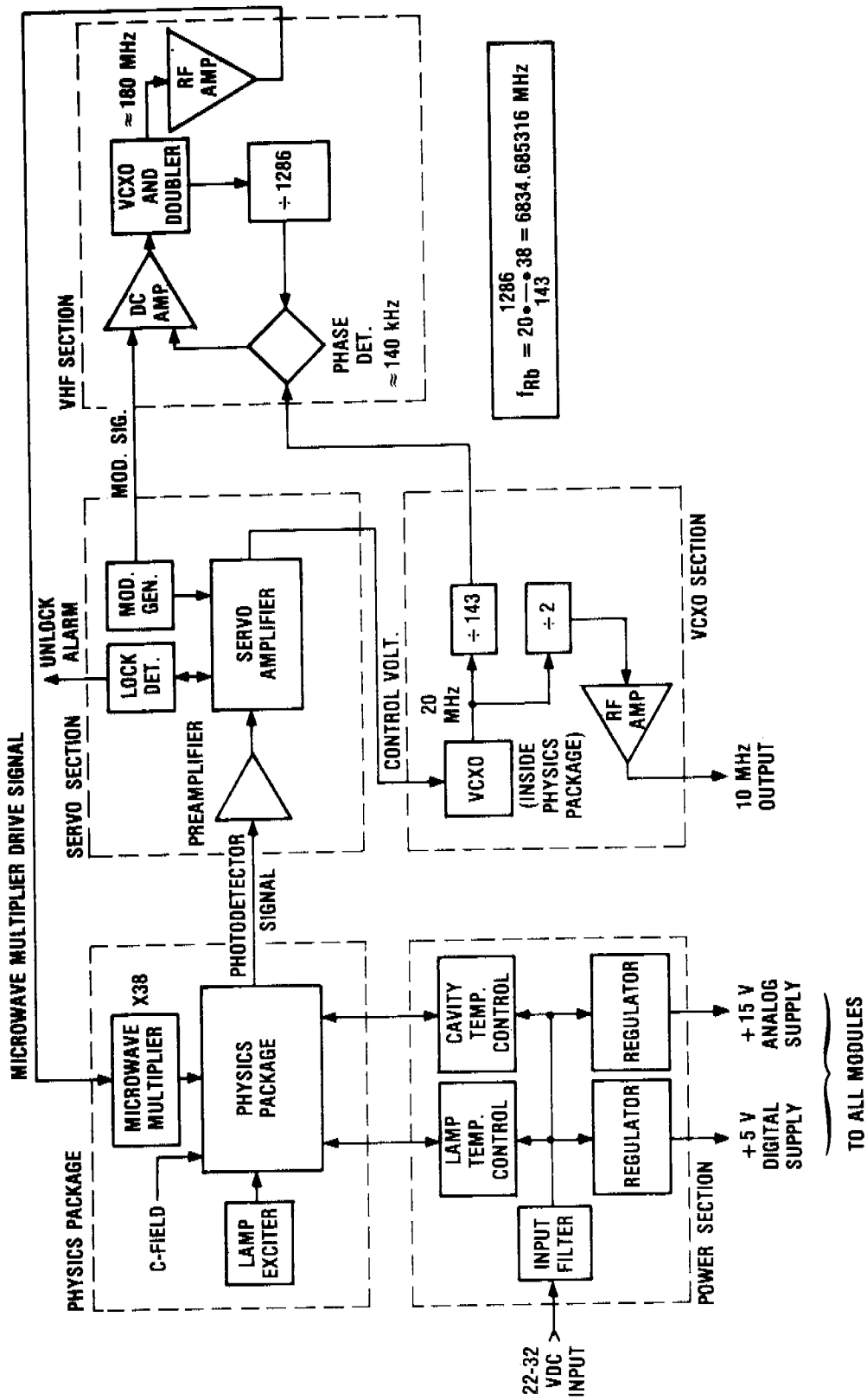


Figure 2. TRFS Block Diagram.

resulting increase in the amount of glass dielectric in the TE<sub>111</sub> cavity also reduces its size.

A further advantage is that the filter and absorption cells become shorter, which is desirable for optimum signal at a high operating temperature.

The physics package includes two lenses in the optical path. The first, located in front of the absorption cell, collimates the lamp output to give a uniform light intensity distribution. The second lens, located behind the absorption cell, focuses the light on the  $\approx 1 \text{ cm}^2$  photodetector to give good collection efficiency.

Two C-field coils are used to provide  $\pm 1\%$  C-field uniformity, which helps to ensure good line homogeneity and minimizes rf power sensitivity.

A nonmetallic conical spacer rigidly connects the lamp and cavity ovens for ruggedness and low vibration sensitivity with low heat transfer between the ovens.

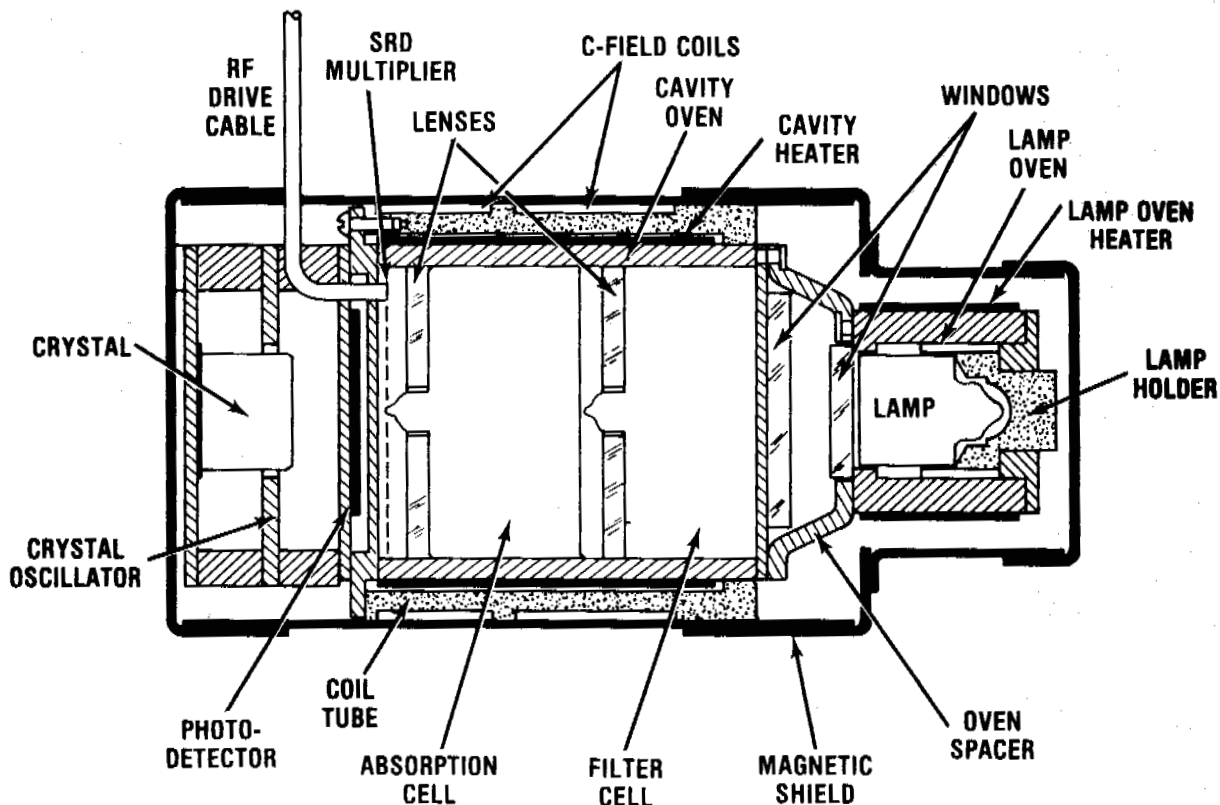


Figure 3. Layout of Miniaturized Physics Package.

The SRD microwave multiplier is incorporated into the temperature-controlled cavity. Its design is both simple and efficient since it works as a straight X38 multiplier.

Table 2 lists some of the physics package parameters and Figure 4 shows the major parts. The synthesizer ratio results in a buffer gas offset that is ideal for such considerations as linewidth, fill tolerance, and barometric coefficient.

Table 2. Physics package parameters.

| Parameter                                                                           | Value                                                                                 |
|-------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| Lamp Size                                                                           | 0.31 in. dia. x 0.45 in. long                                                         |
| Lamp Fill                                                                           | $\approx 100 \mu\text{gram Rb}^{87} + 7 \text{ torr Kr}$                              |
| Lamp Oven Temperature                                                               | 115°C                                                                                 |
| Filter Cell Size                                                                    | 0.81 in. dia. x 0.25 in.<br>inside length                                             |
| Filter Cell Fill                                                                    | $\approx 100 \mu\text{gram Rb}^{85} + 120 \text{ torr Ar}$                            |
| Absorption Cell Size                                                                | 0.81 in. dia. x 0.30 in.<br>inside length                                             |
| Absorption Cell Fill (for $\approx 0$<br>Cavity TC and +2.7 kHz offset)             | $\approx 100 \mu\text{gram Rb}^{87} + 8.4 \text{ torr}$<br>N <sub>2</sub> /Ar mixture |
| Cavity Temperature<br>(for 0 lamp oven TC)                                          | 80°C                                                                                  |
| DC Photodetector Current                                                            | $\approx 100 \mu\text{A}$                                                             |
| Linewidth (full width between<br>inflection points at normal rf)                    | $\approx 600 \text{ Hz}$                                                              |
| Maximum Fundamental Photodetector<br>Signal (at $f_{\text{mod}} = 235 \text{ Hz}$ ) | $\approx 20 \text{ nA rms}$                                                           |
| Discriminator Slope at Photodetector                                                | $\approx 80 \text{ pA per } 1 \times 10^{-10}$                                        |
| Lamp Oven TC                                                                        | $< \pm 4 \times 10^{-11}/^\circ\text{C}$                                              |
| Cavity TC                                                                           | $< \pm 1 \times 10^{-10}/^\circ\text{C}$                                              |
| RF Power Sensitivity                                                                | $< \pm 1 \times 10^{-11}/\text{dB}$                                                   |
| Frequency Stability<br>(1 sec $\leq \tau \leq 1000 \text{ sec}$ )                   | $2 \times 10^{-11} \tau^{-\frac{1}{2}}$                                               |

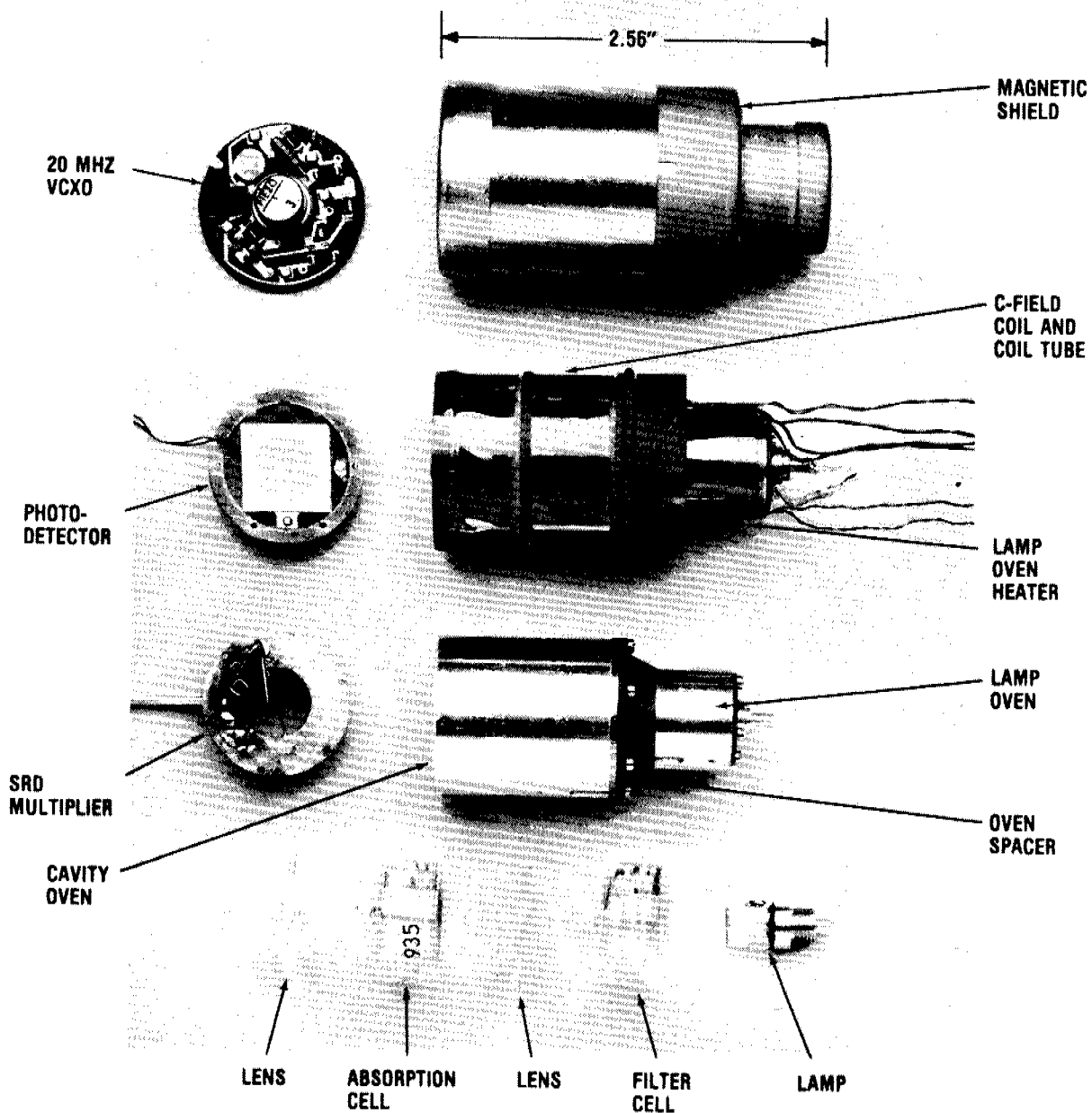


Figure 4. Physics Package Parts.

## SERVO AMPLIFIER

The function of the servo amplifier is to process the error signal from the physics package so as to lock the frequency of the 20 MHz crystal oscillator to the stable rubidium atomic resonance. The major blocks are: (1) a preamplifier that converts the photodetector current to a voltage, (2) a synchronous detector that converts the fundamental ac error signal to a dc voltage, (3) an integrator that develops the control voltage for the crystal oscillator, (4) a second harmonic detector that indicates lock, (5) a sweep circuit that aids lock acquisition, and (6) a modulation rate generator that produces reference signals for the synchronous detectors and phase-modulates the cavity excitation.

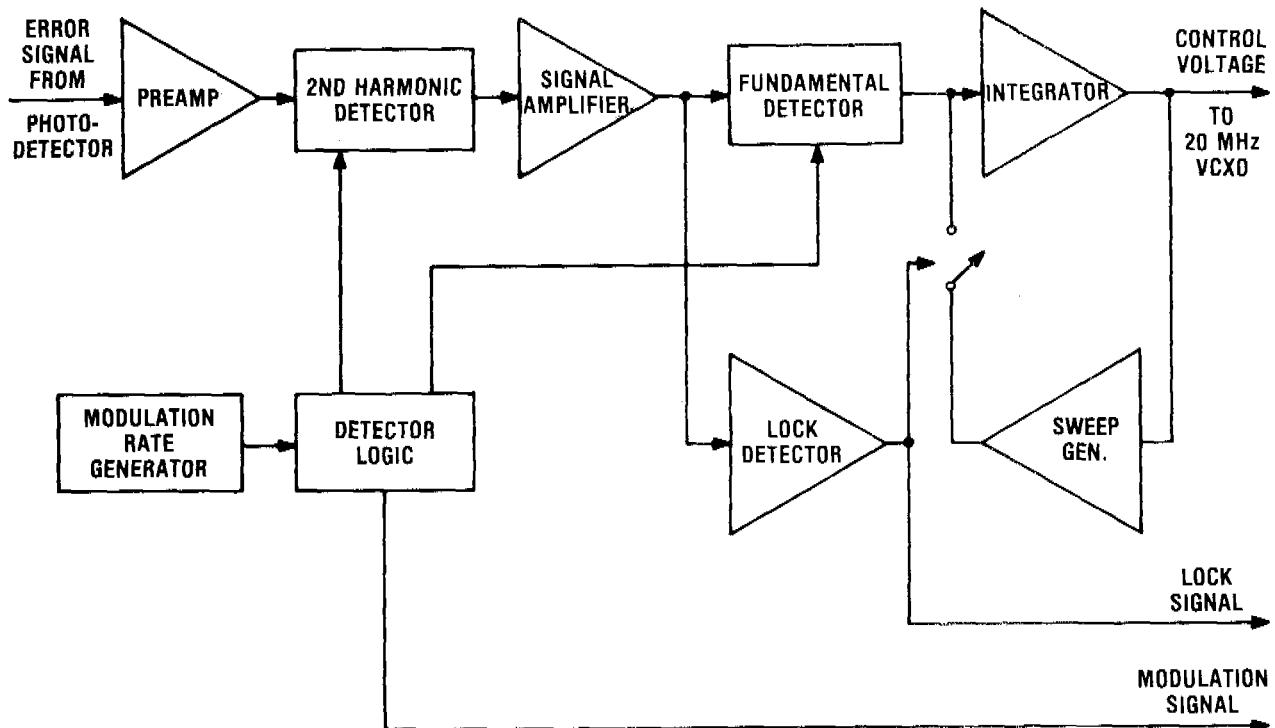


Figure 5. Servo Amplifier Block Diagram.

The TRFS servo amplifier, shown in Figure 5, uses a cascaded detector arrangement wherein the fundamental error signal passes through the second harmonic detector before reaching the fundamental detector. This has the advantage of requiring less hardware. The op amp associated with the second harmonic detector also provides gain for the fundamental signal. The large amplitude second harmonic signal is shifted to the fourth harmonic ahead of the fundamental detector, making it possible to obtain sufficient dynamic range without a bulky notch filter.

## VCXO SECTION

The VCXO section consists of a 20 MHz crystal oscillator, frequency dividers to 10 MHz and  $\approx 140$  kHz, and a tuned amplifier to produce the 10 MHz output.

The voltage controlled crystal oscillator uses a 20 MHz third overtone SC-cut crystal in an HC35/U style holder operated at  $\approx 80^\circ\text{C}$  in the cavity oven. This crystal type is chosen for its small size, ruggedness, fast warmup, and low vibration sensitivity. The VCXO is followed by a high speed comparator to provide isolation and conversion to TTL levels. Straightforward TTL logic divides the 20 MHz by 2 and 143 for the output and synthesizer, respectively. The output amplifier is a differential configuration using a single tuned circuit. Another binary divider section is available to produce 5 MHz as an optional output.

## VHF SECTION

The VHF section generates a signal at  $\approx 180$  MHz that is a direct submultiple (1/38) of the rubidium resonance. This frequency is produced by a phase-locked loop (PLL) that operates as a X1286 multiplier from the  $\approx 140$  kHz reference from the VCXO section. The PLL also serves as the means to apply phase modulation. This approach is hardware efficient and avoids bulky and critical tuned circuits. The rf circuitry consists of a  $\approx 90$  MHz VCXO, a diode doubler, and an rf power amplifier. The PLL consists of an ECL divider, a TTL phase detector, and a loop amplifier/filter. The loop has sufficient bandwidth for vibration immunity and servo modulation.

## POWER SECTION

The power section of the TRFS consists of input filters, temperature controllers for the lamp and cavity ovens, and +5V and +15V power supplies.

The lamp and cavity ovens are supplied directly from the input bus and are controlled by high frequency switching controllers. These controllers provide both warmup and running power and are simple, efficient, operate over a wide dynamic range, and maintain constant thermal gain as the oven power changes. Each controller consists of only one active device and a few discrete components.

All TRFS electronic circuits are powered from +5V and +15V supplies which also use switching regulators. Provision is made for a separate "no-break" input to maintain operation during an interruption in heater power.

## PACKAGING

The overall TRFS packaging is shown in Figure 6. The physics package (including cylindrical inner magnetic shield, VCXO, SRD multiplier, and lamp exciter) is located in the center. It is supported inside the square second magnetic shield by resilient material that provides shock and vibration isolation. The four main electronic circuit boards surround the physics package and plug into a mother board. The electronic components face outward for good access. An L-shaped member provides overall support, while power filters and connectors are mounted to the mother board.

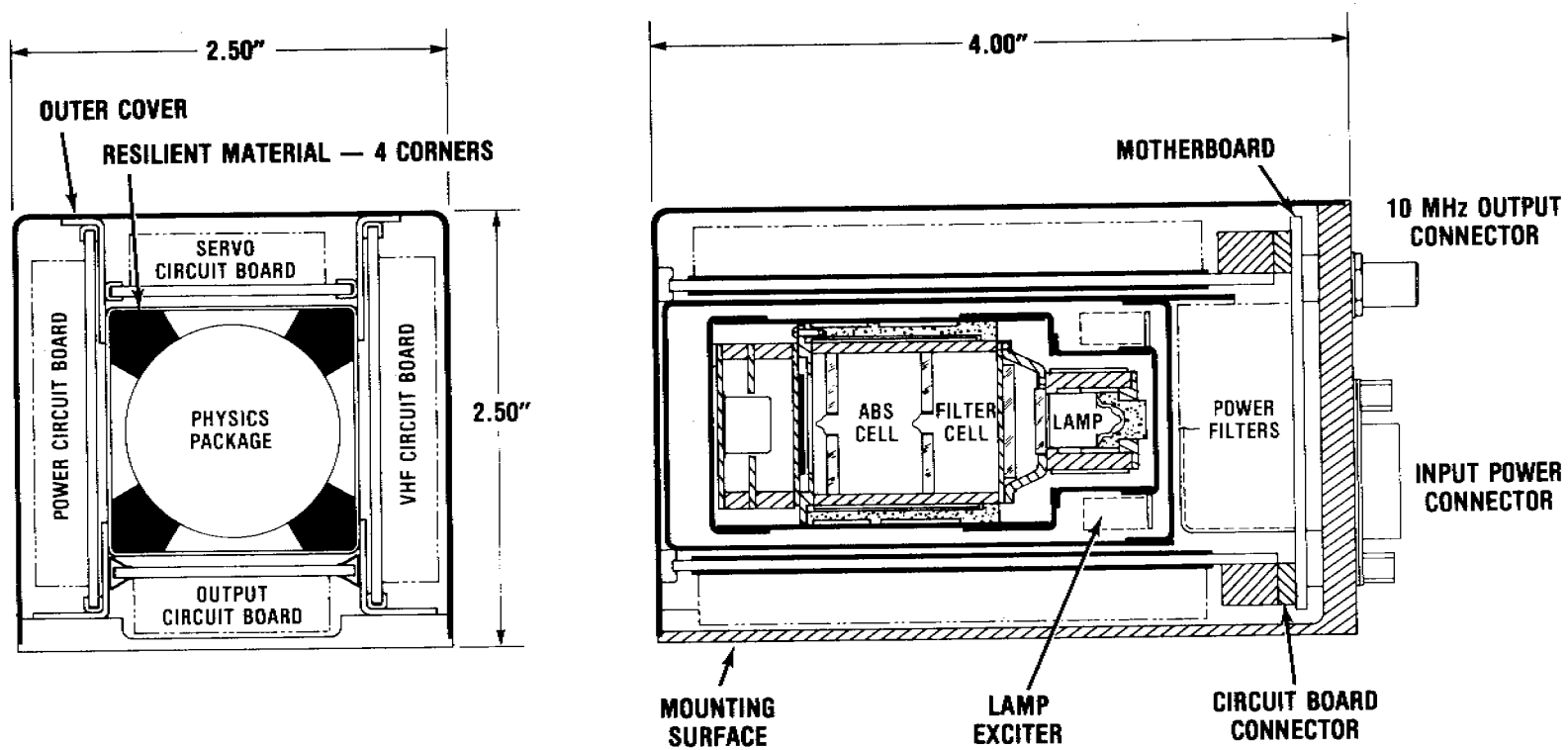


Figure 6. TRFS Packaging Layout.

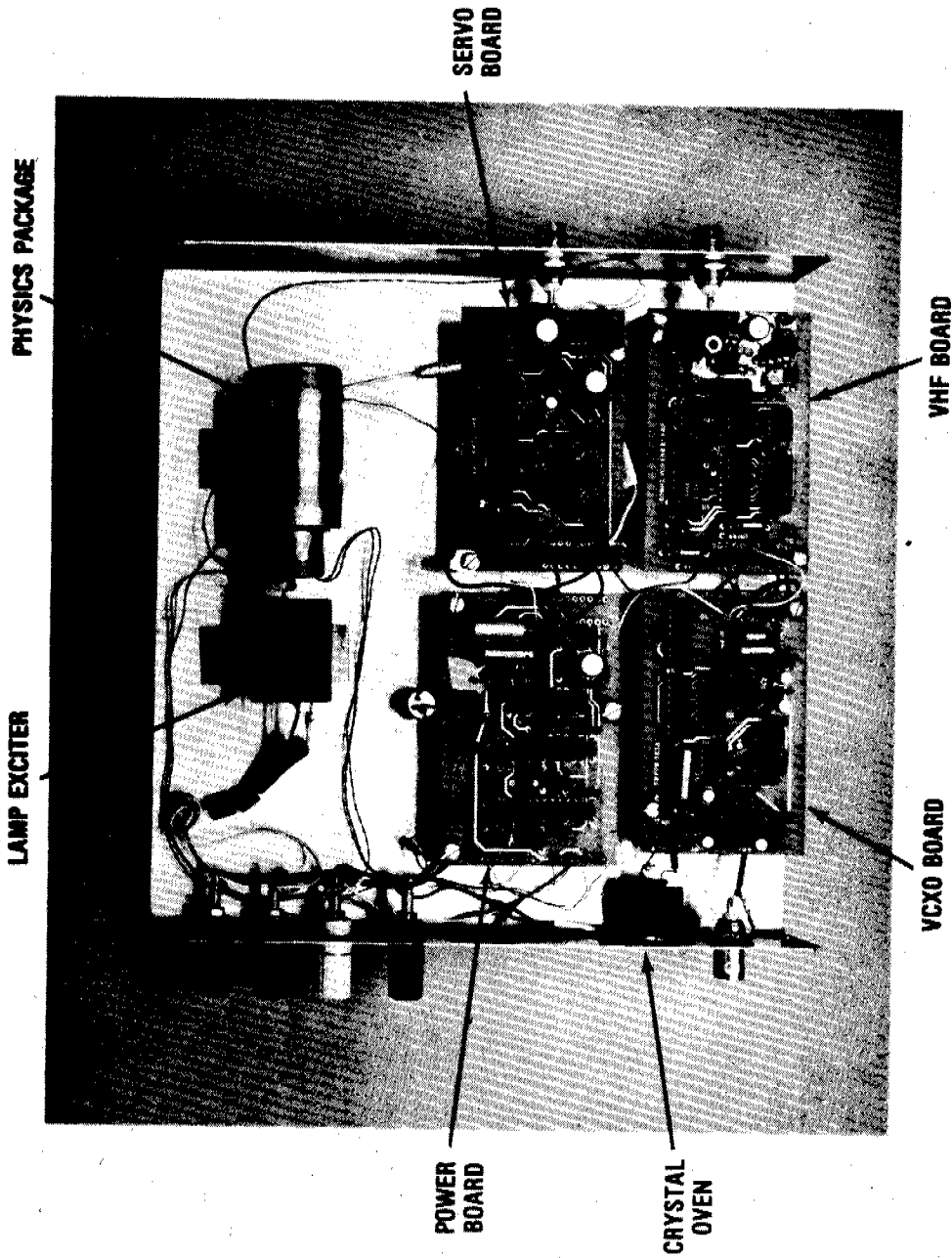


Figure 7. Photograph of TRFS Bench Model.

## PROGRAM STATUS

The TRFS program began with the development and test of the ultraminiature physics package. This was followed by the design of the complete unit. Fabrication and test of a bench model was then accomplished with Air Force funding.

The bench model TRFS consists of the ultraminiature physics package and four circuit boards mounted flat on a 9-inch square pallet as shown in Figure 7. This configuration is well suited for developmental testing.

The physics package is complete out to the first magnetic shield, including a custom low-noise EG&G silicon photodetector and the SRD microwave multiplier. The lamp exciter is housed separately in a small shield box and the VCXO circuit is on one of the main boards with the crystal in a small separate component oven.

Test results on this unit have confirmed the validity of the overall design concept. The program has now advanced through a prototype redesign stage where detailed design has been done for a packaged prototype.

## ACKNOWLEDGMENTS

Support for the TRFS development program has been provided by the U.S. Air Force Electronic Systems Division. At EG&G, Mr. S. Goldberg was responsible for overall scientific direction, and valuable engineering contributions were made by F. Chang, T. Lynch, J. Kirby, K. Lyon, J. McDonald, and E. Sullivan.

## QUESTIONS AND ANSWERS

DR. VESSOT:

I would like to comment that in the 1950's when Bob Dickey, Tom Carver and I were doing some of the early work on hyperfine section and rubidium, we had a room full of equipment and we used to joke that there's no reason you couldn't put this in a match box.

So, we were happy to see progress towards that end.

MR. RILEY:

Well, I never really believed. I heard some comments about putting it into a beer can one time. And I never really believed it for many years, but this is really smaller.