TRIPLY-REDUNDANT PRECISION TIME AND FREQUENCY STANDARD

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ABSTRACT

This paper describes a triply-redundant precision time frequency standard. The standard combines three high performance, field-proven Frequency Electronics devices; namely, the cesium beam frequency standard, the rubidium frequency standard and the SC-cut quartz oscillator in a single 5-1/4" high rack-mounted instrument. Switching between redundant subsystems is accomplished automatically in a glitch-free manner (i.e., negligible phase perturbation), utilizing a process of dynamic phase-matching in conjunction with digital memory circuits.

The system design is based upon the incorporation of a Model FE-5600A Rubidium Standard within the Model FE-5440A (military nomenclature O-1824/U) Cesium Frequency Standard, and utilization of disciplining phase lock loop circuitry from the AN/URQ-23A Disciplined Time Frequency Standard.

In the primary mode, the system functions as a Cesium Standard with a long-term stability of $<1 \times 10^{-11}$. In the secondary (back-up) mode, the rubidium standard provides a thirty day stability of $<3 \times 10^{-11}$. The tertiary (back-up) mode offers the low drift rate of the SC-cut quartz oscillator, namely $<1 \times 10^{-11}$ per day.

Introduction.

The Triply-Redundant Precision Time and Frequency Standard under development at Frequency Electronics, Inc., (FEI) combines features of 3 FEI instruments into a single, cost-effective, rugged device. It has the same configuration and size as the Frequency Electronics Cesium Frequency Standard, the O-1824/U Master Regulator Clock. The frequency standard has been updated to include three redundant modes. Transfer of operation from the primary cesium mode to Rubidium or Quartz backup modes occurs automatically, and glitch-free (i.e., with phase perturbations under 1.6 millidegrees), through use of frequency memory circuits.

Let me show you how 3 instruments are combined into one:

Start with an FEI Cesium Frequency Standard, with a long term stability of 1×10^{-11} in 5 years, (see figure 1). This unit is qualified to MIL-F-28811(EC), and bears the military nomenclature Master Regulator Clock O-1824/U. It provides low noise sinusoidal signals, timing marks, and a serial BCD time code output.

See figure 2 for a look inside. The unused volume was made possible by using the lightweight Cesium beam resonator fabricated at FEI and by incorporating six FEI hybrid circuits. Spare volume permits customization for different applications. FEI can customize for various frequencies up to Ku-Band.

Figure 3 provides a closer look at the FEI Cesium Beam Resonator. An example of hybrids designed and fabricated at FEI is shown in figure 4. Incidentally, Frequency Electronics has built class S hybrids for various military and space programs in the range of dc-44 GHz.

We are now ready to look at the 2nd instrument, the Rubidium Frequency Standard (see figure 5). The entire unit, from physics package to electronics, is fabricated at FEI. Figure 6 is a photograph with cover removed. The version shown contains discrete components; the model currently being manufactured contains six hybrid circuits. The Rubidium Frequency Standard has a 30 day stability of 3×10^{-11} and serves as our back-up standard.

The final ingredients going into the triply-redundant standard are derived form the Disciplined Time Frequency Standard (DTF) shown in figure 7. The device has the capability of being slaved to an external frequency standard. Upon loss of the external signal, the internal digital memory circuits hold the frequency of the internal quartz oscillator constant. The portable unit can operate on internal batteries and thus transport time and frequency to a remote location. With SC-cut quartz crystals g-sensitivity is <3 x 10^{-10}/g in the worst axis, and typically ±1.5 x 10^{-10}/g in other axes. Aging is a few parts in 10^{-11}/day. In mobile environments (i.e., ships, aircraft, land vehicles) it is important that low g-sensitivity crystals are used, to assure maintenance of lock during accelerations.

We don't need the entire DTF unit, so lets just lift some phase lock loop and memory modules, and SC-cut quartz oscillator and an optional phase correction circuit from the DTF. This latter circuit permits synchronization with negligible phase perturbation.

Marrying the various parts, out comes the triply-redundant precision time and frequency standard (see figure 8) with its backup Rubidium Frequency Standard, SC-cut Quartz Crystal Oscillator, and control circuits. Figure 9 shows the front panel of the Standard with status indicators and built-in circuit checks.

The time-of-day clock has been updated to a time-of-year clock, with the capability of providing time codes of optional formats. The clock can be set from an external NAVSTAR GPS Time Code and 1pps time mark. The clock is designed so that radiation-hardened logic components can be used, to operate through hostile military environments.

Key specifications of the Precision Time and Frequency Standard are presented in Table 1.

Redundancy.

Let me briefly describe how redundancy with glitch-free switching is accomplished: The simplified block diagram of the Cesium Frequency Standard is shown in figure 10. The Cesium loop acts as a Hi-Q frequency discriminator, locking the quartz oscillator to the Cesium atom transition frequency of 9.192^{+} GHz.

To build a triply-redundant frequency standard the dotted box is replaced with figure 11 which shows digital memory circuits consisting of comparators, counters, D/A converters and a Rubidium phase lock loop slaved to the Quartz oscillator output.

During normal operation, counter 1 is enabled, and the blocks between integrator and VCXO perform as an infinite memory unity gain element.

(a) In the event of a failure in Cesium:
Disable counter 1; Enable counter 2; Warm up Rubidium.

(b) After a 15 minute Rubidium warm up, the Rubidium is slaved to the Quartz oscillator; disable counter 2, making the Rubidium the backup frequency standard.

(c) Now, to lock the Quartz oscillator to the Rubidium frequency standard:

Switch comparator 1 input to Rubidium: enable counter 3 until comparator 1 input voltage from summer (Σ) equals Quartz control voltage; Disable counter 3; enable counter 1.

The Quartz oscillator is now disciplined to Rubidium, with no phase discontinuities, and the system is in the secondary (backup) mode.

During backup operation:

(a) If Rubidium frequency standard fails:
Disable counter 1, to cause the Quartz oscillator to hold frequency.
The system is now in the <u>tertiary</u> backup mode.

(b) If, instead, the Quartz oscillator fails:
Switch to the 5 MHz Rubidium Frequency Standard output.

The redundant operation is summarized in Table 2. The sinusoidal distribution and Time-of-Year (T.O.Y.) clock inputs and outputs are indicated in figure 12. Note the multiple sinusoidal and timing outputs.

<u>Time-of-Year Clock</u>.

The T.O.Y. clock contains a custom LSI Gate array and microprocessor-controlled time offset and time code generation. Because the code is generated in software, the code is easily customized by changing the programmable read only memory. Operating power is low to maximize battery operating time, if needed; and for application requiring it, the T.O.Y. clock is available with radiation-hardened logic.

Summary.

In summary, information about a rugged, militarized triply-redundant precision time and frequency standard that uses field-proven FEI devices has been presented. The Cesium Beam Resonator, Rubidium physics package, SC-cut Quartz crystal, and hybrid circuits are critical system elements that are fabricated and quality-controlled at Frequency Electronics. The unit can be modified to provide customized outputs. The versatile Time-of-Year microprocessor-controlled clock can provide optional time code formats with fiber optic or wire-transmission drivers, and with radiation-hardened logic elements, for applications having these requirements.

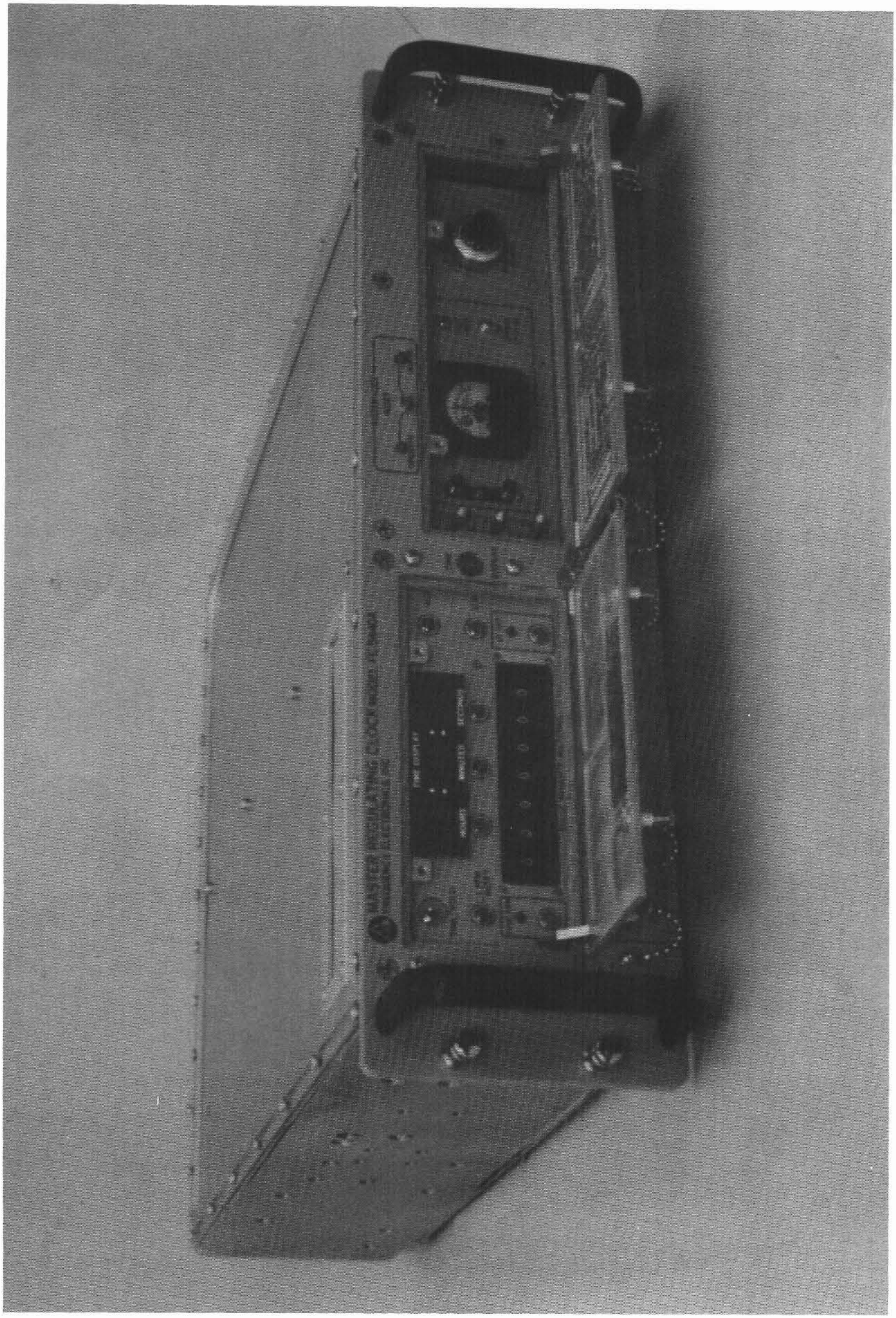


FIGURE 1

CESIUM FREQUENCY STANDARD, MODEL FE-5440A

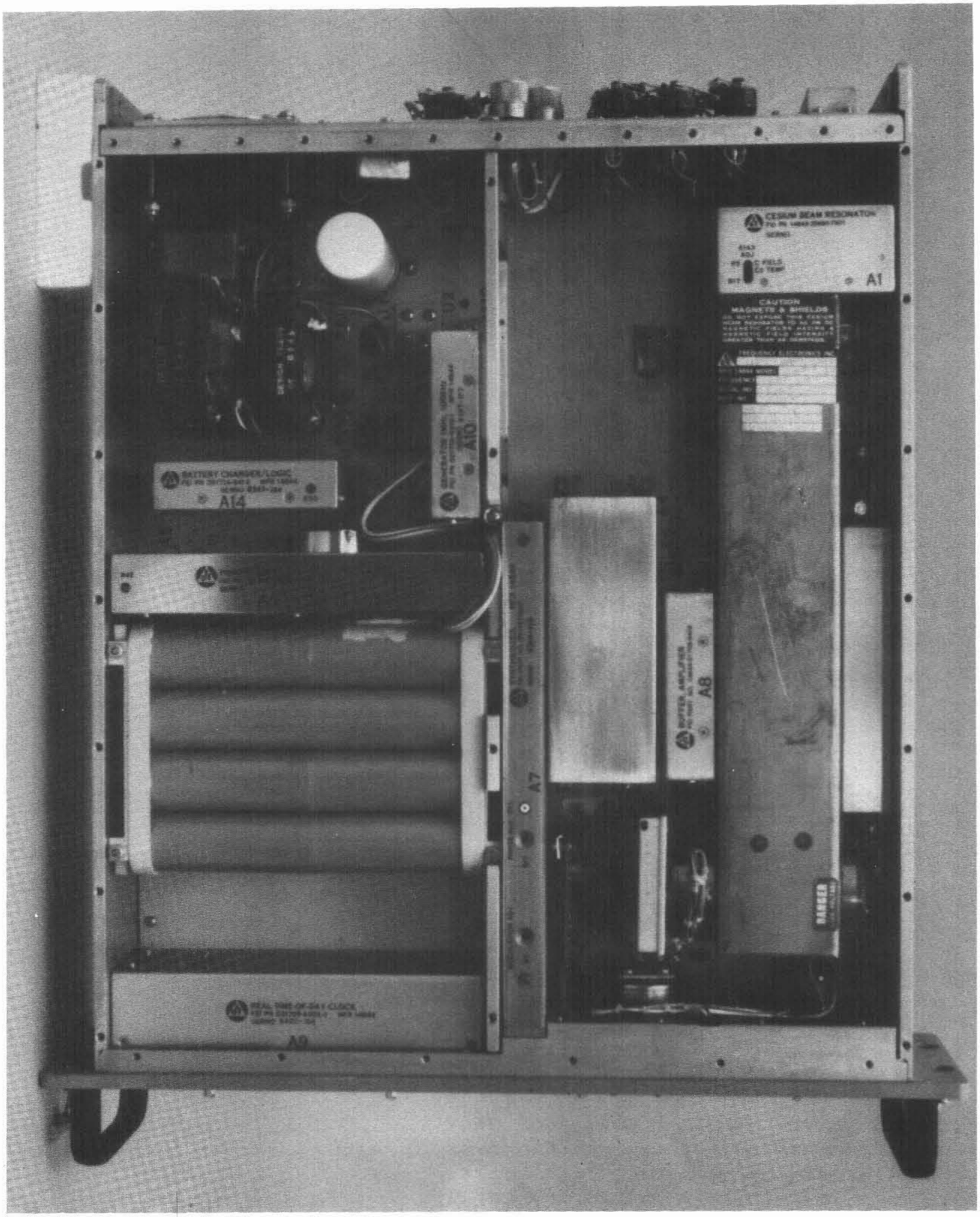


FIGURE 2

CESIUM FREQUENCY STANDARD

(TOP COVER REMOVED)

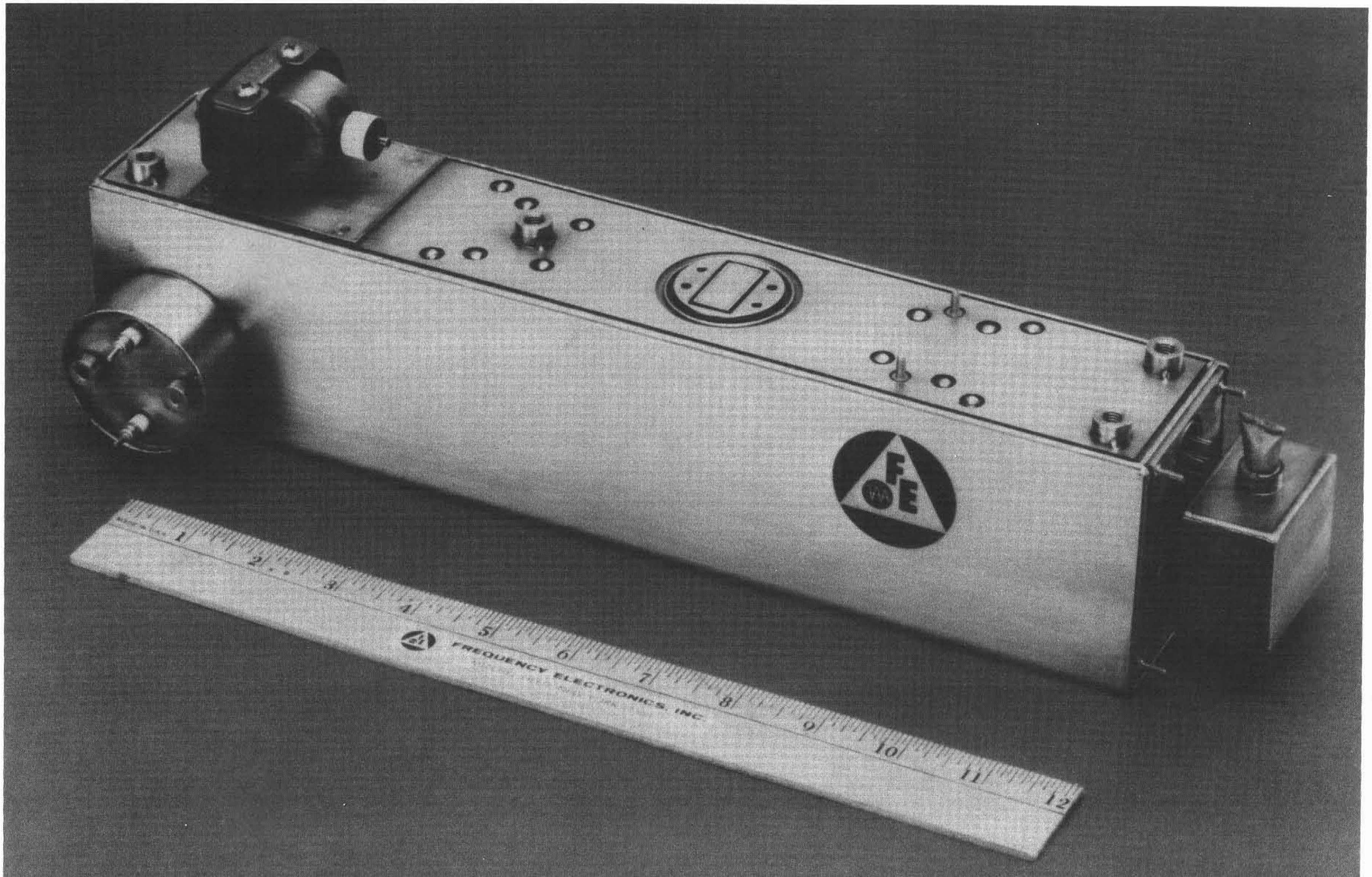
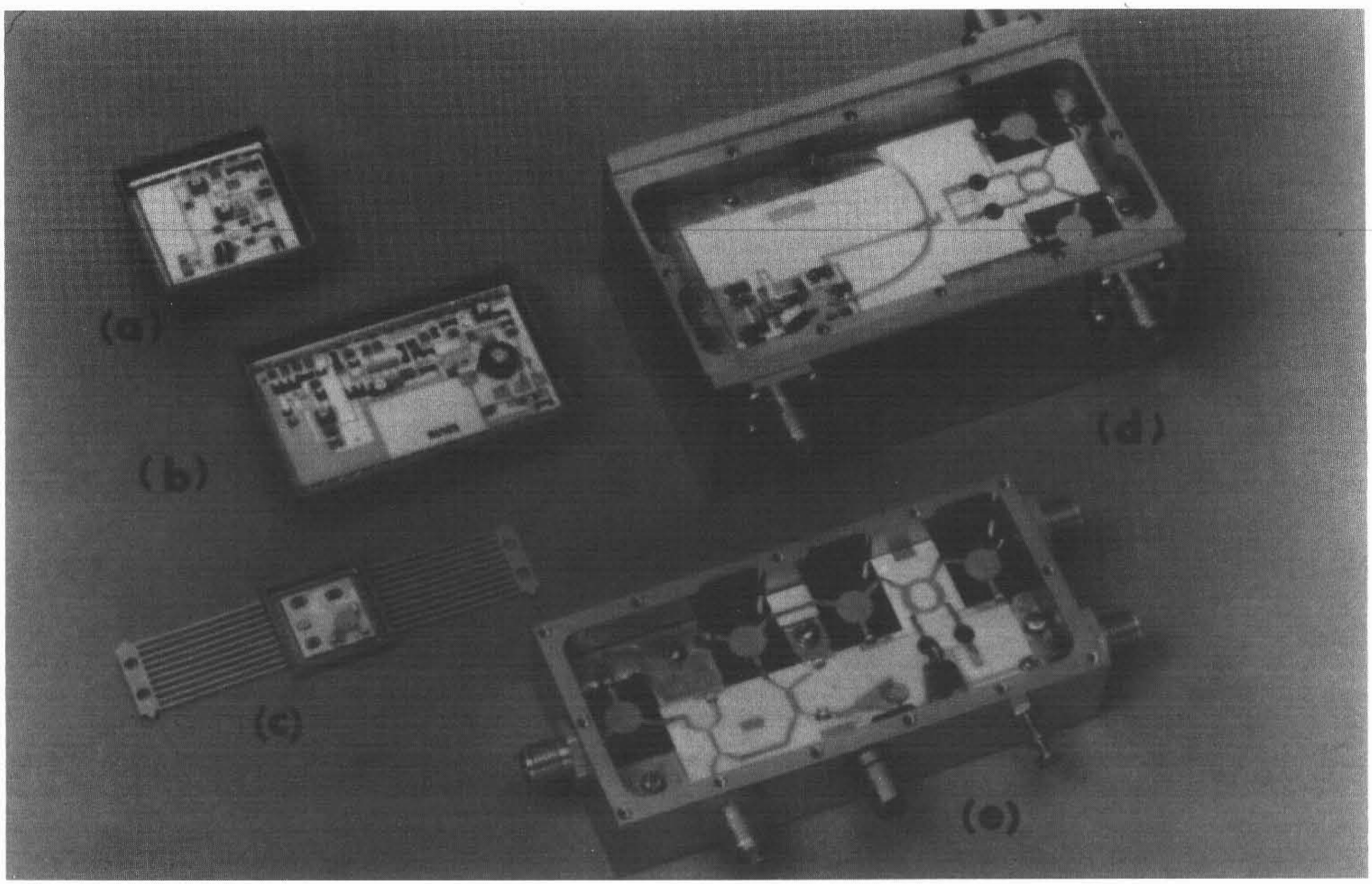


FIGURE 3

CESIUM BEAM RESONATOR



Thick Film Hybrids
- (a) 90 MHz to 180 MHz Multiplier/Driver
- (b) 5.115 MHz Multiplier/Amplifier

Thin Film Hybrids
- (c) 21 MHz Crystal Oscillator
- (d) "X" Band Up Converter
- (e) "C" Band Mixer-Coupler

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FIGURE 4

THICK AND THIN FILM HYBRIDS

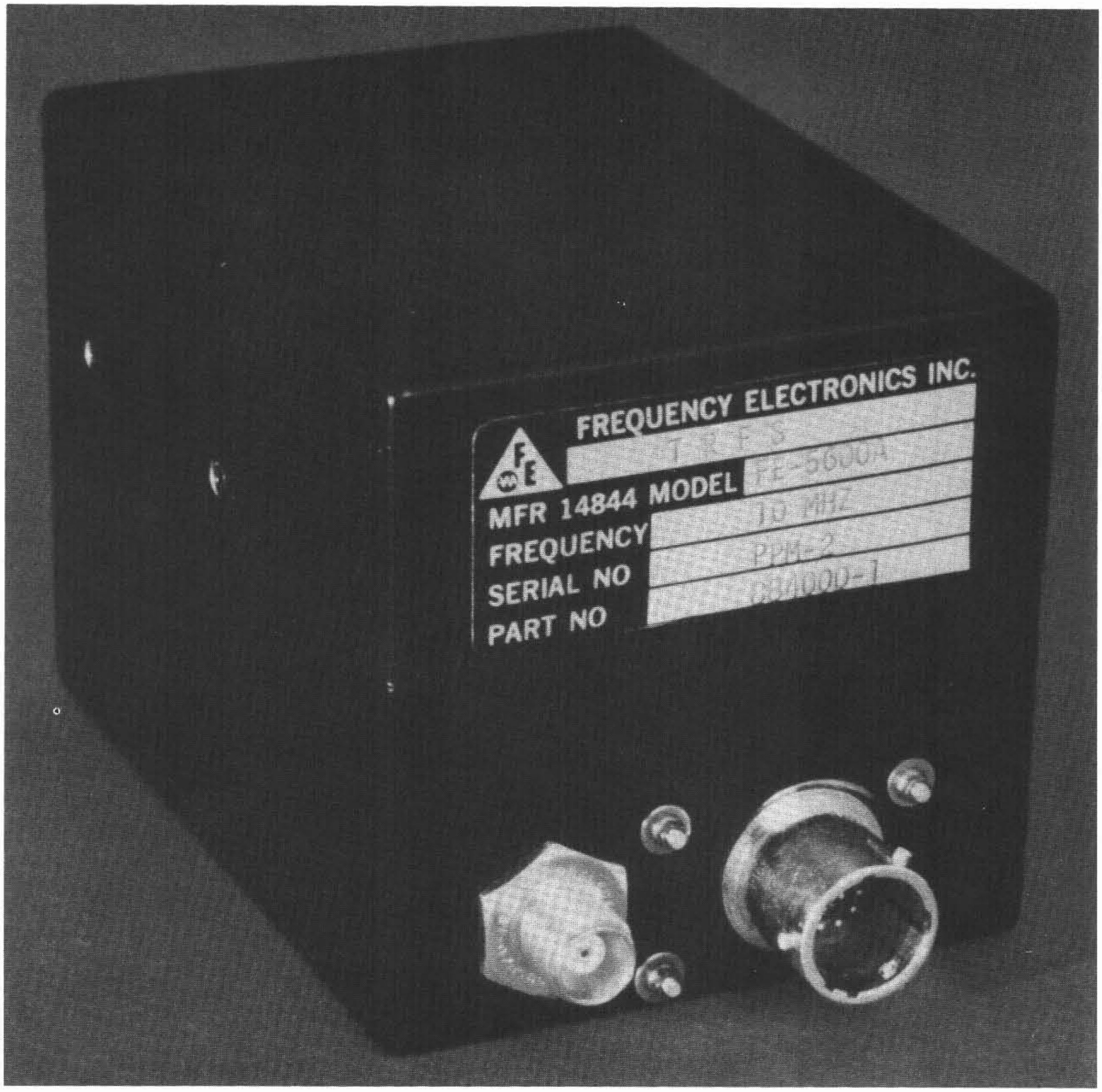

FIGURE 5

TACTICAL RUDIBIUM FREQUENCY STANDARD

(TRFS)

MODEL FE-5600A

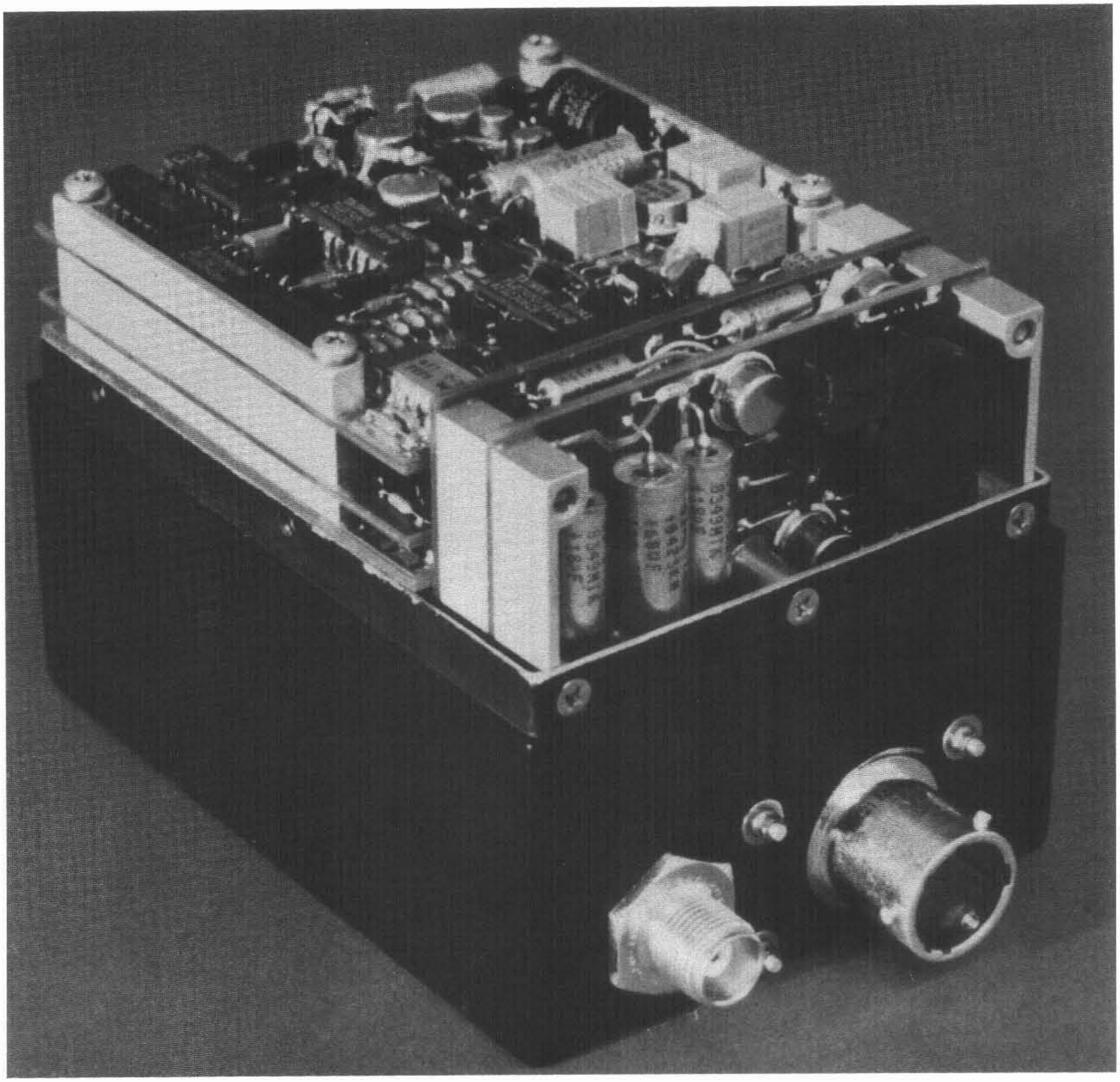

FIGURE 6

TACTICAL RUDIBIUM FREQUENCY STANDARD

(TRFS)

MODEL FE-5600A

FIGURE 7

DISCIPLINED TIME FREQUENCY STANDARD

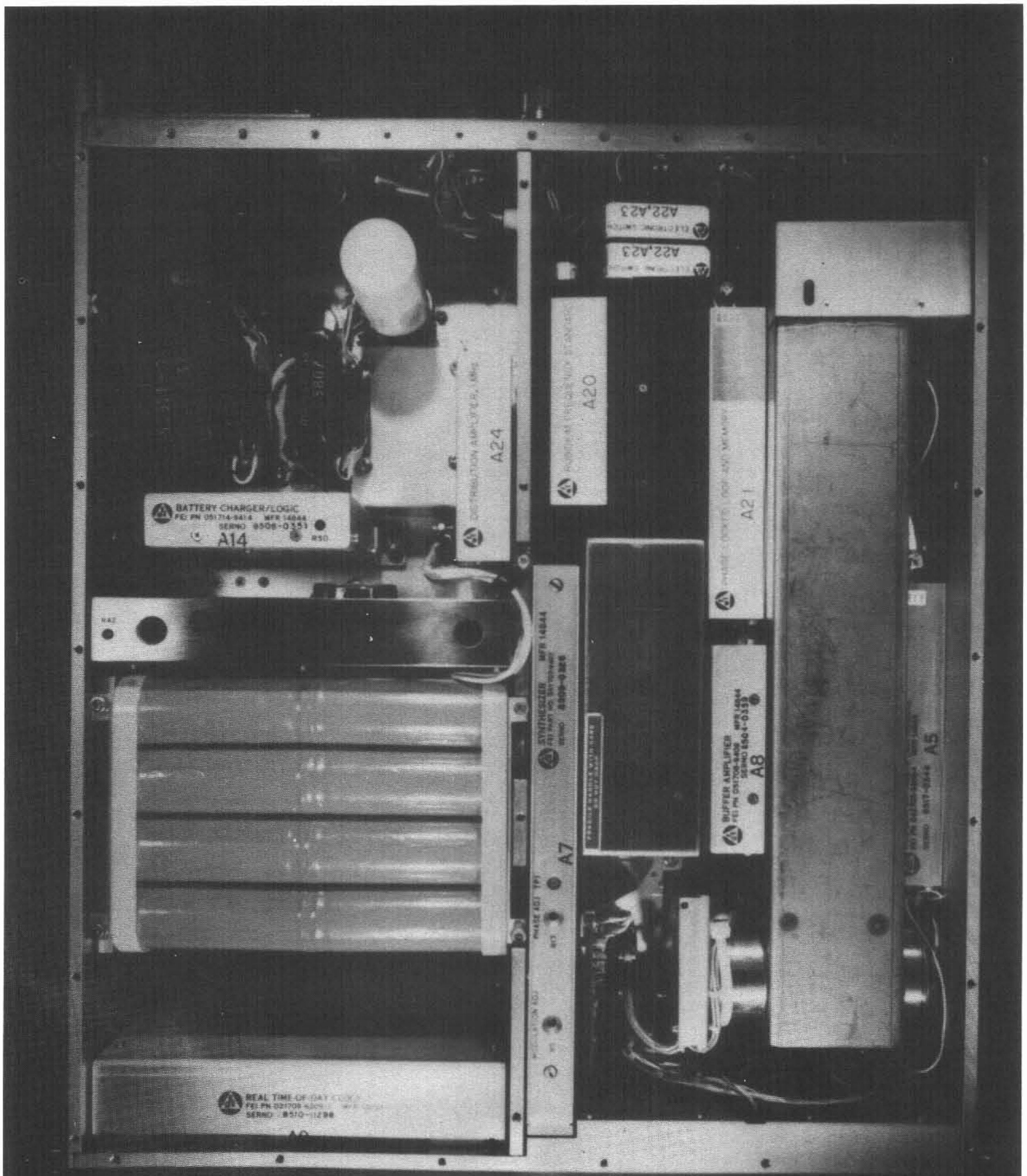

FIGURE 8

TRIPLY-REDUNDANT PRECISION TIME AND

FREQUENCY STANDARD (COVER REMOVED)

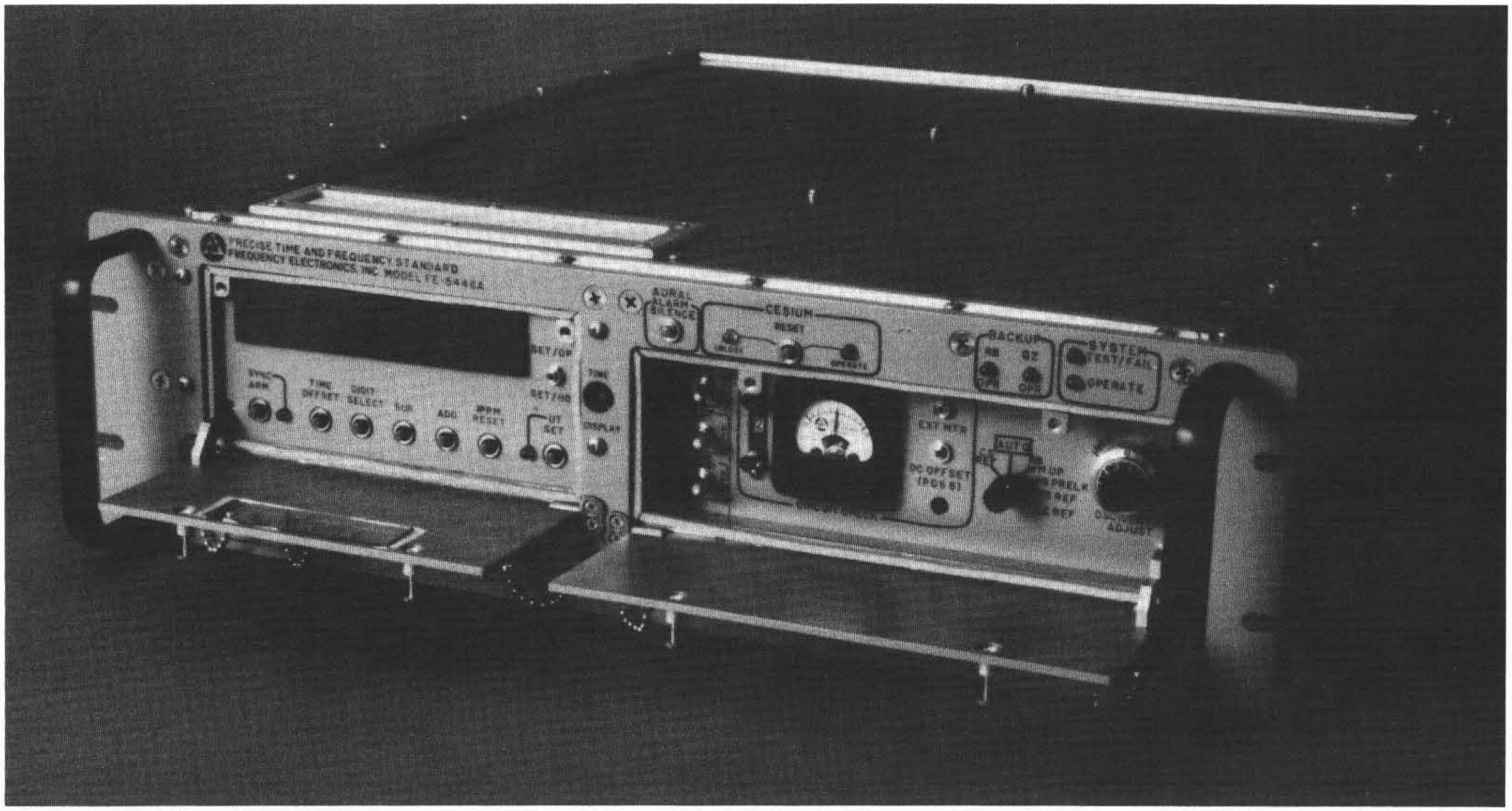

FIGURE 9

PRECISION TIME AND FREQUENCY

STANDARD MODEL FE-5446A

PRECISION TIME AND FREQUENCY STANDARD
MODEL FE-5446A

FEATURE	CAPABILITY	SOURCE INSTRUMENT *
• LONG-TERM STABILITY	$1X10^{-11}$ PRIMARY MODE $1X10^{-11}$/MONTH BACKUP MODE $1X10^{-11}$/DAY TERTIARY MODE	MRC RFS & DTF MRC & DTF
• SHORT-TERM STABILITY (>10 SECONDS)	$<3X10^{-11}/\sqrt{\tau}$	MRC
• SSB PHASE NOISE 1Hz BW	-150 DBc > 1 KHZ FROM SIGNAL	MRC & DTF
• SINUSOIDAL OUTPUTS	5 MHZ, 1 MHZ @ 13 DBM	MRC
• SWITCHING OF OPR MODES	AUTOMATIC, GLITCH-FREE (<.0016 DEGREE)	DTF
• TIMING SIGNALS	1 PPS, 1 PPM, SERIAL BCD TIME-OF-YEAR WITH OPTIONAL FORMATS AND TRANSMISSION LINE DRIVERS (RS-232C, RS-422A, RS-423A, OPTICAL)	MRC
• POWER SOURCES	AC, DC, INTERNAL BTRY	MRC
• CIRCUIT MONITORING	BUILT-IN METERING & STATUS LED'S	MRC & DTF

* MRC - MASTER REGULATING CLOCK MODEL FE-5440A
RFS - RUBIDIUM FREQUENCY STANDARD, MODEL FE-5600A
DTF - DISCIPLINED TIME FREQUENCY STANDARD, MODEL FE-1050A

TABLE 2

REDUNDANCY SEQUENCING
FOR PRECISION TIME AND FREQUENCY STANDARD, MODEL FE-5446A

EVENT	OPERATION
NO FAILURES	• CESIUM LOOP ENERGIZED, RUBIDIUM OFF PRIMARY MODE
CESIUM LOOP FAILS	• QZ OSC. HOLDS FREQUENCY DURING 15 MIN. RUBIDIUM WARMUP. • RUBIDIUM DISCIPLINED TO QZ OSC. FREQUENCY • RUBIDIUM HOLDS FREQUENCY WHILE PHASE CORRECTION IS MADE • QZ OSC. DISCIPLINED TO RUBIDIUM FREQUENCY SECONDARY (BACKUP) MODE
RUBIDIUM FREQUENCY STD FAILS	• QZ OSC. HOLDS FREQUENCY TERTIARY (BACKUP) MODE
QZ FAILS WHILE DISCIPLINED TO RUBIDIUM FREQUENCY STD.	• RUBIDIUM SUPPLIES OUTPUT FREQUENCY VIA RF SWITCH (NOT GLITCH-FREE) A FOURTH BACKUP

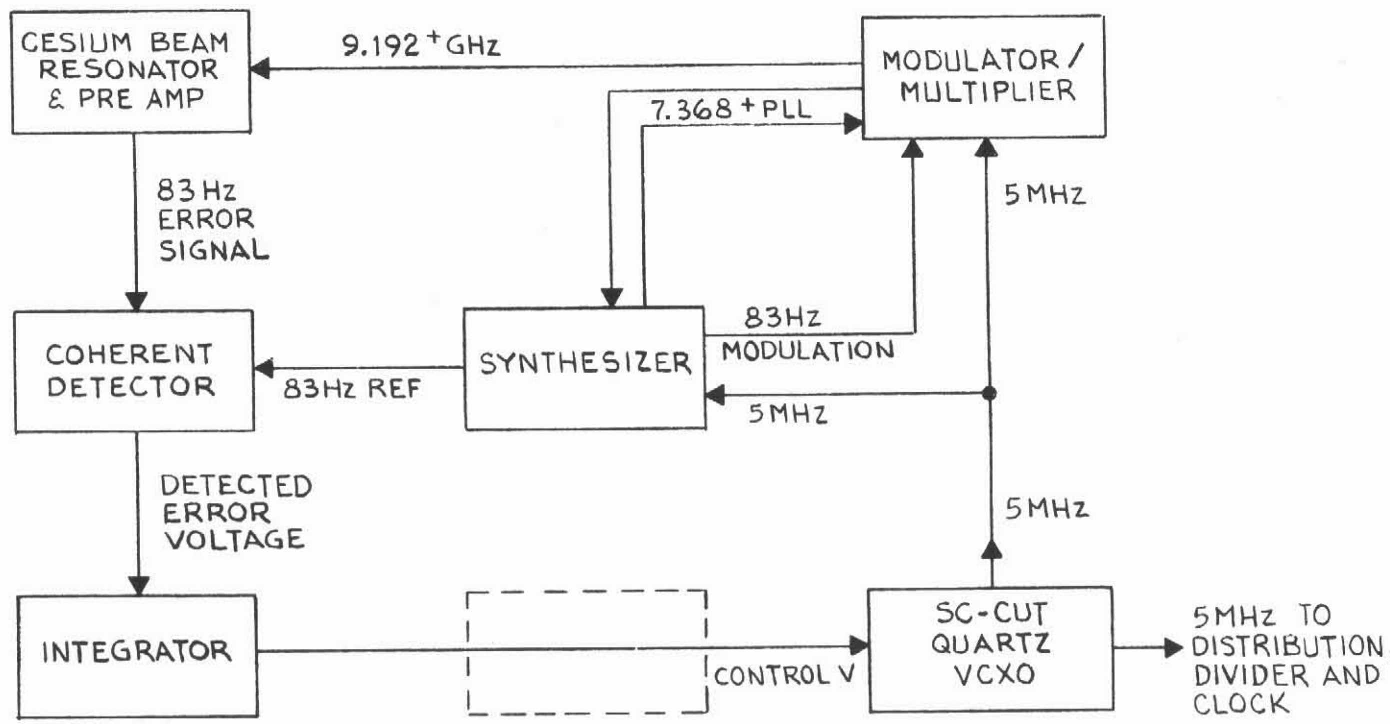

FIGURE 10

PRIMARY LOOP-CESIUM FREQUENCY STANDARD

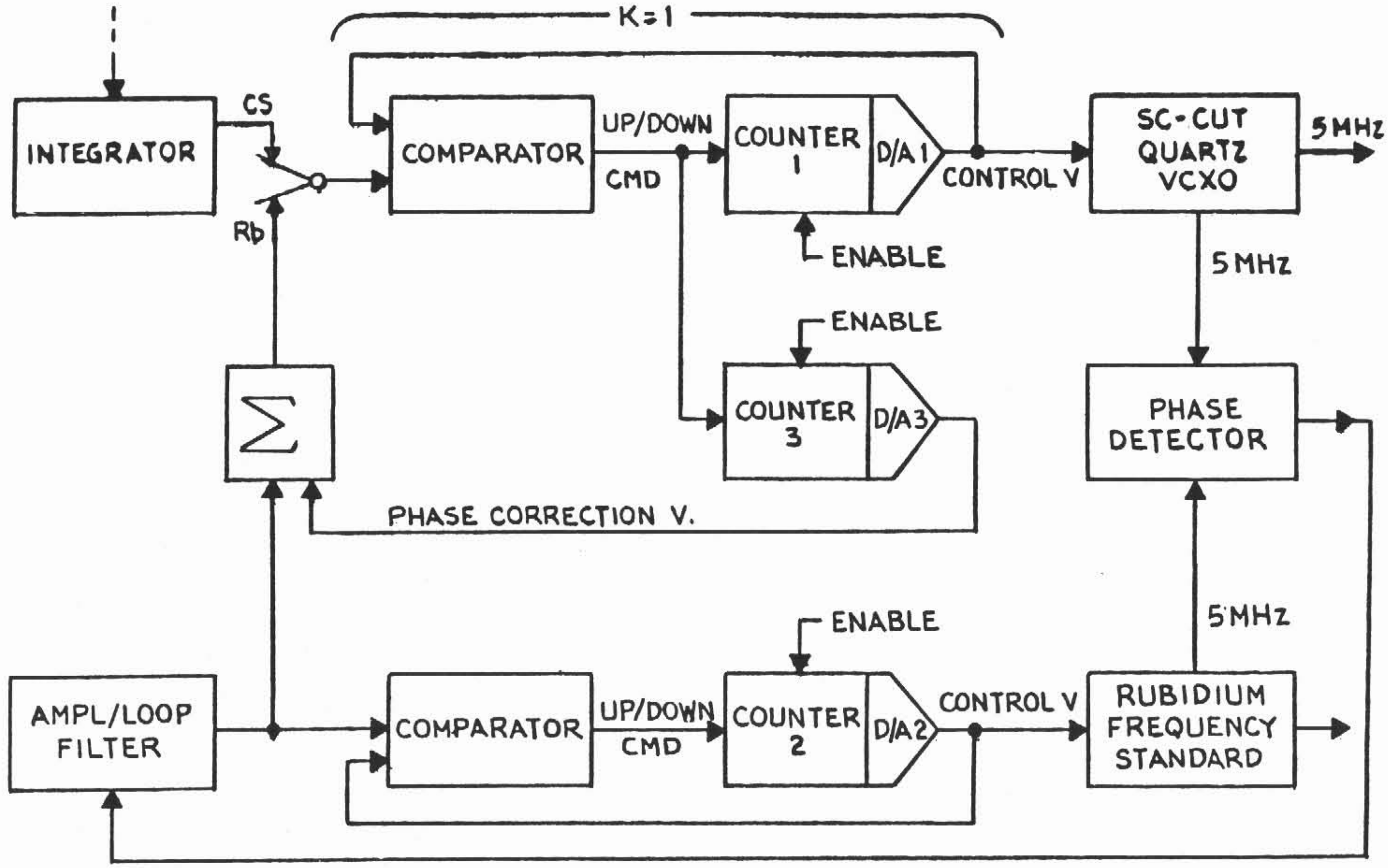

FIGURE 11

RUBIDIUM PHASE LOCK LOOP & MEMORY CIRCUIT
BACKUP LOOP

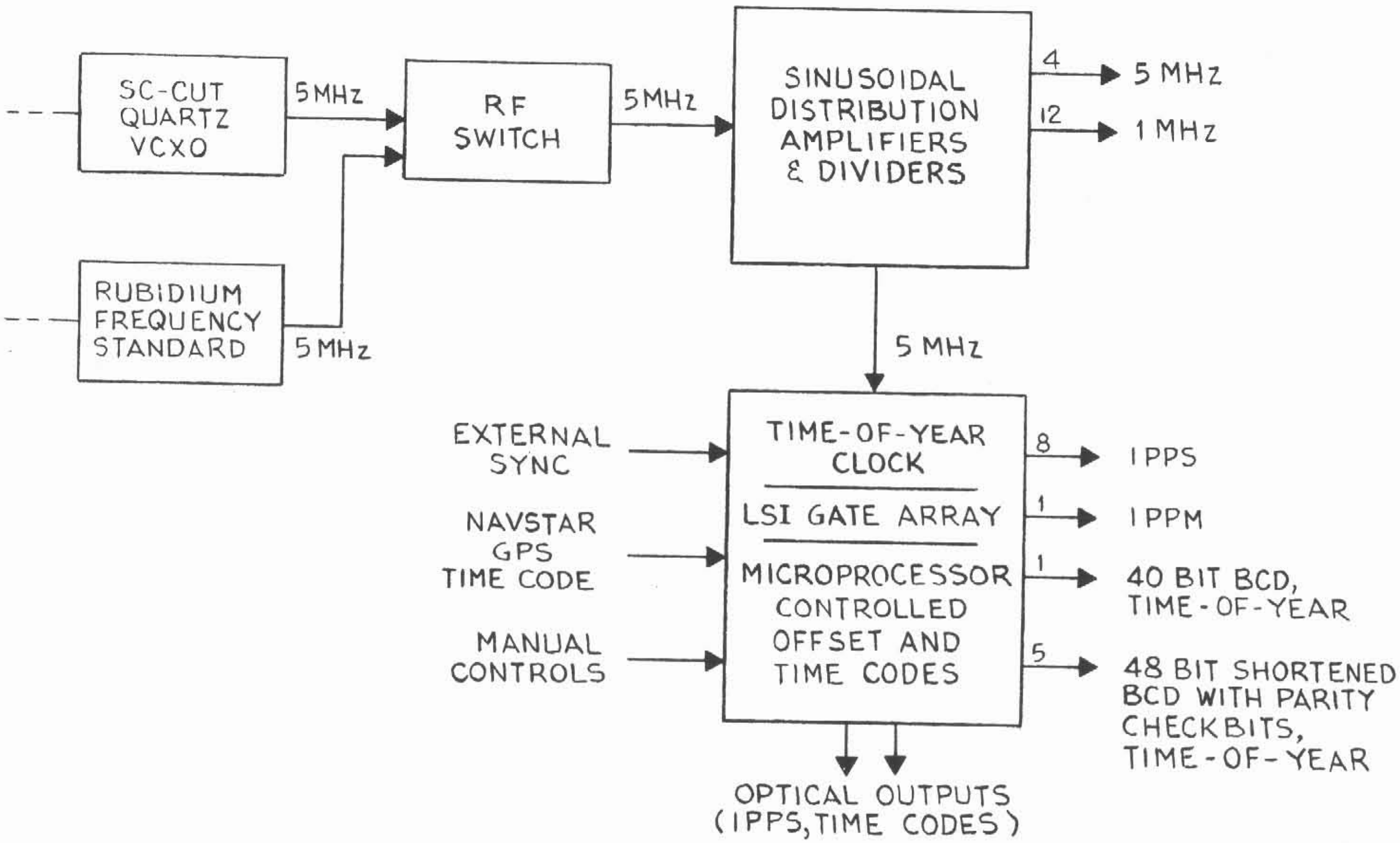

FIGURE 12

SINUSOIDAL DISTRIBUTION & TIME-OF-YEAR CLOCK

QUESTIONS AND ANSWERS

Andy Johnson, Naval Observatory: Could you replace your rubidium with another cesium in that loop?

Mr. Silvermetz: Certainly it could be done externally. In this particular package where we had space available inside the MRC (Master Regulating Clock) it fitted itself very nicely to our rubidium standard with some other circuitry from out disciplined time and frequency standard.

Albert Kirk, Jet Propulsion Laboratory: You have an up– down–counter in your feedback loop. At what rate does that counter run?

Mr. Silvermetz: We are using a sixteen bit D/A converter which runs at 32 kHz. That is the clocking rate.

Mr. Kirk: Do you have any data on the spurious signals on the 5MHz output?

Mr. Silvermetz: We have made measurements using our phase measuring instruments and have not been able to see any difference. I bypassed it, I left it in and could see no difference.