AN ENVIRONMENTALLY HARDENED PRECISION QUARTZ OSCILLATOR

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ABSTRACT

Frequency and Time Systems has recently completed the design of a new ovenized quartz oscillator, the FTS 2000A. This design responds to the growing need for precision reference sources which perform under extremes of environmental stress.

Comprehensive performance data will be presented for the 2000A design. Sensitivity to acceleration and temperature, short term stability, and phase noise performance will be discussed. Warm-up behavior and aging results will be given, as will results of vibration qualification tests.

INTRODUCTION

With the advent of the GPS system a need has developed for a class of high precision ovenized quartz oscillators, which are compact, rugged, warm-up rapidly, and consume little power. Traditional features of the ovenized oscillator, such as low aging and good short term stability, must be maintained. These requirements are also common to many other systems, in particular instrumentation for avionic and land mobile applications.

In developing the 2000A oscillator to meet these needs we saw an opportunity to improve the performance and manufacturability of the unit. New components were available which promised performance improvements; the most important of these was the SC-cut crystal.

The 2000A oscillator (see Figure 1) was designed to provide reproducible performance on a production basis. We will present data for a production run of 70 units, at approximately 10 MHz, to demonstrate the performance achieved with the 2000A design.

DESIGN

The primary features which we wanted to build into this new design included fast warm-up capability, small size, and ruggedness. With the use of an SC-cut crystal a fast warm-up oscillator was now feasible. The low thermal sensitivity of the SC crystal enabled us to achieve acceptable thermal performance without using a dewar, minimizing size and weight of the oscillator, and maintaining the ruggedness of the design.

Functionally a precision oscillator can be easily partitioned into three modules: the oscillator circuitry, the oven control circuitry, and the interface circuitry (comprising voltage regulators and buffer amplifiers). This partitioning allowed the implementation of straightforward fabrication and test concepts, thus streamlining the production process.

The 2000A oscillator is a Colpitts type oscillator with active signal level stabilization circuitry, which uses a third overtone SC-cut crystal resonator in the 4–16 MHz range. This SC crystal provides a number of advantages. SC crystals can be used in fast warm-up oscillators, as they do not suffer from the dynamic thermal overshoot effect and the slow recovery that AT crystals exhibit. They also have a frequency vs. temperature coefficient approximately 10 times smaller than the AT crystal. The SC-cut crystal can be driven at a higher current without degrading stability; leading to improved phase noise performance. The crystal uses a four point mounting system for survivability in high shock and vibration environments.

The oven control circuit is based on an integrating servo loop, eliminating offsets in oven temperature due to changes in ambient temperature or supply voltage. The oven servo controls two power MOS transistors, which apply heat to the oven isotherm surrounding the oscillator and oven control circuitry.

The interface section contains the voltage regulators, buffers and associated circuitry. These components are outside the oven to limit the temperature rise inside the oven isotherm. The advantage of separating these components is the ease with which the oscillator can be modified. The 2000A is available in a wide variety of configurations. Input voltages can range from 13-33 V, and a number of options for output levels and waveforms, tuning slope, grounding configurations, and various monitor functions are available.

The separation of the circuitry into different functional modules provides important advantages. Each subassembly can be tested individually and modifications of a single subassembly can be made and tested, without concern about the effects on other parts of the oscillator. This shortens the design cycle for adding new features, and provides the capability to meet special requirements, such as nonstandard supply voltages, grounding configurations, or output waveforms.

The mechanical package has been designed for ruggedness, with the oscillator and oven control electronics mounted within a small copper oven. The oven assembly is held within a conforming molded foam shell, which provides efficient mechanical support and thermal insulation while allowing for easy assembly. Electrical connections between the oven assembly and the interface circuitry are made with flexible ribbon cable to eliminate hand wiring, thus increasing reliability and ease of assembly. The outer enclosure of the oscillator is a deep drawn tinned steel can, which can be hermetically sealed if desired.

RESULTS

The 2000A oscillator was designed to be produced in quantity; the following data is presented to demonstrate the reproducible behavior achieved with this design. Table 1 shows the specifications for some of the relevant performance characteristics of the 2000A, along with the average results for the oscillators from the first lot of approximately 70 units. In many cases the observed behavior surpasses our initial design specifications.

Warm-up

The 2000A oscillators warm-up to within $2x10^{-8}$ of final frequency in 10 minutes. Thirty minutes after turn on, the oscillators are within $2x10^{-10}$ of their final frequency. The warm-up behavior of these oscillators is very reproducible, showing only minor variations from unit to unit.

The potential for even faster warm-up exists with this oscillator design. Data for an optional design, which provide faster warm-up than the standard oscillator, are demonstrated in Figure 2. This unit will reach $2x10^{-8}$ after only 6 minutes, with an input power of 30 Watts.

Stability and Phase Noise

The stability of the 2000A oscillator was measured 30 minutes after turning on the oscillator. The Allan variance at 1,10, and 100 seconds was calculated in two different ways; both with the frequency drift included, and with this drift removed, so as to measure the true random noise properties of the oscillator. The oscillator frequency was modeled as a cubic polynomial, and fit using the least square technique. The calculated frequency drift was then subtracted from the measured results. This left only the random frequency fluctuations, from which to calculate the Allan variance.

There are two reasons to measure the Allan variance in both ways. In some sophisticated system designs the drift of an oscillator is monitored and compensated for; system performance is therefore limited only by the random noise of the oscillator. In many other systems this is not feasible, and the user is concerned with the total frequency fluctuations, including drift. The other reason for removing the drift in our stability calculations was to measure the true random noise shortly after turning the power on. Our measurements have shown that after several minutes on, the oscillator noise is roughly constant near its final value within a few minutes after turning on the oscillator. The Allan variance of an oscillator after stabilization can therefore be estimated without having to wait a long time for the oscillator to settle down.

Figures 3-5 show the 1, 10 & 100 second Allan variance after 30 minutes warm-up. These results include the drift terms, which only significantly change the 100 second Allan variance. The 100 second stability with drift removed shows major improvement and is shown in Figure 6.

At 1 Hz the single sideband phase noise averages -104 dBc as shown in Figure 7. This performance reflects the oscillator effective Q of 250,000; this includes the contribution from crystal noise. At frequencies far from the carrier the 2000A shows improved phase noise characteristics, due to improvements in our circuitry, and the higher drive levels allowed with the SC crystal. Results from this lot show an average phase noise level of -150 dBc from 100 Hz to 10 kHz, as shown in Figure 8.

Temperature Stability

The use of an oven without a dewar imposes limitations on the degree of isolation from environmental temperature fluctuations. The design of the 2000A uses an isotherm surrounding the oscillator components and an integrating oven control servo loop to minimize the effect of ambient temperature fluctuations on the oscillator. Frequency stability of < $5x10^{-9}$ over the range -28° to +71° C is routinely achieved, as shown in Figure 9. The foam thermal insulator used in the 2000A has a lower thermal resistance between the oven and the environment than a dewar would have. However, the power dissipated by the oscillator electronics will cause a smaller temperature rise in the oven than would occur in a oscillator with a dewar, allowing the oscillator to operate at a higher maximum ambient temperature.

Acceleration Sensitivity

The oscillator specification for acceleration along the most sensitive axis, is $2x10^{-9}/g$. As can be seen in Figure 10 there is significant variability in the results obtained from these units. The acceleration sensitivity is a function of the crystal resonator and oscillator circuitry. Our tests of phase noise under vibration show no evidence of significant mechanical resonances which would seriously degrade the dynamic acceleration sensitivity of the oscillator. The resonator is not aligned to reduce the acceleration sensitivity along any particular axis. Better results for a particular axis can be achieved through alignment.

Aging

Due to the manufacturing variability of resonators the oscillator aging is specified very conservatively. The results obtained from this lot show that the oscillator aging is better than the specified rate of $5x10^{-10}$/day. This is true even though the oscillators in this lot were measured after only three days of burn-in (or until the aging rate was below $1x10^{-9}$/day). Figure 11 shows the aging rates measured for these oscillators. It has been our experience that the observed aging rate improves with longer burn-in time.

Vibration

These units are designed to operate under high levels of vibration; tests have been performed at vibration levels of up to 8 g's RMS integrated from 10 to 500 Hz.

Reliability

The reliability of these units was calculated using MIL-HDBK-217D. The results for ground benign and airborne inhabited transport environments are shown in Table 12.

CONCLUSION

FTS has designed a new environmentally hardened precision oscillator which exhibits excellent performance. Results from the first lot demonstrate that this oscillator can be built in a reproducible, cost effective manner. The design allows for easy modification, which makes the 2000A oscillator useful for applications requiring precision timing and frequency stability over a wide range of environmental conditions.

Parameter	Specification	Average Performance
Maximum Frequency Change		
Supply Voltage(10% change)	$5x10^{-10}$	$0.7x10^{-10}$
Acceleration	$2x10^{-9}$	$1.7x10^{-9}$
-28° to +71° C	$5x10^{-9}$	$3.8x10^{-9}$
Short Term Stability		
1 sec	$8x10^{-12}$	$2.6x10^{-12}$
10 sec	$8x10^{-12}$	$2.8x10^{-12}$
Long Term Stability		
1 day	$5x10^{-10}$	$2.9x10^{-10}$
SSB Phase Noise		
1 Hz	-90 dBc	-104.6 dBc
10 Hz	-120 dBc	-127.4 dBc
100 Hz	-140 dBc	-148.6 dBc
10 kHz	-150 dBc	-150.1 dBc

Table 1. Specified vs. Actual Performance of the FTS 2000A Oscillator

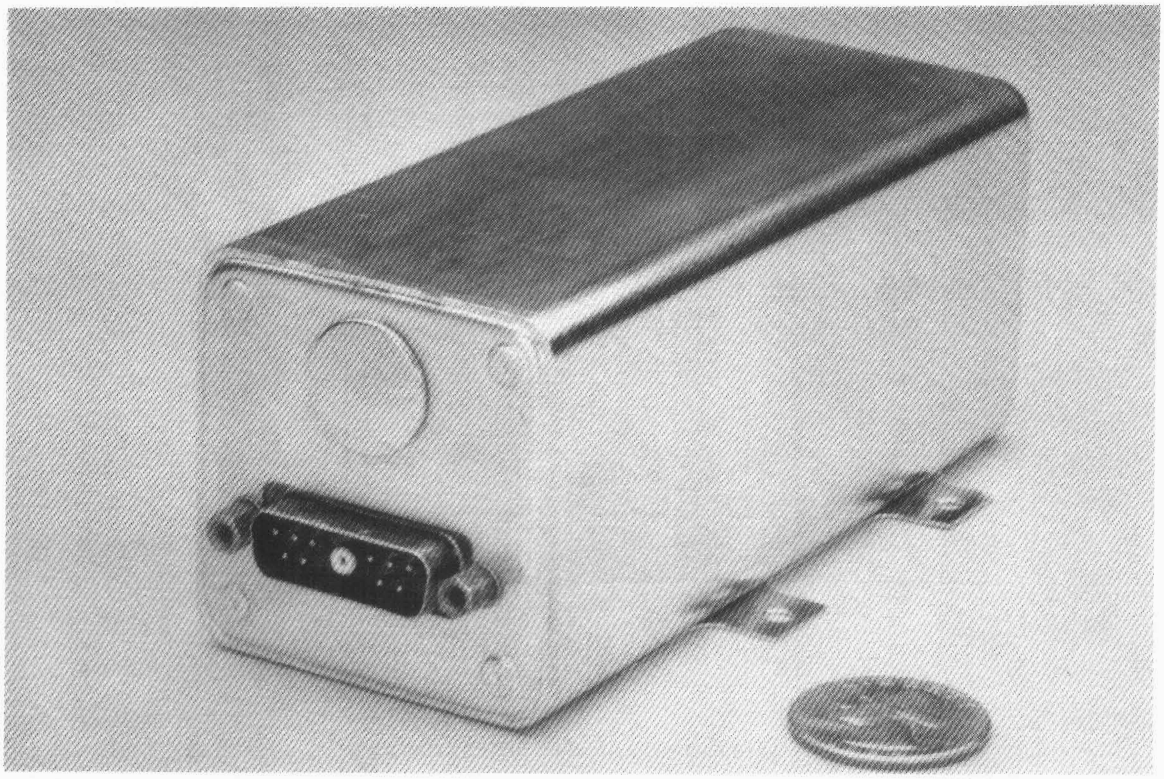

Figure 1. The FTS 2000A Oscillator

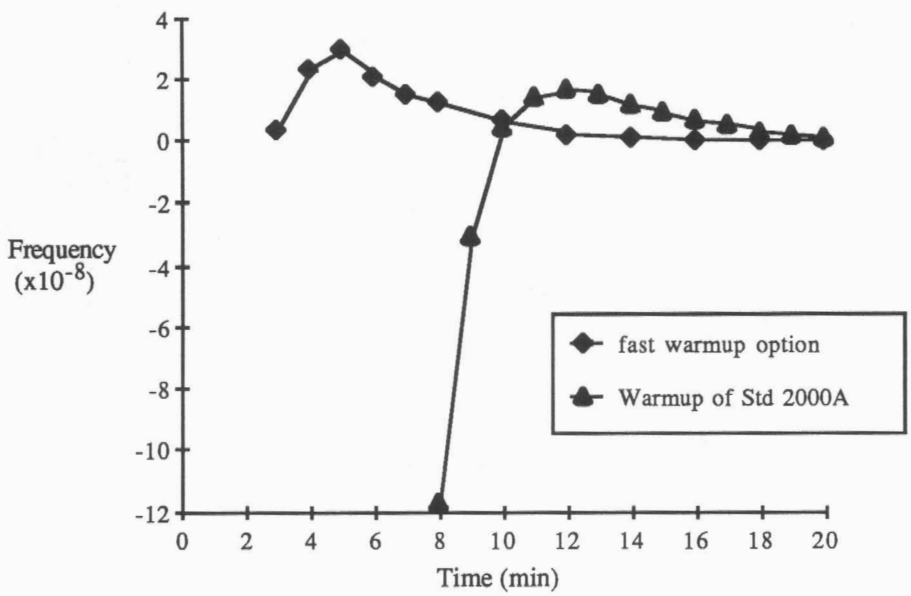

Figure 2. Fast Warmup Option Compared to Std 2000A

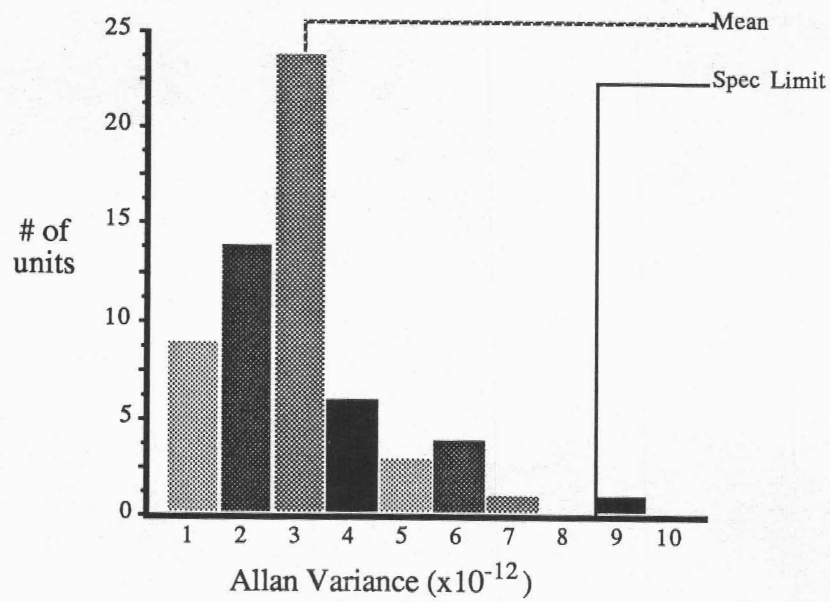

Figure 3. 1 Second Allan Variance Including Drift

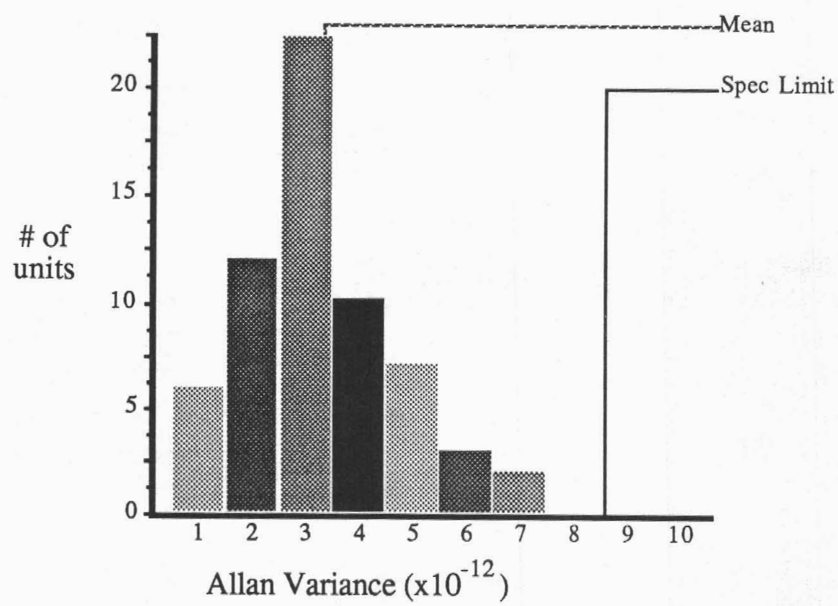

Figure 4. 10 Second Allan Variance Including Drift

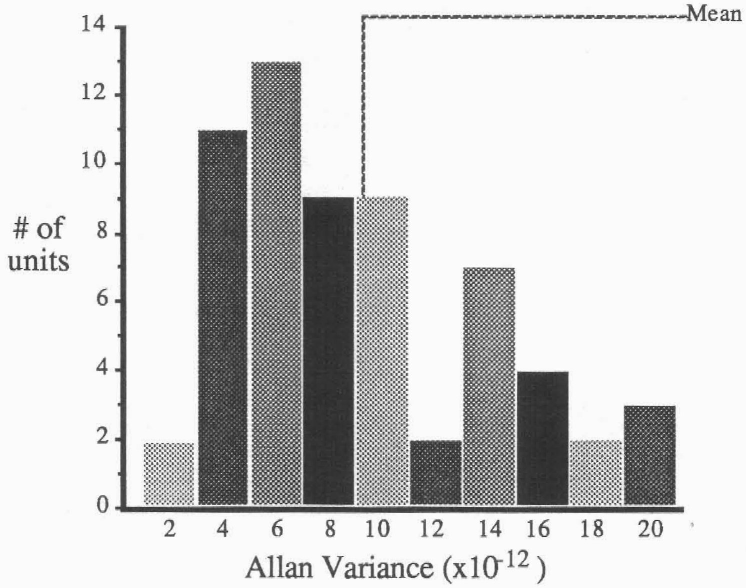

Figure 5. 100 Second Allan Variance Including Drift

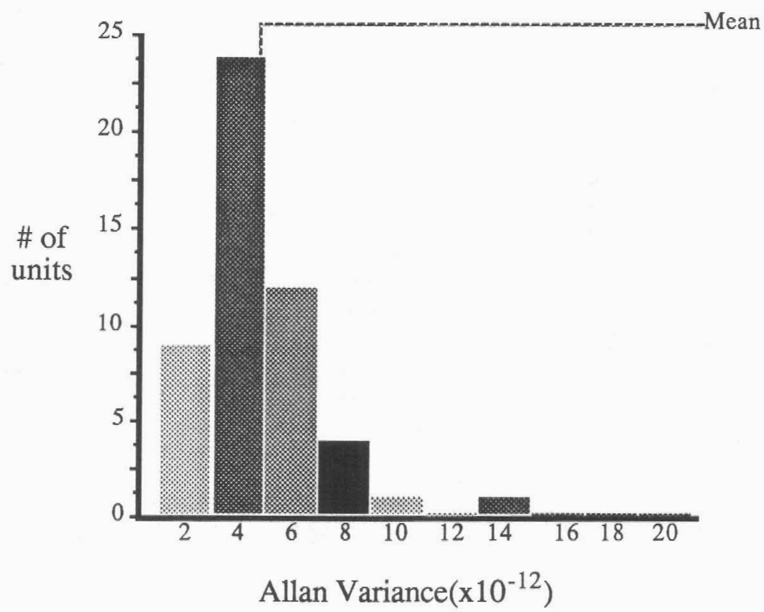

Figure 6. 100 Second Allan variance with Drift Removed

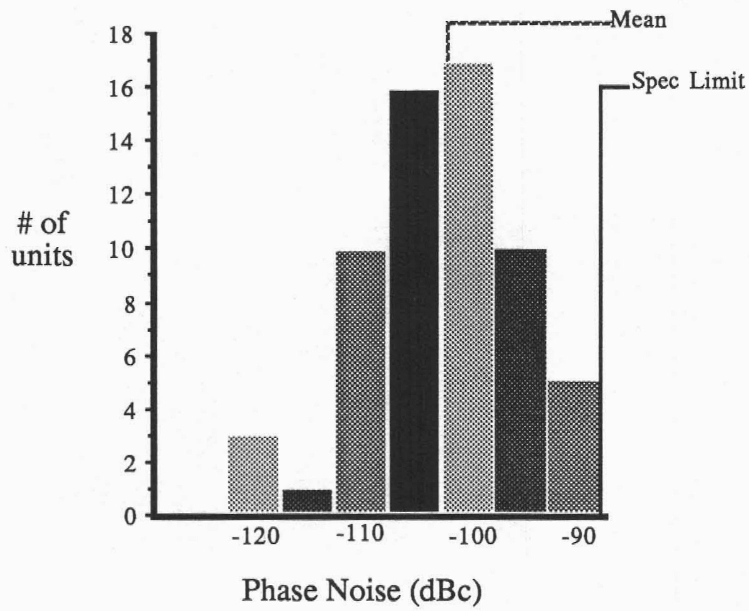

Figure 7. 1 Hz SSB Phase Noise

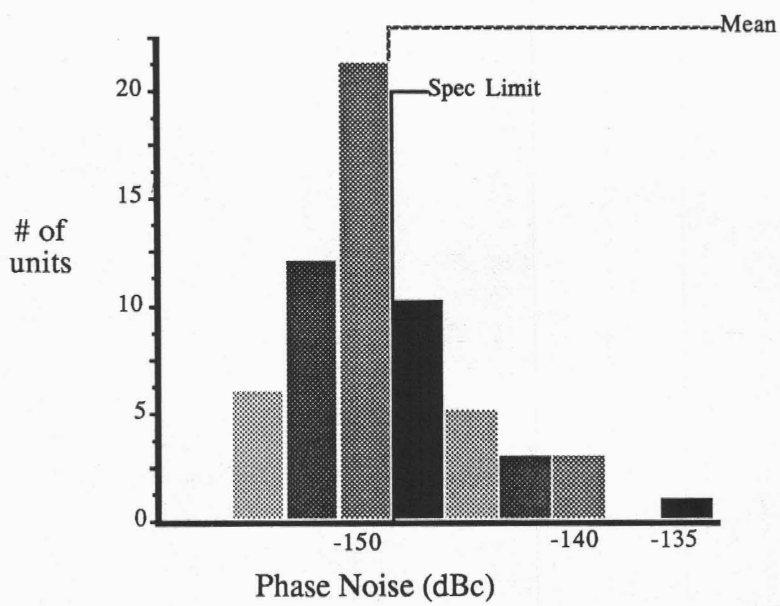

Figure 8. 10 kHz SSB Phase Noise

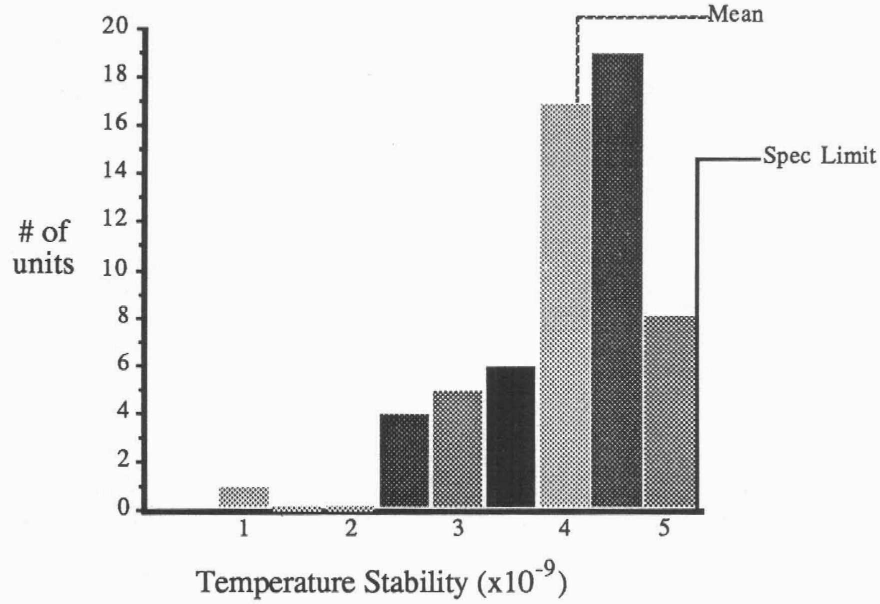

Figure 9. Temperature Stability -28° to +71°C

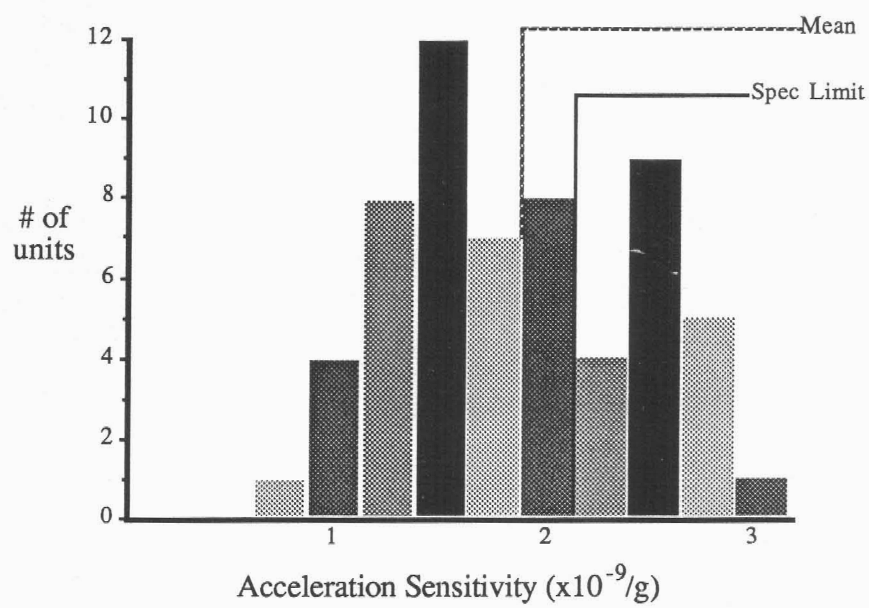

Figure 10. Acceleration Sensitivity (most sensitive axis)

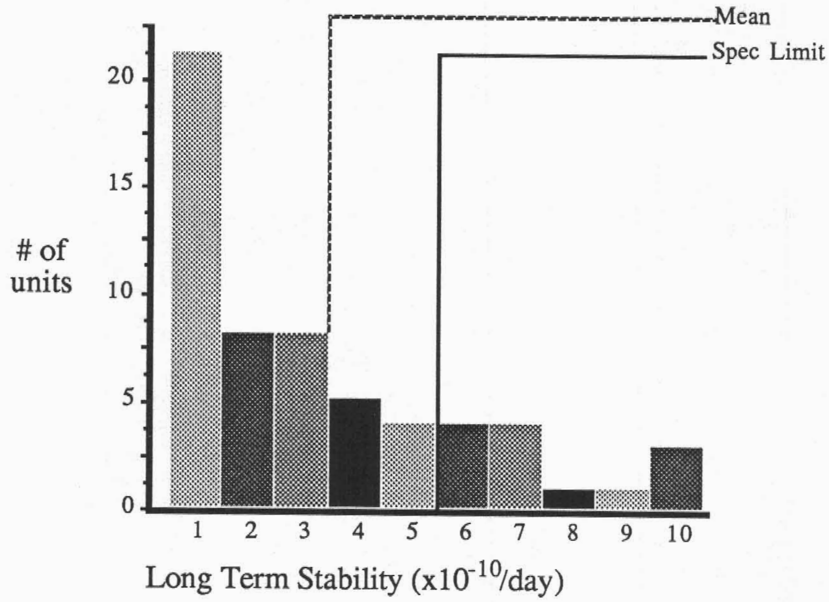

Figure 11. Long Term Stability

Environment	MTBF
Ground Benign	183,987 hrs
Airborne Inhabited Transport	65,700 hrs

Table 2. Reliability of the FTS 2000A Oscillator

QUESTIONS AND ANSWERS

DAVID ALLAN, NATIONAL BUREAU OF STANDARDS: A very important question for many military applications is what happens to the power spectral density of phase in the presence of vibration.

MR. BASS: I will let the person that performed the tests answer that. Mr. Melliren.

BRYAN MELLIREN: We have looked at the spectral density of phase fluctuations under a flat spectrum, 10 Hz to 2 kHz. It goes down about 20 dB per decade as you would expect.