A NEW RUGGED LOW NOISE HIGH PRECISION OSCILLATOR

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ABSTRACT

This paper describes the performance characteristics of a new, rugged 5 MHz quartz crystal oscillator having good short and long term stability. It exhibits high spectral purity at frequencies close to the carrier, with phase noise typically -120 db at 1 Hz. Short term stability is characterized by $\sigma(\tau)$ less than 1×10^{-12} for sample times of 1 second to 100 seconds.

The oscillator provides a precision low-noise source suitable for high order frequency multiplication in navigation or communications systems which must survive physical abuse as well as hostile radiation environments. It meets the demanding environmental specifications of the satellite portion of the NAVSTAR GPS system. Power consumption of less than two watts is compatible with the requirements of a satellite-borne cesium frequency standard. Linear voltage controlled tuning permits operation over a 5-year satellite mission duration.

Frequency stability against ambient temperature changes is an important consideration in the design. The oscillator exhibits stability of better than 5×10^{-10} over the ambient range of $-55^{\circ}C$ to $+61^{\circ}C$. Thermal stability data and results of shock and vibration testing will be presented.

INTRODUCTION

A rugged high precision 5 MHz oscillator has been developed for applications requiring a frequency source which has good spectral purity and frequency stability, and which is able to withstand severe shock and vibration. The oscillator exhibits very low phase noise close to the carrier, typically -120 db in a 1 Hz bandwidth at 1 Hz. Short term frequency stability is characterized by an Allan variance σ (τ) of less than 1 x 10^{-12} for sample times of 1 to 100 seconds. (Fig. 1)

The oscillator thus provides a precision low-noise source suitable for high order frequency multiplication in navigational or communications systems which must survive physical abuse, extremes of temperature, or severe radiation environments. In spite of the overriding design requirements of physical survivability, it has been possible to achieve the kind of low-noise performance described by Brandenberger et al (1), and we have been fortunate in being able to draw on that experience.

The 5th overtone AT cut quartz crystal and associated electronics are held at the frequency turnover point in a proportionally controlled oven whose temperature is maintained constant to better than $0.1^{\circ}C$ over an ambient temperature range of $-55^{\circ}C$ to $+61^{\circ}C$.

At present we produce the oscillator in two configurations; one designed specifically for GPS application, and one in a slightly modified package for more general applications in severe environments.

To emphasize the survivability aspect of this design, I will first describe the 5.115 MHz variation being produced for satellite cesium frequency standards in the NAVSTAR GPS system. Then I will discuss detailed specifications and performance of this new oscillator design, the FTS Model 1000.

SATELLITE OSCILLATOR REQUIREMENTS AND PERFORMANCE

One of the tasks of FTS in the NAVSTAR GPS program was to provide prototype model cesium standards, with a low aging rate quartz oscillator which would demonstrate the required survivability for rocket launch and a long term space mission. The first units were delivered to NRL early in 1976 for evaluation and use in the NTS-2 satellite. Quartz resonators were fabricated from premium Q grade swept quartz and then subjected to extensive testing, selection and processing before use.

The next generation Engineering Development Model oscillator contains selected, screened parts, the requisite radiation resistant circuitry, and appropriate shielding for the GPS-NDS satellite missions.

In the satellite cesium standard back-up mode, the oscillator may operate independently of the cesium control loop as a prime frequency source with low drift rate and good frequency stability. The 5.115 MHz output is frequency doubled outside the oscillator, and additional circuitry provides the desired radiation-immune user signal at the 10.23 MHz GPS frequency.

Figure 2 shows the GPS environmental specifications as well as typical performance. The oscillator has undergone repeated random vibration testing at the (previous) 23.2 g (rms) qualification level both separately, hard mounted to the test fixture, and as part of the EDM cesium standard chassis. Oscillators have also been successfully tested at higher levels up to 29 g (rms).

During 10 g (rms) random vibration tests on an operating oscillator, frequency excursions are well within the electronic control tuning range, with recovery to original frequency in less than 1 hour. The transient excursion is double valued, so the accumulated phase error in a timekeeping system tends to average to zero.

The specified pyrotechnic shock, 2300 g peak at 1850 Hz, is a non-operating survival test, but we have monitored frequency during test of an operating oscillator and find $\Delta f/f$ shifts of a few parts in 10^{10} per pulse. A sequence of 12 pulses produced a final offset of the order of 5×10^{-11} in one instance.

Frequency offset for various ambient operating temperatures is an important consideration. The upper temperature limit of operation becomes especially important in vacuum. It has been our goal to permit stable operation over as wide a range of temperature as might be expected in diverse nonlaboratory applications. Especially important in the prime frequency source back-up mode is frequency stability during temperature changes, since the frequency deviation response to time gradients is in general much larger than for steady operation. In addition to the requirement of operation to +50°C in vacuum, the GPS NTS-2 mission required that all operating specifications be met when the temperature of the mounting surface is controlled to within 4°C at any given operating temperature. From knowledge of the oven control gain and thermal time constants, verified by experimental results, we know that an ambient temperature slew rate of a few degrees per hour will produce less than 10^{-10} offset and no degradation of short term frequency stability.

The decision not to vacuum-seal the oscillator unit has several consequences for vacuum operation. First is the transient frequency shift associated with changing the stress environment of the resonator, coupled with the thermal perturbations of rapid air removal from the oscillator. The transient frequency offset is typically 10^{-8} for rapid pump-down, with recovery to the initial frequency in about one hour. Secondly, the thermal resistance between oven and ambient increases so that oven consumption decreases. Internal heat sources then produce a larger temperature differential than normal, and this has been taken into account when setting the upper limit for frequency stable operation.

The low power consumption in vacuum environment is an additional asset for satellite applications. The GPS oscillator typically requires less than 2 w in vacuum even though three buffered signal outputs are provided.

Figure 3 shows the GPS short term frequency stability requirement for the back-up mode (oscillator as prime frequency source). The Allan variance is σ (N=2, T= τ , τ). Also shown are typical data for τ between 1 sec and 100 sec.

The observed short term stability is typically 5×10^{-13}, consistent with the measured phase noise in the f^{-3} region of L(f). For τ less than 1 second, one expects a region of τ^{-1} behavior, with $\tau \times \sigma (\tau) = 1.4 \times 10^{-13}$ based on the measured -145 db white phase noise floor and a 1 kHz measuring system bandwidth.

Figure 4 shows the measured phase noise spectrum for an oscillator after undergoing random vibration to 20.8 g (rms) six minutes on each axis. There was no measurable degradation. The GPS specification for phase noise at the 10.23 MHz user frequency is also shown.

FTS MODEL 1000 OSCILLATOR

Detailed specifications for the FTS Model 1000 oscillator are shown in Figure 5. The weight of 1.9 lbs (0.86 kg) and 62 cubic inch size make it compact for an oscillator exhibiting this state-of-the-art performance. The oscillator requires less than 2 w normal operating power at room temperature, and typically 3.2 w at -55°C. Warm-up requires 14 w for less than 15 minutes, and frequency is within 10^{-9} of the final value one hour after turn-on. At this time the rate of change of frequency is less than 10^{-12} per second.

The model 1000 has two independent well buffered outputs at 1 v rms into 50 ohms, short circuit proof. An additional two buffered outputs can be provided. The harmonic distortion is at least 40 db below the rated output, and spurious output is better than 100 db down. Sensitivity of frequency change to output loading is $< 5 \times 10^{-11}$ for a 10% change from 50 ohm load.

Both mechanical and electrical frequency adjustments are provided, with the important feature that they are linear. A 25-turn screwdriver adjustment gives a minimum of 4×10^{-7} tuning range, and external dc voltage control (-10 V to +10 V) provides $\Delta f/f = 2 \times 10^{-7}$. These tuning ranges are additive and linearity is good over the whole range. Fig.6 shows the typical frequency shift with control voltage. The integral linearity is better than 5% for voltage control at either end of the mechanical adjustment range. This feature is of particular utility in phase locked loop applications where it is desired that the loop gain not vary with frequency offset.

The phase noise performance specification is shown in Fig.7 along with data taken using a noise measuring system such as described by Allan, et al (2). This is the single sideband phase noise per oscillator in a 1 Hz bandwidth at the fourier frequency f. A low noise mixer is followed by a very low noise amplifier system and loose phase lock to maintain the signals in quadrature. The noise voltage is then measured with a spectrum analyzer.

The behaviour of frequency offset as a function of ambient temperature is shown in Figure 8 for several oscillators. Our specification is shown by the total excursion of 5×10^{-10} over the range, and representative data from several units are shown. This performance is the result of careful attention to the control of thermal gradients, since the actual stability of a single proportional oven is not simply dictated by the loop gain. The demonstrated stability of frequency versus changing ambient is an important point when one expects high quality low noise performance in less than ideal physical conditions.

Finally, we see the usual static g sensitivity of about a part in 10^9 per g, as is typical for the high Q thickness shear mode AT cut crystals. Because the reduction of g sensitivity is a topic of great interest, we have experimented with a scheme to compensate for static g changes along the most sensitive crystal orientation, and indeed very preliminary results show that the sensitivity can be reduced to that of the other axes. However, considerable effort will need to be expended to solve the real problem of dynamic sensitivity.

Acknowledgement

The author wishes to acknowledge the contributions of James Burkhardt and Alain Jendly of FTS to this work. We gratefully acknowledge the support of the Naval Research Laboratory under contract no. N00014-74-C-0061.

References

(1) H. Brandenberger et al, Proc. 25th Ann. Symp. Frequency Control, 1971, pp. 226-230
(2) D. W. Allan et al, 1974, NBS Monograph 140 pp 151-204

FREQUENCY & TIME SYSTEMS, INC.

PRECISION 5 MHz OSCILLATOR

- RUGGED - SATELLITE APPLICATION
- RADIATION HARDENABLE - NAVSTAR GPS
- VERY LOW CLOSE-IN PHASE NOISE
- STABLE OVER WIDE AMBIENT TEMPERATURE RANGE
- MODEST POWER CONSUMPTION

FIG. 1

FREQUENCY & TIME SYSTEMS, INC.
ENVIRONMENTAL PERFORMANCE

	GPS SPECIFICATION	PERFORMANCE
RANDOM VIBRATION	20.8G(RMS) 20-2000Hz	SURVIVES 23G(RMS) 3 AXES 3 MIN EACH, REPEATEDLY
PYROTECHNIC SHOCK	2300G MAX 1850Hz PEAK(5% DAMPING)	SURVIVES SHOCK TEST AND SHOWS ΔF OF ± A FEW PARTS IN 10^{10} PER PULSE
ACCELERATION	±10G ALONG EACH OF 3 AXES 5 MINUTES	10G(RMS) TESTS ON OPERATING OSCILLATOR SHOW ΔF DURING 5 MIN WELL WITHIN ELECTRONIC TUNING RANGE
THERMAL	MUST OPERATE AFTER BEING SUBJECTED TO $-10^{\circ}, +50^{\circ}C$	$\frac{\Delta F}{F} < 5 \times 10^{-10}$ OVER THE RANGE $-50^{\circ}C$ TO $+61^{\circ}C$
NON-OPERATING	$-54^{\circ}C$ TO $+60^{\circ}C$ (DESIGN GOAL)	$-60^{\circ}C$ TO $+80^{\circ}C$

FIG. 2

FREQUENCY & TIME SYSTEMS, INC.

OSCILLATOR SHORT TERM FREQUENCY STABILITY

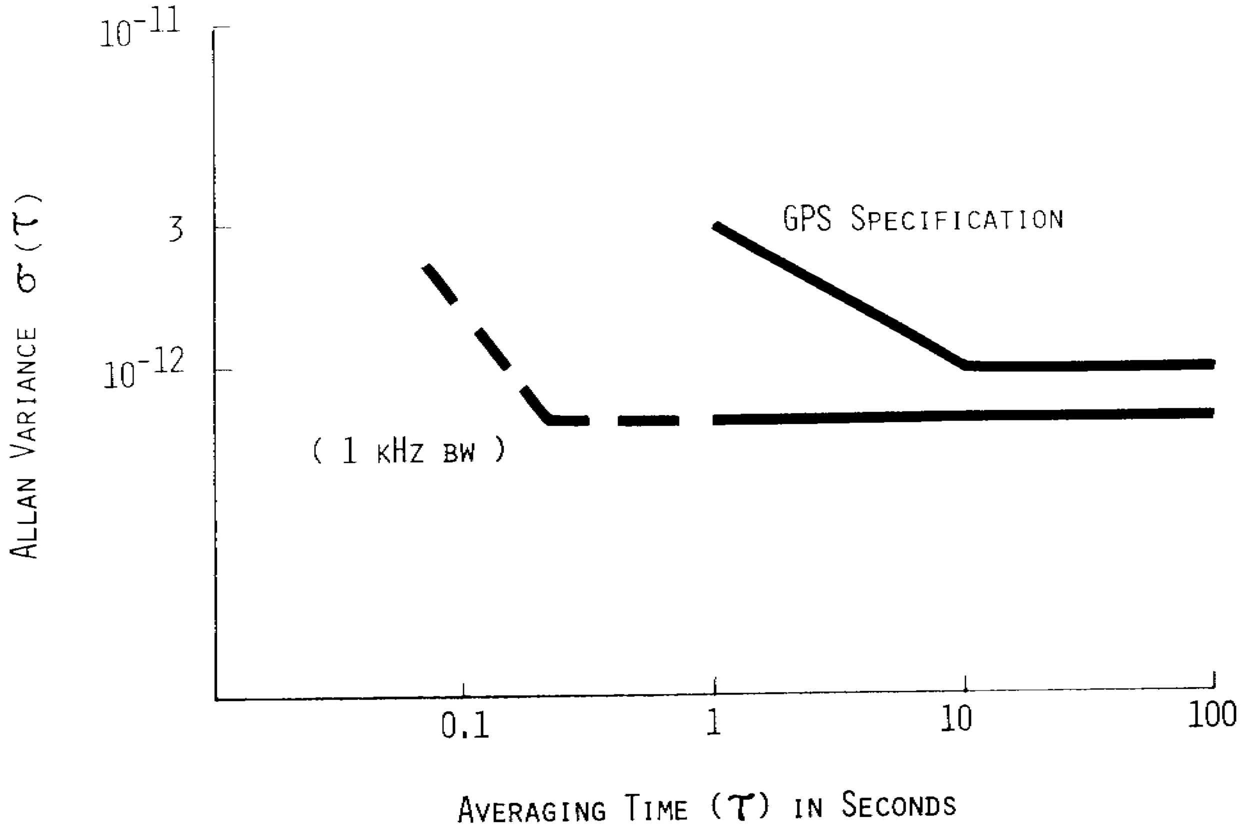

FIG. 3

FREQUENCY & TIME SYSTEMS, INC.

5.115 MHZ OSCILLATOR PHASE NOISE

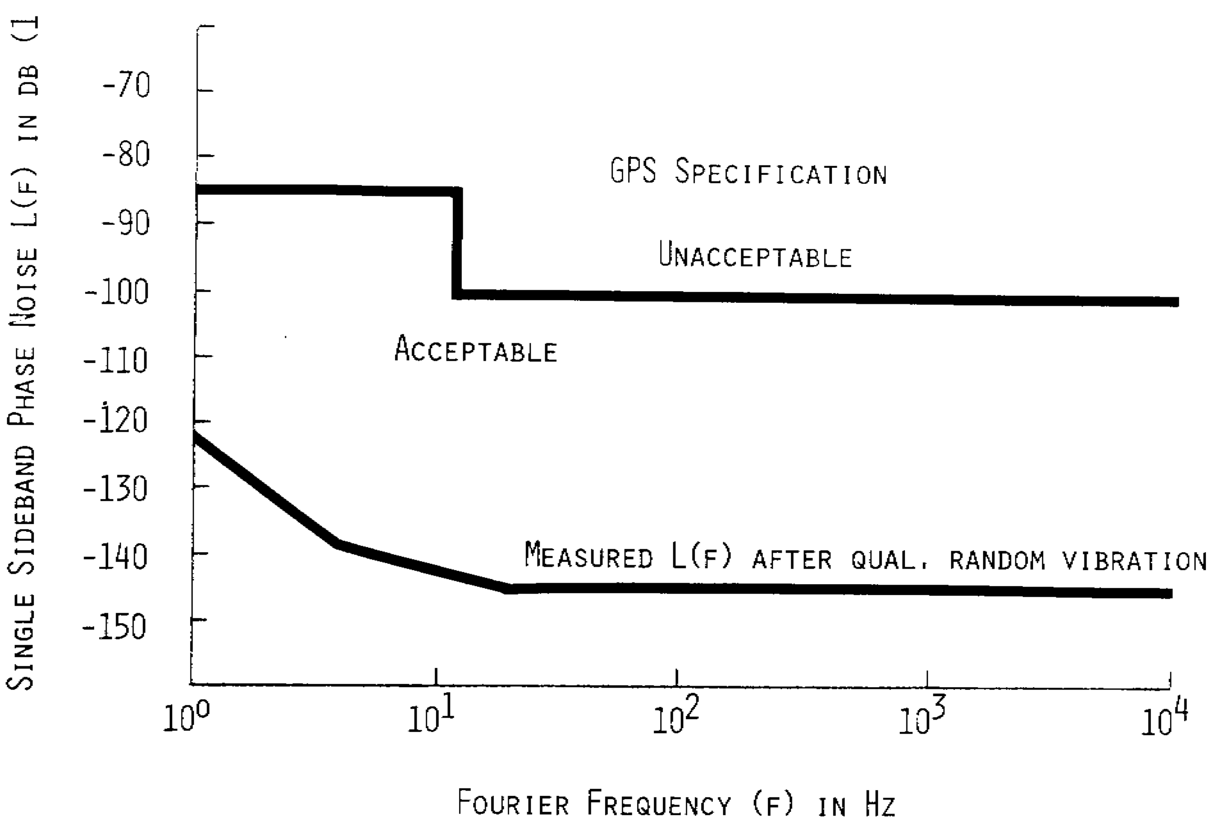

FIG. 4

FREQUENCY & TIME SYSTEMS, INC.

SPECIFICATIONS MODEL 1000 OSCILLATOR

OPERATING CONDITIONS

SUPPLY VOLTAGE	+24 VDC NOMINAL (+22 TO +30 VOLTS)
POWER REQUIREMENT	<2 WATTS OPERATING (25°C) 14 WATTS WARM-UP
OPERATING TEMP. RANGE	-55^{o}C TO $+61^{o}$C

ENVIRONMENTAL NON-OPERATING

STORAGE TEMP. RANGE	-60^{o}C TO $+80^{o}$C
VIBRATION	23 G (RMS) RANDOM, 20,2000 Hz
SHOCK	PYROTECHNIC SPECTRUM, 2300 G PEAK AT 1850 Hz (5% DAMPING)

MECHANICAL DATA

DIMENSIONS	3.00 x 3.00 x 6.88 INCHES
WEIGHT	1.9 LBS
CONNECTORS	
POWER/CONTROL	M24308/3-1,
OUTPUT	SMA JACK

FIG. 5

FREQUENCY & TIME SYSTEMS, INC.

Specifications Model 1000 Oscillator

Outputs	2 independent buffered outputs
Frequency	5 MHz
Frequency Adjustment	
Mechanical	4×10^{-7} by 25-turn screwdriver adjustment
Electrical	2×10^{-7} by external DC voltage (-10 to +10v)
Level	1 v rms/50 ohms
Harmonic Distortion	At least 40 db below rated output
Non-harmonic Components	At least 100 db below rated output
Frequency Stability	
Long Term (aging)	$<1\times10^{-10}$/day after 30 days of continuous operation
Short Term	Allan Variance 10^{-12} for 1-100 sec.
Warm-up	Within 10^{-9} in 1 hour
Temperature Effect	$<5\times10^{-10}$ over -55°C to +61°C range of ambient
Load Sensitivity	$<5\times10^{-11}$ for 10% change from 50 ohms
Supply Voltage Effect	$<5\times10^{-11}$ for 24 volts ± 10%
Static Acceleration	1×10^{-9}/G typical

Fig. 5 (Cont'd.)

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MODEL 1000 QUARTZ OSCILLATOR LINEAR TUNING

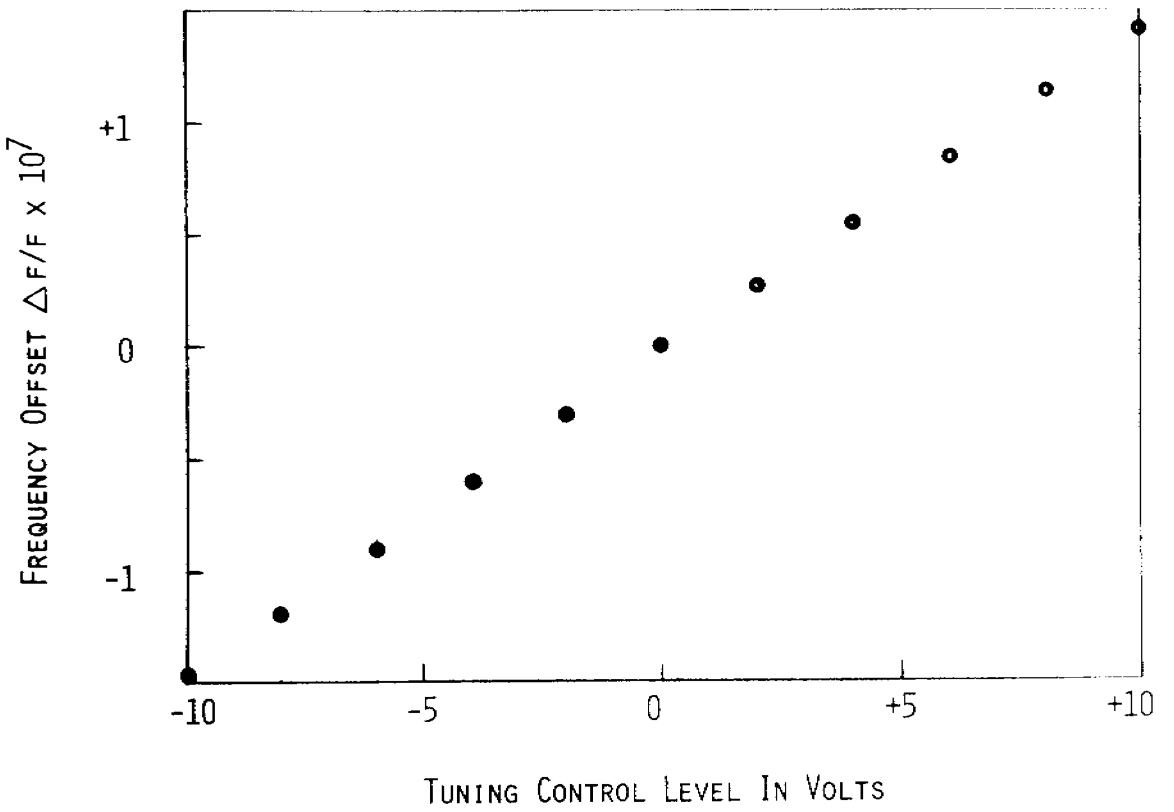

FIG. 6

FREQUENCY & TIME SYSTEMS, INC.

MODEL 1000 PHASE NOISE PERFORMANCE

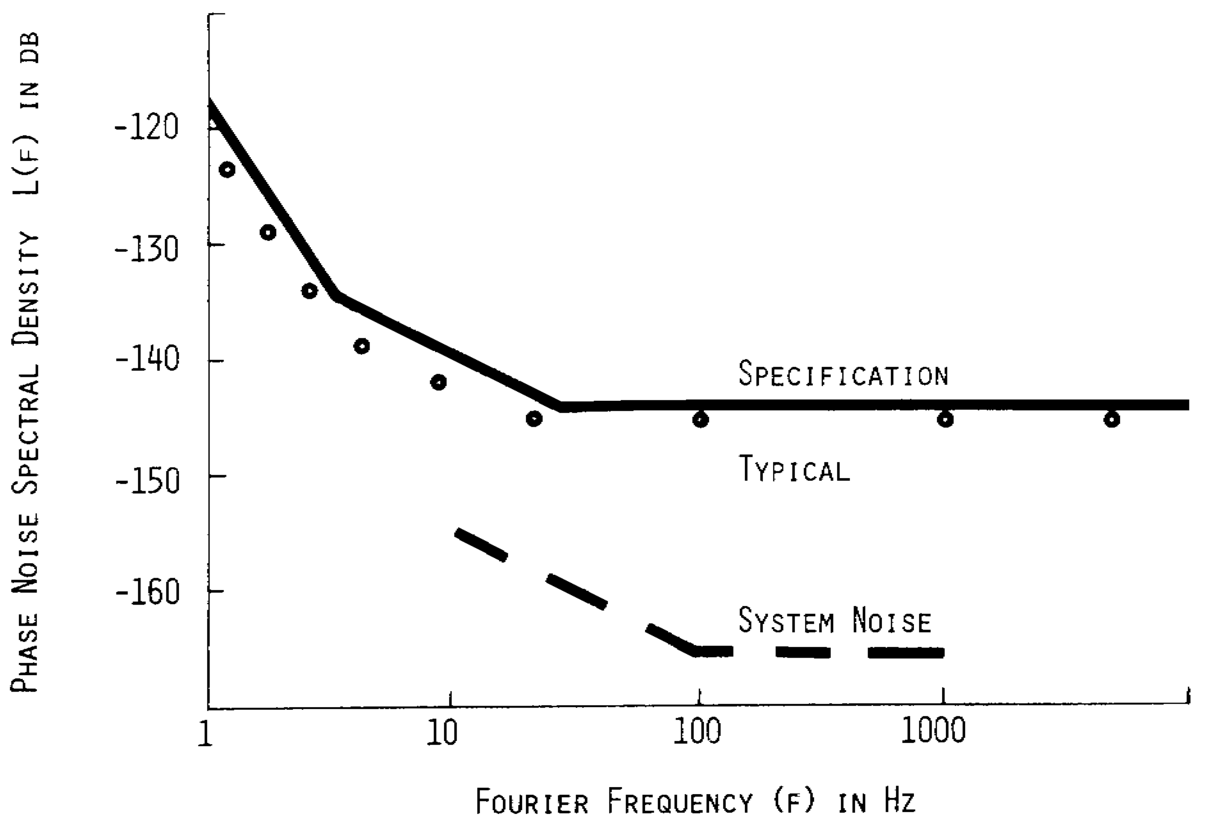

FIG. 7

FREQUENCY & TIME SYSTEMS, INC.

OSCILLATOR FREQUENCY STABILITY VS AMBIENT TEMPERATURE

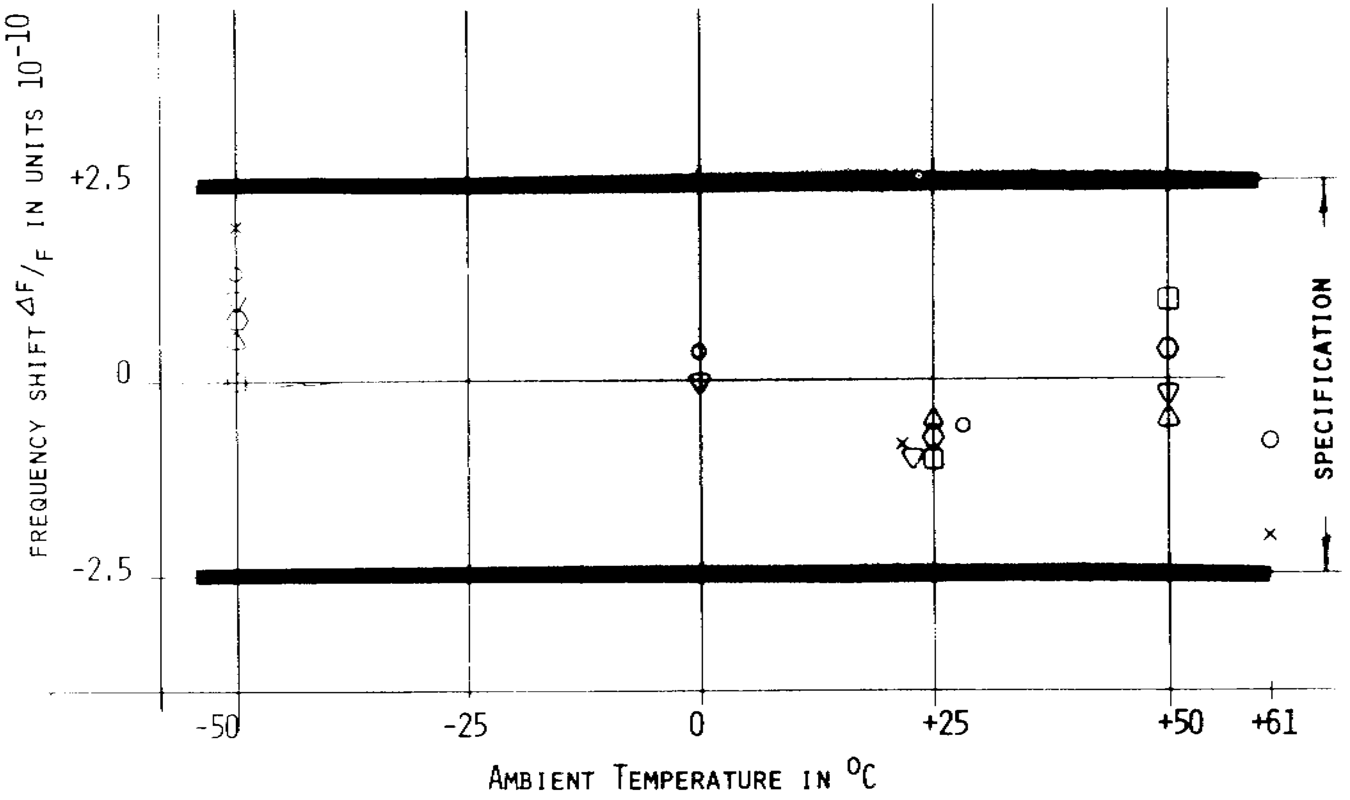

FIG. 8