PERFORMANCE OF PREPRODUCTION MODEL CESIUM BEAM FREQUENCY STANDARDS FOR SPACECRAFT APPLICATIONS

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ABSTRACT

The first of a series of Preproduction Model (PPM) Cesium Beam Frequency Standards for spaceflight application on Navigation Development Satellites has been designed and fabricated and preliminary testing has been completed. The PPM is identical in form, fit and function, to the production cesium standards for the GPS NAVSTAR System.

The PPM evolved from an earlier Prototype Model launched aboard NTS-2 (June, 1977) and the Engineering Development Model (EDM) to be launched aboard NTS satellites during 1979. A number of design innovations, including a hybrid analog/digital integrator and the replacement of analog filters and phase detectors by clocked digital sampling techniques will be discussed.

Thermal and thermal-vacuum PPM testing has been concluded and test data will be presented. Stability data for 10 to 10^4 seconds averaging interval, measured under laboratory conditions, will also be shown.

INTRODUCTION

The Preproduction Model (PPM) Cesium Beam Frequency Standards are the most recent version of a series of atomic frequency standards specifically designed for spacecraft applications in the Global Positioning Satellites (GPS). The first atomic frequency standards to be successfully operated on an orbiting satellite were the rubidium devices flown by the U.S. Naval Research Laboratory aboard NTS-1 in 1974. Two Prototype Model Cesium Standards were launched on NTS-2 in June, 1977.[1] Figure 1 is a photograph of the prototype units. The next stage in the evolution of the GPS cesium standards was the Engineering Development Model (EDM).[2] EDM Number 2 is currently installed and awaiting launch on the U.S. Air Force NDS-4 payload and EDM Number 3 is in test on the NDS-5 satellite. A photograph of the EDM Standard is shown in Figure 2.

The PPM is similar in size, weight and outward appearance to the EDM; internally there are a number of electrical and mechanical refinements. The PPM is intended to be representative, in all physical and performance aspects to the production model phase III cesium standards for GPS satellites. Figure 3 is a photograph of the qualification model PPM in the initial test phase.

DESCRIPTION

Two fundamental requirements for the GPS frequency standard are that the standard operate in space for at least five years without adjustment and that it be capable of operating in the specified radiation environment. These two requirements strongly influenced the design of the PPM, particularly in the servo loop and integrator.

An overall block diagram of the PPM cesium beam standard is shown in Figure 4. The basic building blocks are common to all cesium standards; a high-quality voltage-controlled crystal oscillator (VCXO), a phase-modulated frequency multiplier and a digital frequency synthesizer to generate the 9.19 GHz cesium hyperfine transition frequency, a cesium beam tube, a low-noise modulation signal amplifier and filter, a phase detector, an integrator, and power supplies and controllers. As indicated in the block diagram, these blocks can be loosely combined into four functional subsystems, servo/integrator, cesium-beam, r.f. and power supply.

Servo/Integrator Subsystem

The servo/integrator subsystem is shown in block diagram form in Figure 5. The modulated signal at the output of the beam tube is amplified and filtered by the first stage. The second stage is a commutative filter which samples the amplified beam signal at twice the modulation rate. The sample-and-hold filter is followed by a synchronous detector and the hybrid analog/digital integrator.

The integrator in a cesium beam standard is a problem in any application. Given the five-year life and the radiation hardening requirements of GPS, the problem is particularly severe. The loop gain and loop time constant dictate an integrator time constant, however, is limited by the bias current of the amplifier and the leakage resistance of the integrator capacitor and the circuit board. The hybrid integrator, shown in the block diagram of Figure 5, uses a combination of analog and digital techniques to circumvent these problems. The rate-of-change of the output voltage of an integrator can be increased by increasing the R - C time constant or, more simply, by attenuating the output by means of a resistance divider. The difficulty with the second approach is that the maximum output voltage that can be obtained is reduced by the attenuation factor. The attenuation can be tolerated if the analog integrator is augmented by a digital-to-analog converter which is incremented (or decremented) by one count whenever the analog integrator reaches its upper (or lower) limit, the digital-to-analog converter is implemented in the PPM cesium standard by using latching relays as the digital switches. The relay contacts have no offset voltages or series resistances as do semiconductor switches, but more importantly, they provide a non-volatile memory which retains the last oscillator control voltage setting in the event of a radiation-induced transient. Each count of the D-to-A converter corresponds to approximately 10 mV, a $\Delta f/f$ of approximately 1×10^{-10} for the VCXO. Interpolation between discrete converter steps is provided by attenuating the ±10 mV output range by 1024, to about ±10 μV, and adding this voltage to the output of the D-to-A converter.

Cesium Beam Tube Subsystem

The cesium beam tube subsystem consists of the cesium beam tube, the C-field regulator, and the cesium oven controller. The beam tube is the FTS-1A; used in the Prototype Model and EDM standards as well as the 4000 series manufactured by Frequency & Time Systems.

The C-field current regulator uses a latching-relay-controlled D-to-A converter similar to that used in the digital integrator. The latching relays provide immunity to radiation induced transients while allowing ground-commanded adjustments to the field current. The resolution of the C-field is one part in 1024 which corresponds to a change in the normalized standard frequency of approximately 4×10^{-13}.

The cesium oven is maintained at a constant temperature by a variable-duty-cycle switching regulator. The cesium oven temperature is sensed by a thermistor on the cesium oven located within the cesium tube;

the thermistor forms one leg of a resistance bridge which is balanced at the oven setpoint temperature.

R.F. Subsystem

The 10.23 MHz signal for the satellite GPS systems is generated by doubling the 5.115 output frequency from a modified FTS Model 1000 precision voltage-controlled crystal oscillator.[3] The doubler output is carefully filtered to suppress the 5.115 MHz subharmonic by at least 100 dB.

The 36th harmonic of 5.115 MHz, at 184.14 MHz is generated by the low-order frequency multiplier. The input stage of the low-order multiplier is square-wave phase (frequency-impulse) modulated at approximately 450 Hz, the cesium beam tube line-width. The output stage of the multiplier in turn is phase modulated by the 14.36...MHz output of the digital frequency synthesizer. The 184.14 MHz carrier, with its complex phase modulation spectrum, is fed to the X50 high-order multiplier; the first sideband, 9192.631770 MHz phase-modulated at 450 Hz, is selected by an output filter to excite the Ramsey cavity within the cesium beam tube.

Power Supply Subsystem

The PPM power supplies provide +15V, -15V, and +5V to operate the servo, and r.f. electronic circuitry. A separate +24V supply is used for the VCXO and two high-voltage supplies to power the cesium tube ion pump and the electron-multiplier.

All of the PPM supplies are preregulated by a high efficiency switching regulator followed by a series-pass regulator. The output of the preregulator feeds two transformer-coupled inverter stages which supply all of the required voltages.

The preregulator switching regulator and both inverters are clocked from a stable oscillator at approximately 37 KHz. The clock frequency is selected to minimize power supply ripple at the Zeeman frequency and the harmonics of the Zeeman frequency.

The normal power consumption is approximately 24 watts after a one-hour warmup period. The maximum power consumption of the PPM is approximately 44 watts at startup.

Mechanical Construction

The mechanical design of the PPM is very similar to that of the EDM. The PPM package is 15 inches (38.1 cm) long, 7.6 inches (19.4 cm) high, and 5.1 inches (13 cm) wide and weighs 25.5 lbs. (11.6 kg).

The PPM packaging concept differs in only relatively minor respects from the EDM; the PPM circuit boards are connectorized, rather than hard-wired, and the cesium tube in the PPM has a soft mount. Although the FTS-1A cesium beam tube used in the PPM survived the 23 g qualification-level vibration test when hard-mounted to the shake table, the chassis structure resonances increase the vibration levels imposed on the installed tube to the point that it seemed prudent to shock mount the tube. The shock mounting consists of relatively thin elastomer strips sandwiched between stainless steel clamping bands.

QUALIFICATION REQUIREMENTS

The PPM Cesium Beam Frequency Standard must survive the vigors of the launch environment and then perform within specified limits for a minimum of five years in space.

Environmental Requirements

Qualification testing of the PPM, scheduled to begin on 27 November 1978 includes vibration, shock, EMI, thermal vacuum cycling, phase noise, and temperature stability tests. The qualification vibration levels for the PPM are shown in Figure 6. Three minutes of random vibration in each of three mutually perpendicular axis are required.

The qualification levels for a three-axis simulated and pyrotechnic shock test are shown in Figure 7. The thermal profile for the long-term thermal cycling test is shown in Figure 8. Twenty-four full cycles at atmospheric pressure and eight cycles in vacuum are required for qualification.

Performance Requirements

The PPM performance limits with respect to frequency stability, frequency versus temperature spurious signal levels and phase noise must be maintained over a baseplate temperature range of 20 to 45°C.

Figure 9 is a plot of the frequency stability requirements as a function of averaging time, from one second to 10^5 seconds.

Figure 10 shows the acceptable spurious signal levels as a function of frequency offset from the carrier.

Figure 11 is a plot of the phase noise requirement as a function of frequency offset from the carrier.

The maximum allowable temperature coefficient of frequency for the PPM is 5×10^{-14} per degree C averaged over any 20 degree interval within the 20 to 45°C operating range.

PRELIMINARY PERFORMANCE DATA

The temperature coefficient of frequency of the PPM qualification model has been measured in vacuum with the results shown in Figure 12. The coefficient is approximately $1.5 \times 10^{-14}/^{\circ}C$ averaged over the +15 to +45°C temperature range, significantly better than the 5×10^{-14} per degree C contractual requirement. The frequency offset at 25°C, in air at atmospheric pressure, is shown on the figure to indicate the measured change in frequency from air to vacuum at constant baseplate temperature.

The measured frequency stability, expressed as the Allan variance for averaging intervals of 10 to 10^4 seconds is shown in Figure 13. The broken line on the figure represents the contractual requirement; again the PPM performance exceeds the minimum requirements by a substantial margin. The phase noise as a function of offset frequency from the carrier has not been measured for the PPM. However, since the phase noise characteristics at offset frequencies greater than one Hz are determined solely by the crystal oscillator, the EDM data[3] is representative of the phase noise performance expected for the PPM.

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References

1. J. White, F. Danzy, S. Falvey, A. Frank, J. Marshall, "NTS-2 Cesium Beam Frequency Standard for GPS", Proceedings of the Eigth Annual PTTI Applications and Planning Meeting, December, 1976.
2. T. Gregory, "New Cesium Beam Frequency Standards for Flight and Ground Applications", Proceedings of the 31st Annual Symposium on Frequency Control, June, 1977.
3. D. Emmons, "A New Rugged Low-Noise High Precision Oscillator", Proceedings of the Eigth Annual PTTI Applications and Planning Meeting, December 1976.

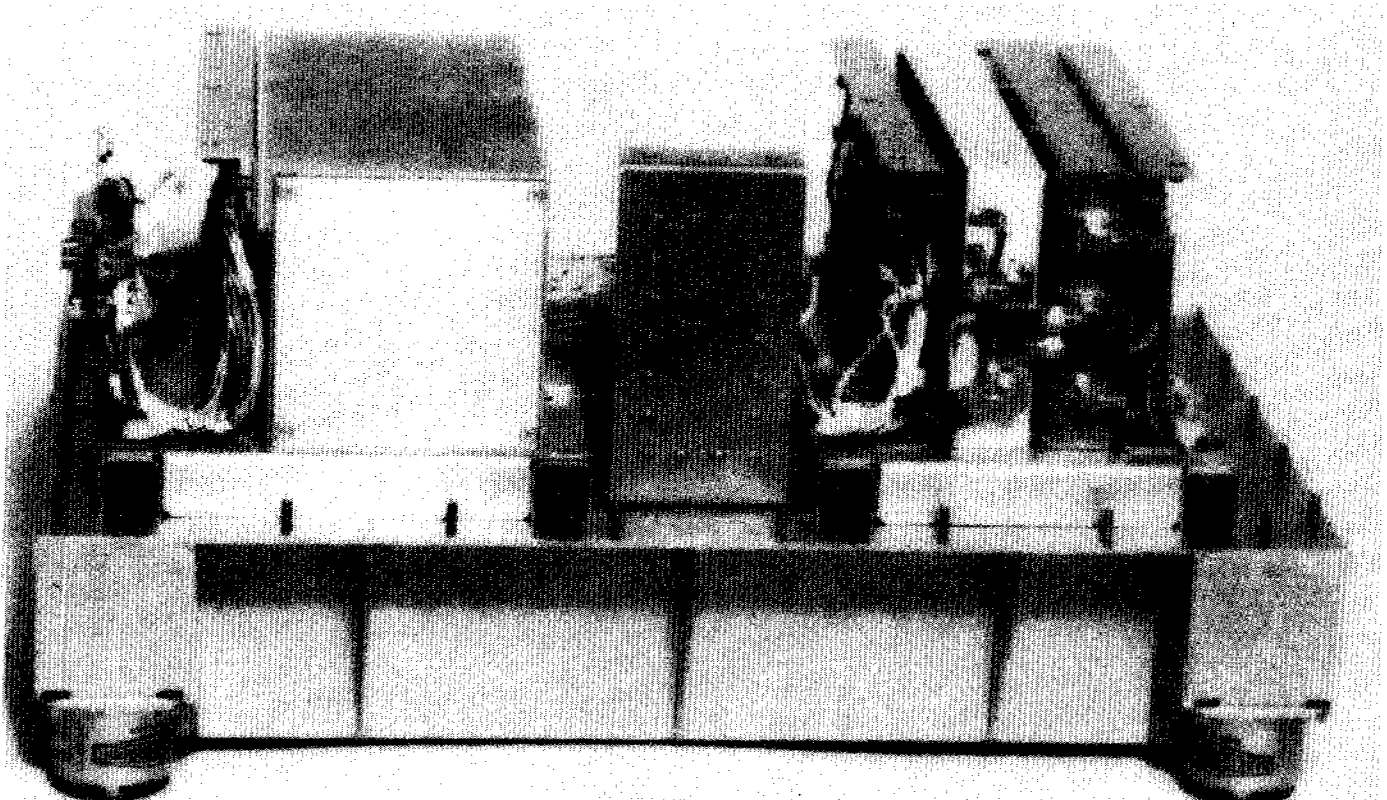


Figure 1
PHOTOGRAPH OF
PROTOTYPE MODEL

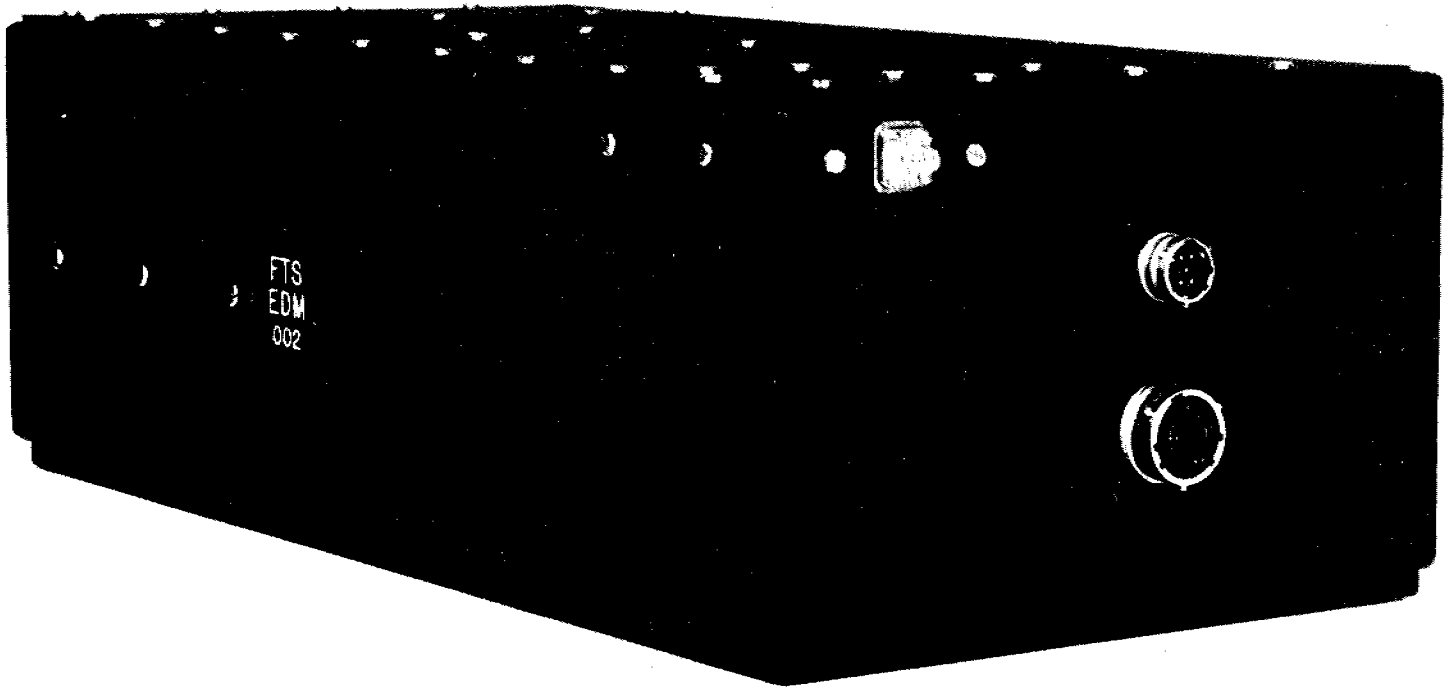


Figure 2

PHOTOGRAPH OF
EDM

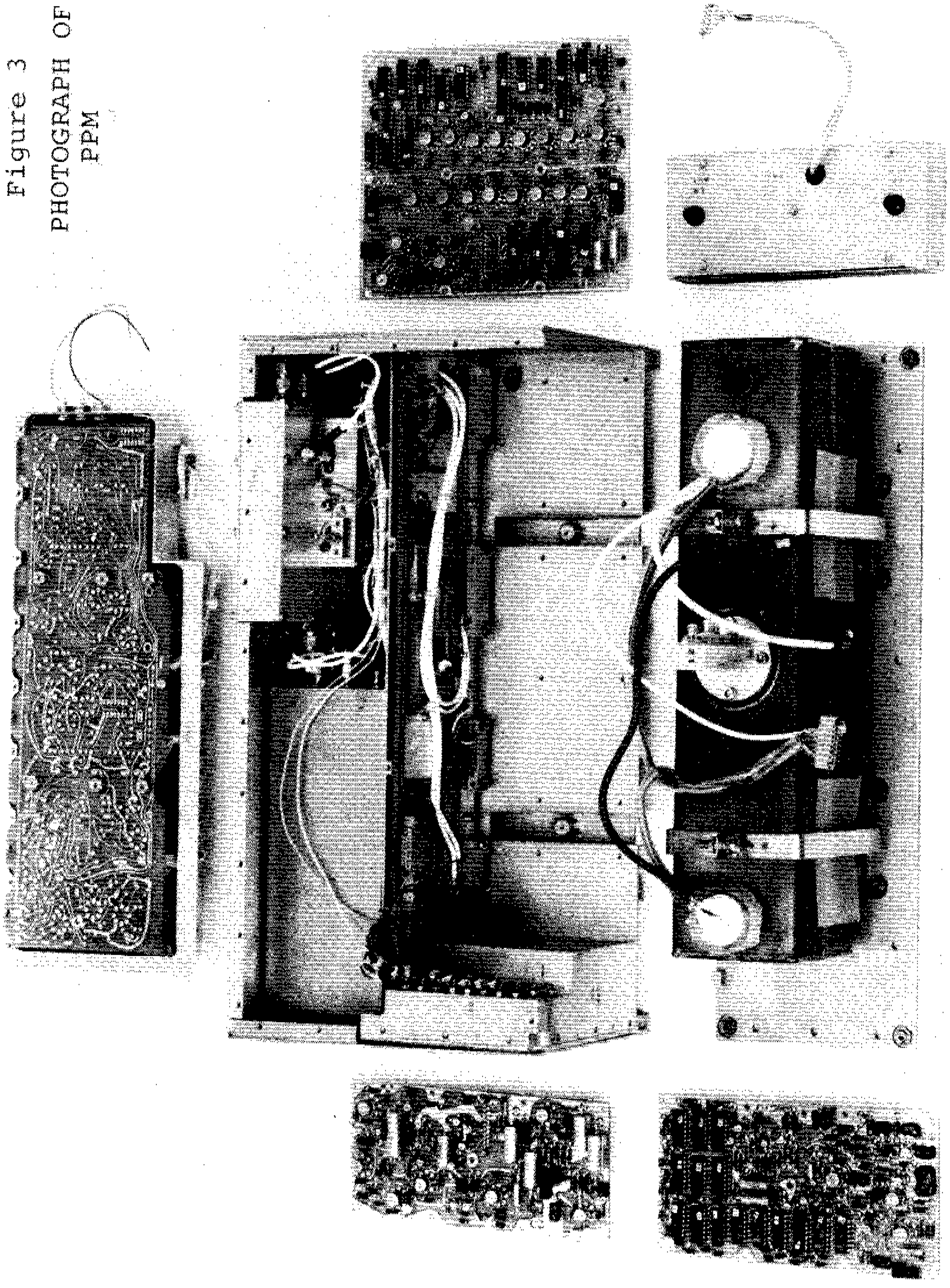


Figure 3
PHOTOGRAPH OF
PPM

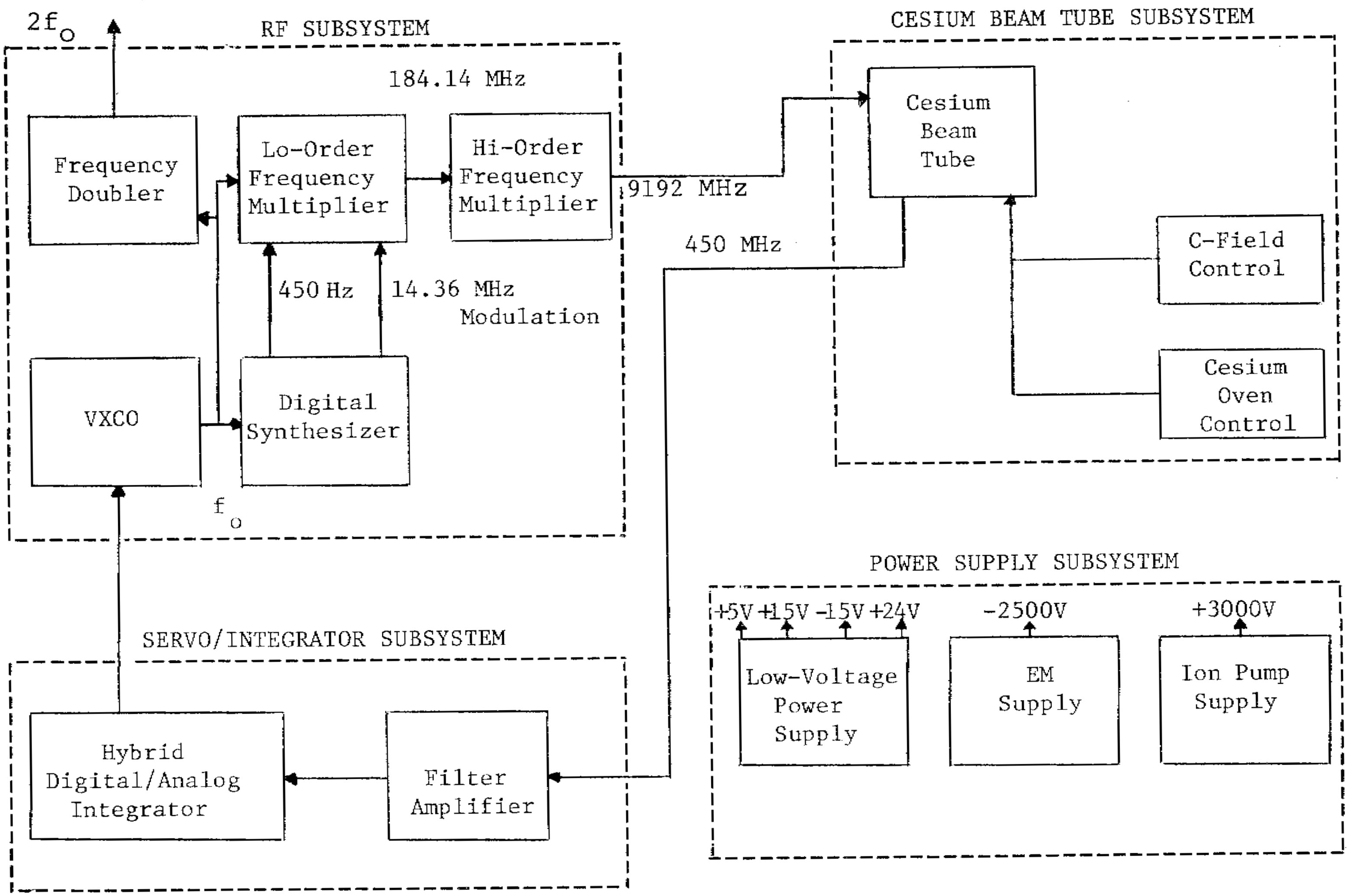


Figure 4

PPM CESIUM BEAM FREQUENCY STANDARD

System Block Diagram

11/14/78 MWL

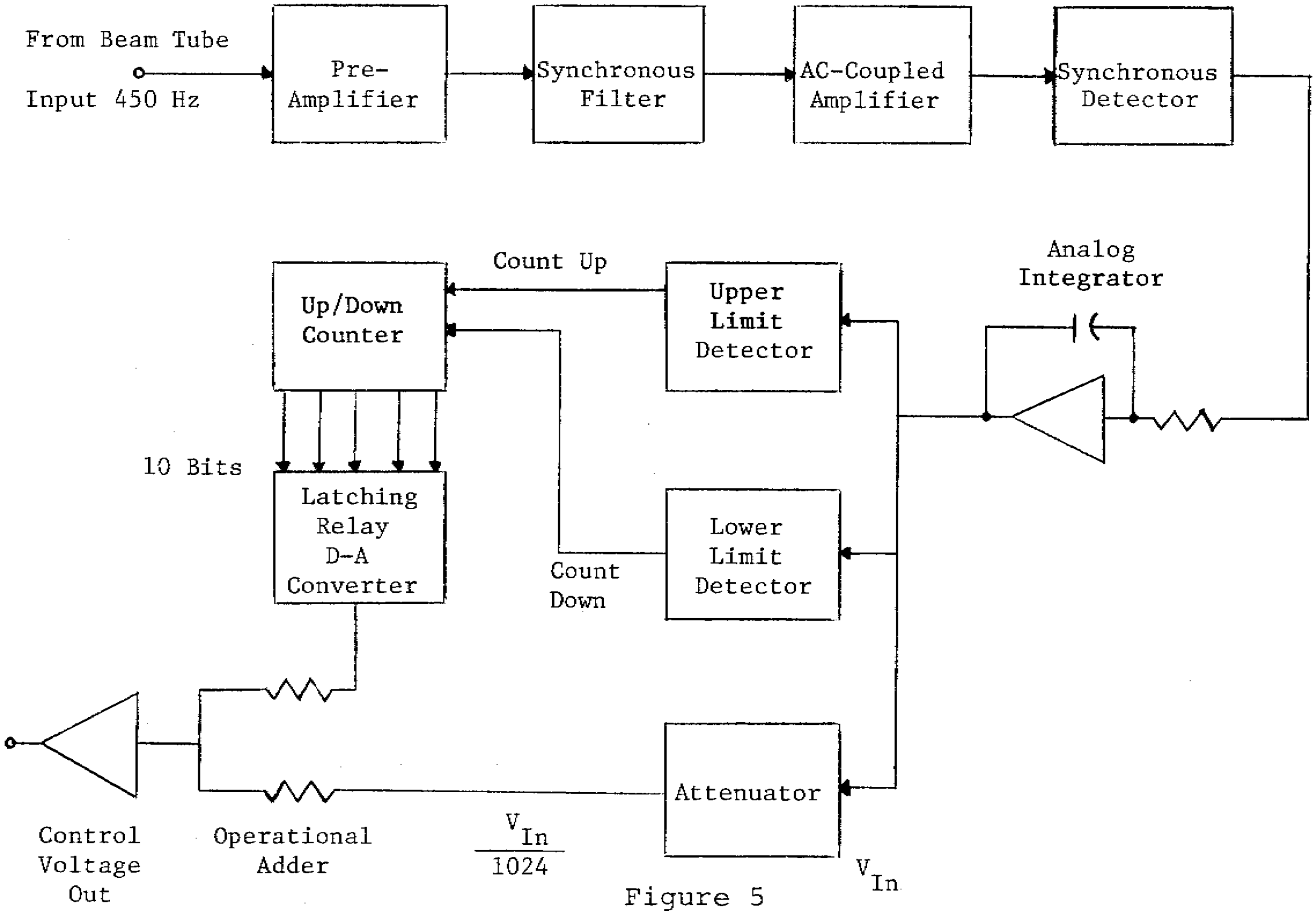


Figure 5
PPM SERVO/INTEGRATOR SUBSYSTEM
BLOCK DIAGRAM

11/14/78 MWL

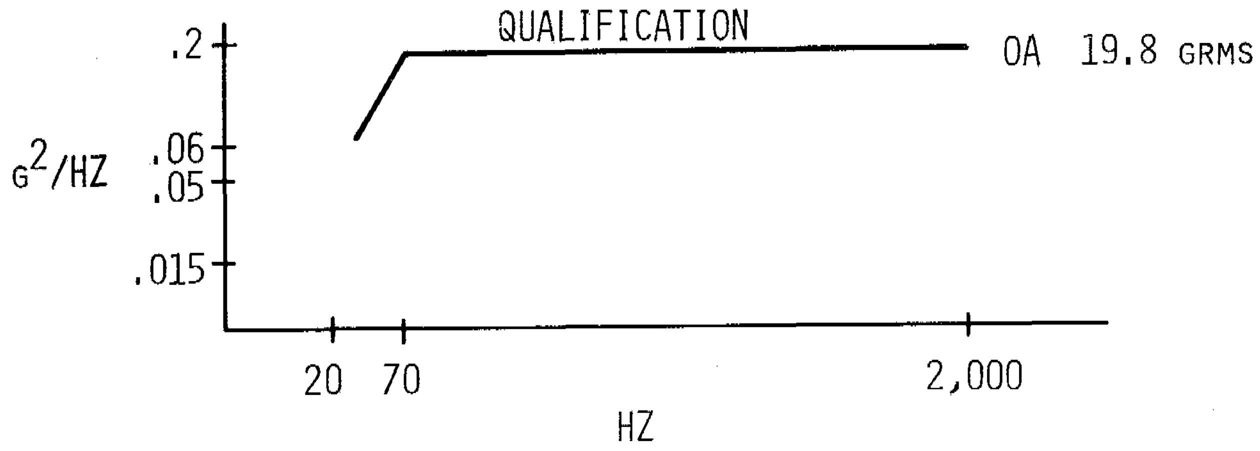


Figure 6. Vibration Level Requirements

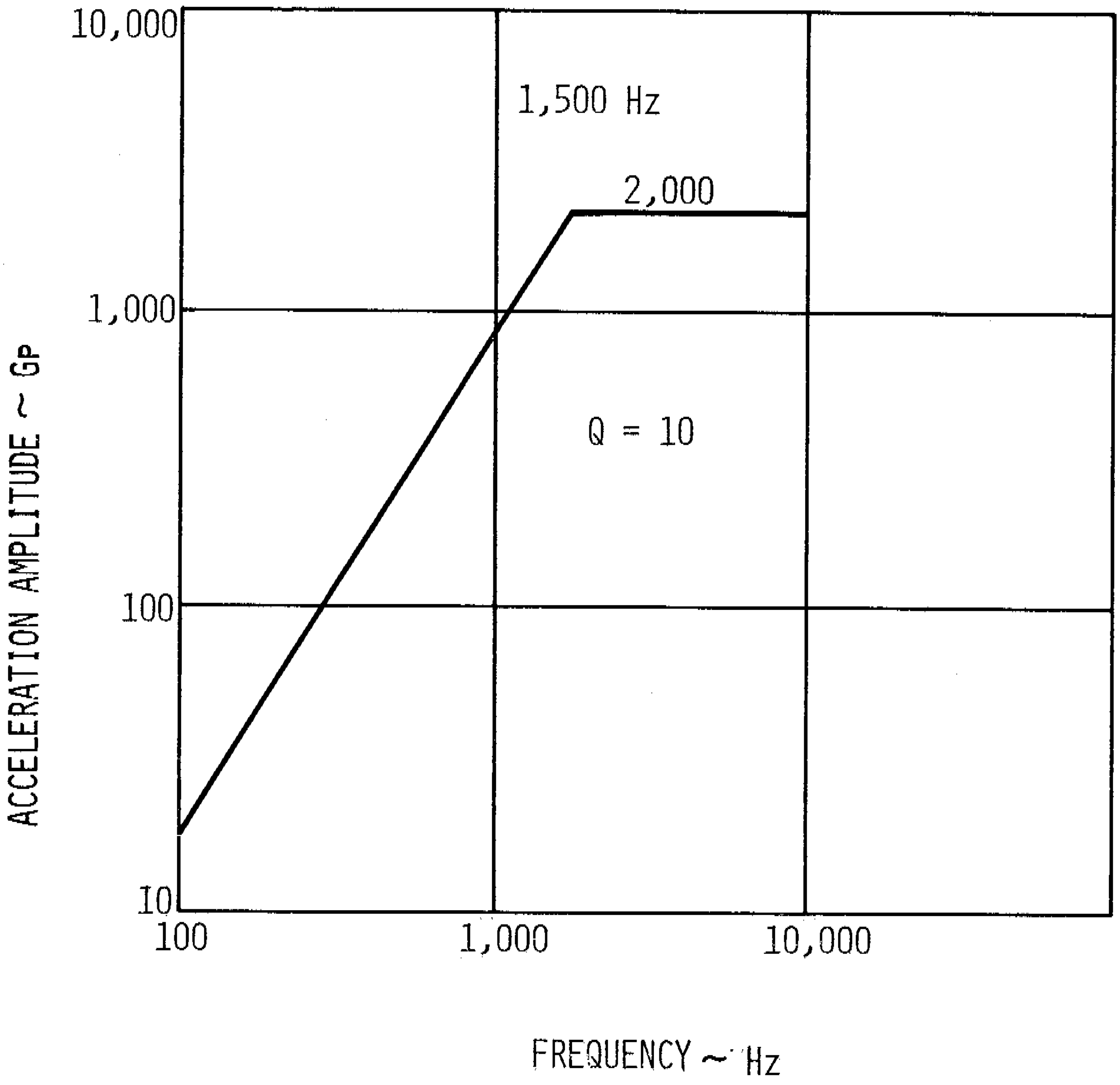
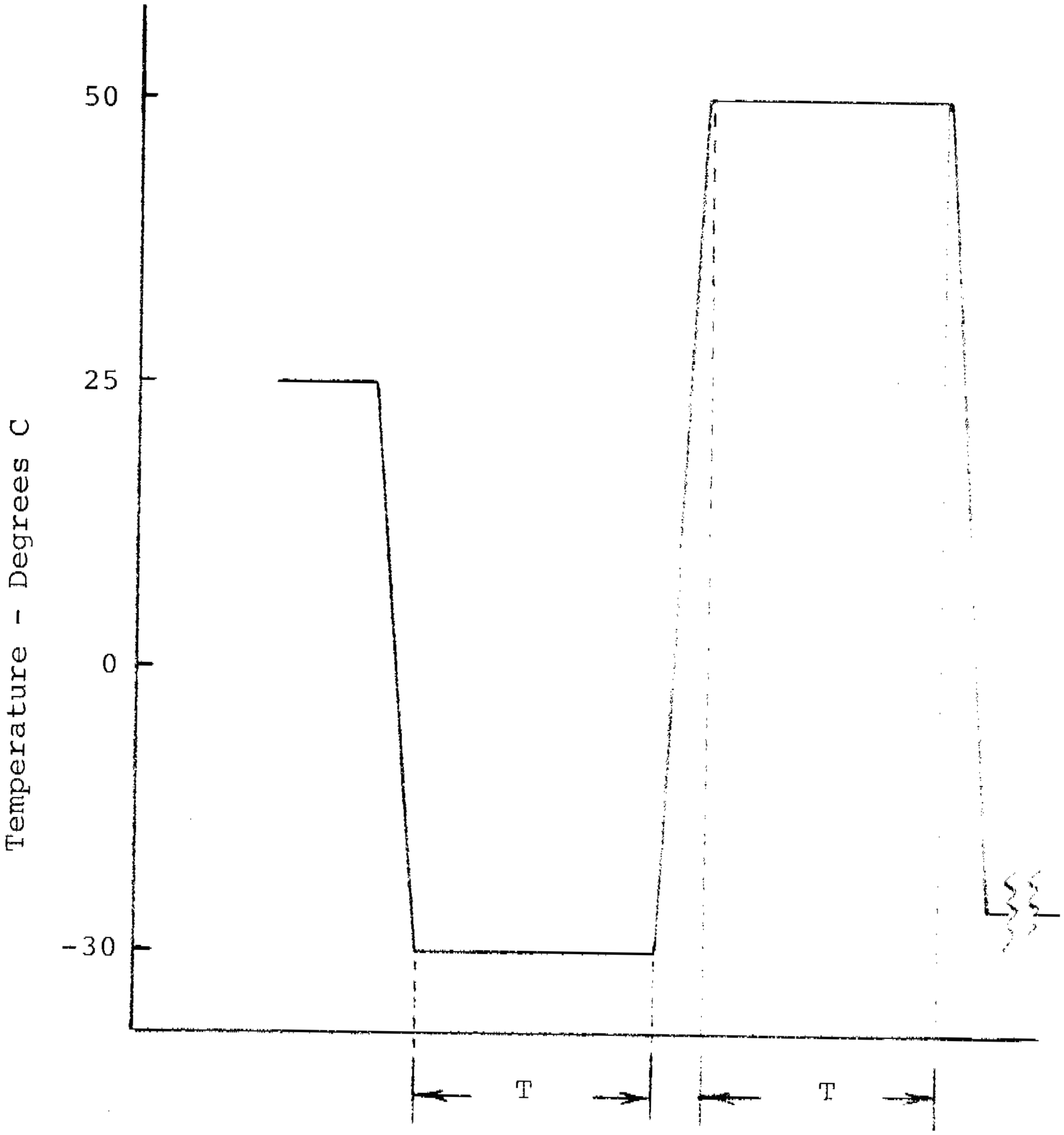


Figure 7. Shock Level Requirements for Qualification



T = 1 hour in air

T = 12 hours in vacuum

Figure 8

TEMPERATURE CYCLING REQUIREMENT FOR QUALIFICATION

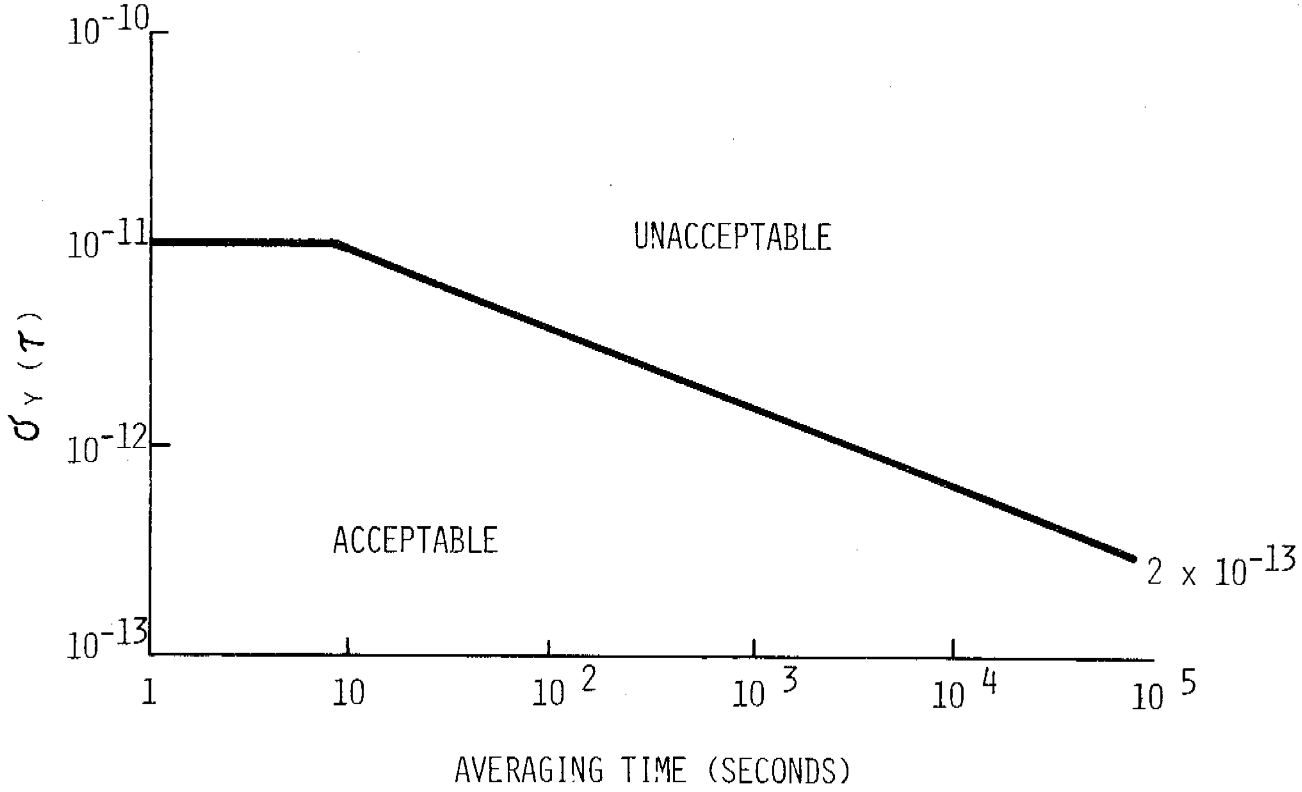


Figure 9. Frequency Stability Requirements

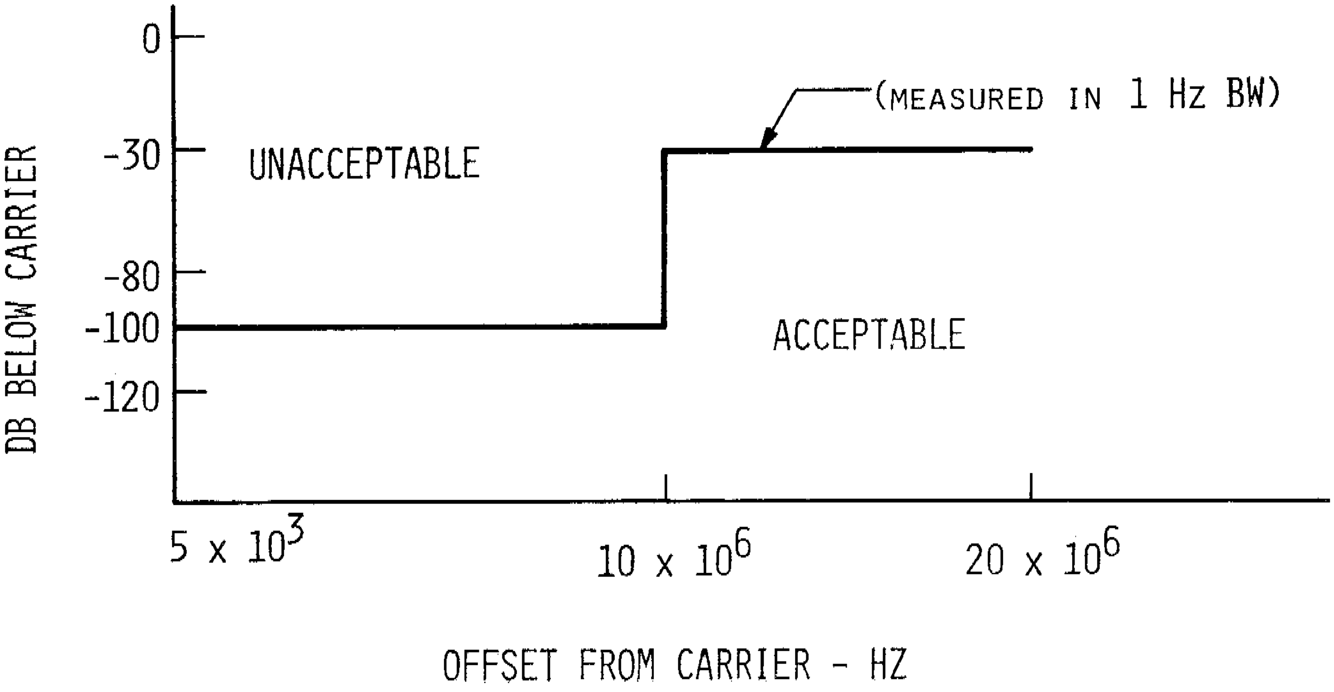


Figure 10. Spurious Signal Levels

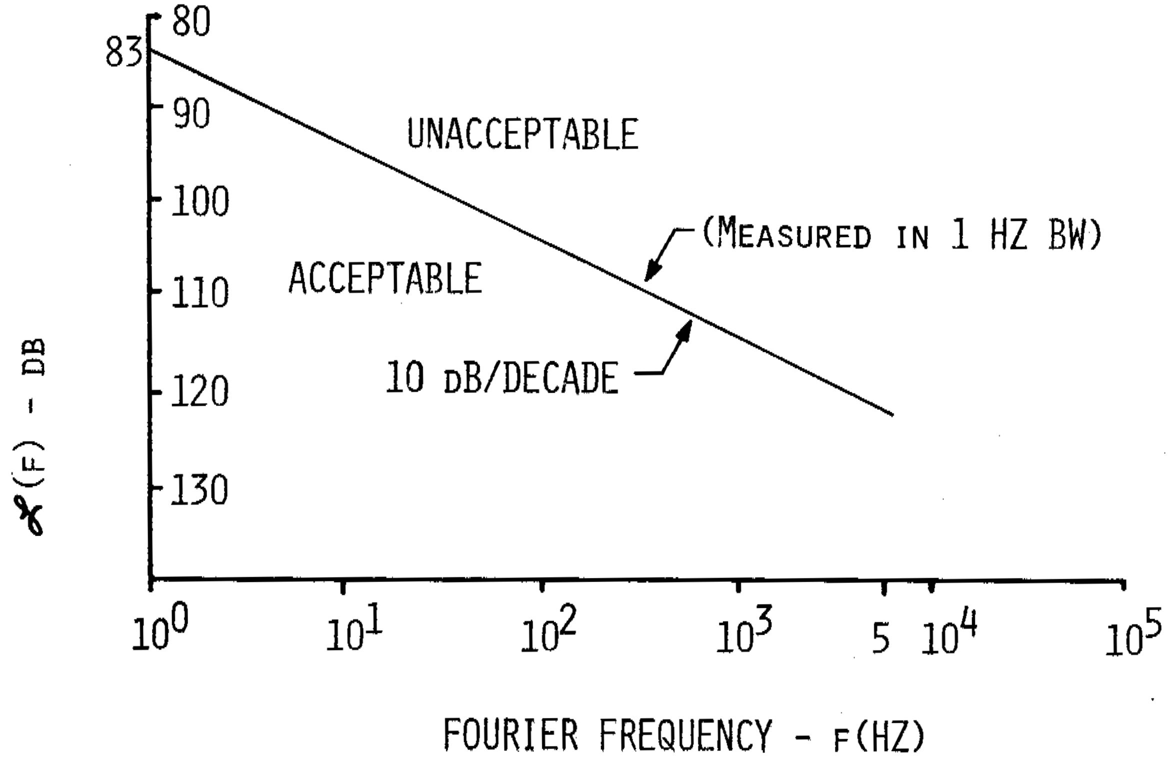


Figure 11

Phase Noise Versus Frequency Offset

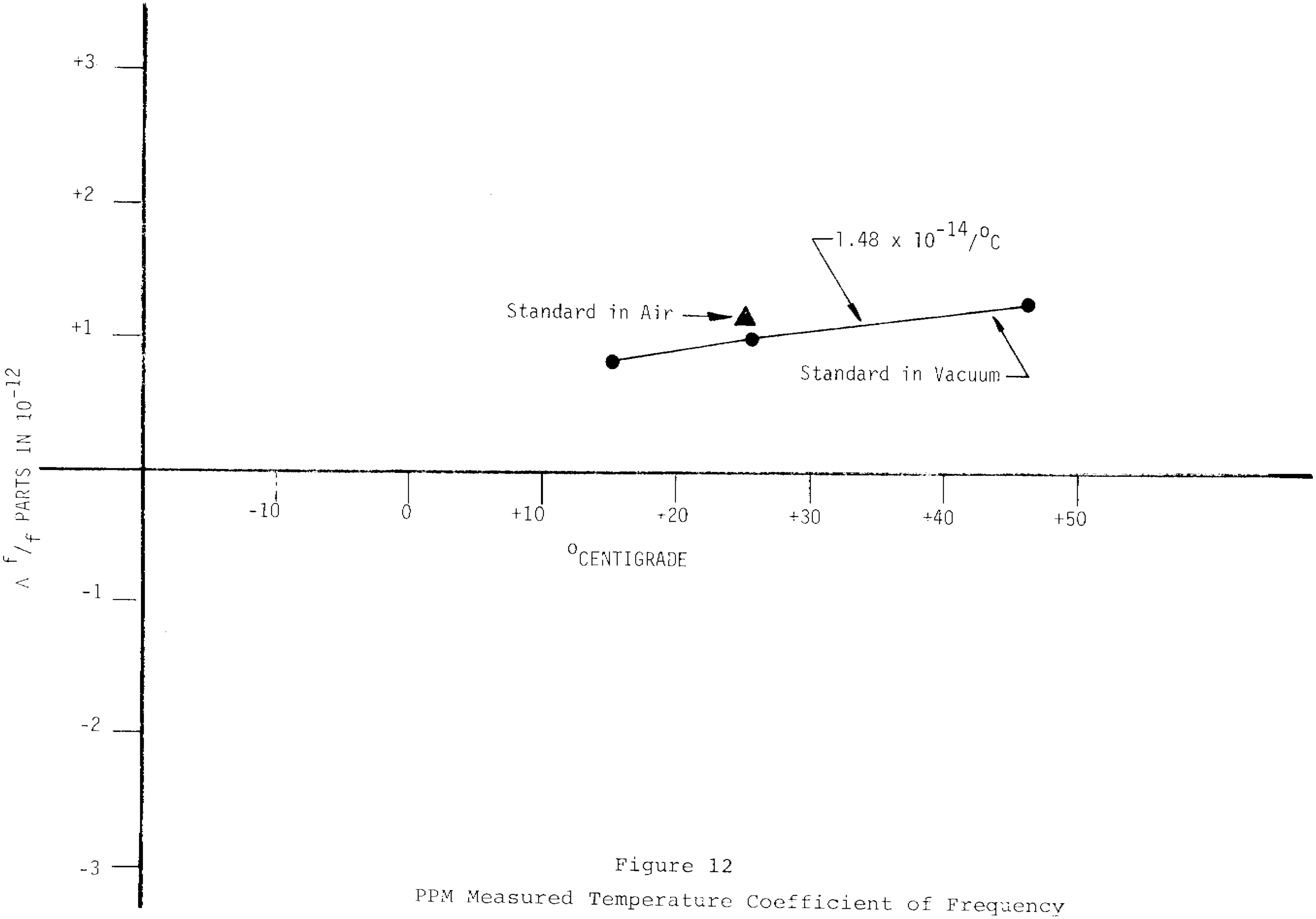


Figure 12

PPM Measured Temperature Coefficient of Frequency

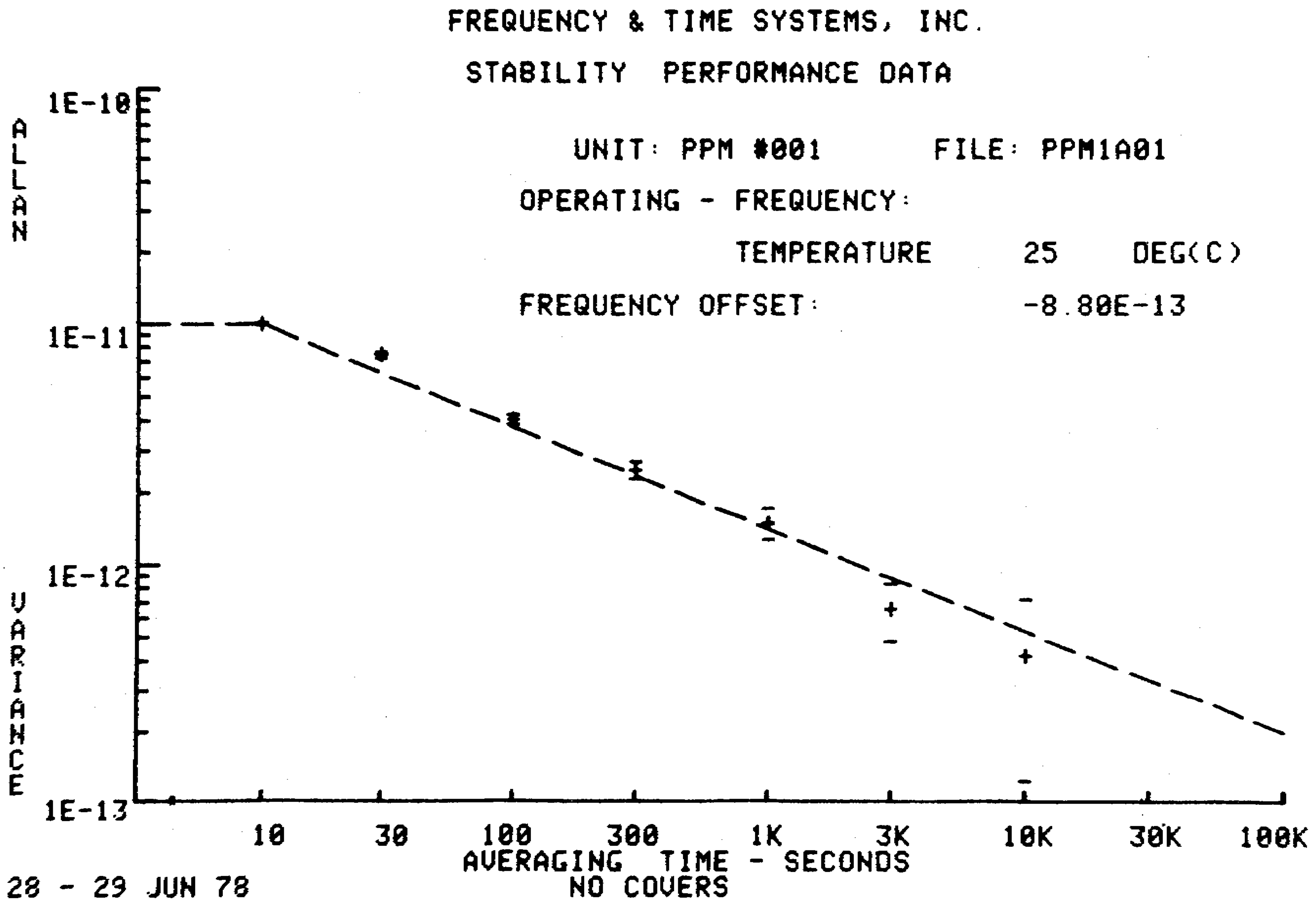


Figure 13

PPM Frequency Measured Stability

QUESTIONS AND ANSWERS

DR. HELMUT HELLWIG, National Bureau of Standards:

I have a comment. I am glad to see a portable clock finally, because I am getting tired of building my own--a portable clock in the sense of being really independent of power. You said eight hours?

DR. EMMONS:

Six hours. Two hours per pack. There are two battery packs, and, cleverly concealed under those is a last ditch pack spread out.

DR. GERNOT M. R. WINKLER, U.S. Naval Observatory:

Could you carry additional packs with you and plug them in, midterm, and prolong the clock's life if you see that you are stuck?

DR. EMMONS:

As each pack dies, you plug in another--before it dies.

MR. JECHART:

It would mean the purchase order for a lot of these--I would say we can do this order.

DR. EMMONS:

How many does he have?

DR. HELLWIG:

Efratom wants a purchase order also, if there are enough. A little more on the serious side; if there is a marketable product, I think somehow it will be built. And the technology for that (portable clocks) has existed for quite some time. Maybe we should ask FTS Company, "What do you expect as a market for this kind of device?" Don't answer if you don't want to.

DR. EMMONS:

I had better not. I don't feel up to that one.

DR. HELLWIG:

Maybe Dr. Winkler has a comment. No? No guess at the Market? You know the clock carrying business.

DR. WINKLER:

I think the answer depends entirely upon performance; I mean, performance under practical field conditions. And after we see that, we will say.

DR. EMMONS:

There has been a real snag, and that is in eliminating....well, since the advent of travel restrictions and anti-first class policies, we find a little bit of backlash concerning no more first class necessities.

DR. HELLWIG:

So that may create a market--no more first class travel. You are forced into economy or subeconomy, and then you have to buy little clocks that fit under the seat. Then they will be produced.

DR. WINKLER:

What is the price?

DR. EMMONS:

I would have to check from the floor here. Would someone care to comment on the price?

MR. THOMAS PARELLO, Frequency and Time Systems:

$26,000, and it is not GSA scheduled.

DR. EMMONS:

There is one back behind the screen if anyone wants to look at it.

MR. DAVID W. ALLAN, National Bureau of Standards:

A couple of questions, Don. On the stability slide, you showed just the white noise. Have you looked long enough to see if it starts to flatten and you get flicker noise or some other problems? And if so.....

DR. EMMONS:

My feeling is that we haven't looked long enough. I don't have any hot off the press data. I'm sorry.

MR. ALLAN:

The stability of 10^4 seconds is 4×10^{-13}, I believe you reported, and that seems inconsistent with the nominal 10 second data, as if it doesn't go as white noise. I was just curious whether you get some other strange thing there.

DR. EMMONS:

Well, I am inclined to say that maybe we have enough statistical spread to cover that.

MR. ALLAN:

To cover your tracks.

DR. EMMONS:

I will let you look in detail at it here.

DR. VICTOR REINHARDT, NASA Goddard Space Flight Center:

On the commercial units, since we have a little bit of interest in that, are the data that you got on the temperature coefficient, on the spacecraft unit, expected in the commercial unit? The 1.5 in 10^{14} per degree C?

DR. EMMONS:

I'm sorry. I don't have good numbers with me, but the commercial unit behaves very well over temperature. Do you remember some numbers, Tom?

MR. PARELLO:

Not precisely, but if I had to take a guess, I would say it is perhaps parts in 10^{12} over the full -28 to +61 degree C range.

DR. EMMONS:

Yes, over the full temperature range, parts in 10^{12}.