DESIGN CONSIDERATIONS AND PERFORMANCE OF A SPACEBORNE HYDROGEN MASER FREQUENCY STANDARD[1]

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ABSTRACT

An engineering development model (EDM) of a compact hydrogen maser atomic clock for spaceborne applications has been built by Hughes Aircraft Company, Space and Communications Group (S&CG). The clock weighs 29.1 kg and has a power consumption of 64 Watts. The clock has demonstrated an excellent immunity to baseplate temperature variations during thermal vacuum tests, maintaining a fractional frequency stability of 2×10^{-15} for a 10^5 sec averaging time in the presence of a 10°C sinusoidal baseplate temperature modulation. The drift rate is also quite low, a few parts in 10^{-15}/day as measured against a VLG11 conventional maser. The design criteria, several technical solutions and the possibility of further reductions in size and weight are discussed.

INTRODUCTION

In May of 1983, Hughes S&CG was awarded a contract by the Naval Research Laboratory to build a hydrogen maser for use on GPS satellites. The design is based on an oscillating compact maser developed at Hughes Research Laboratories (HRL).[2] Although the basic design and overall functionality remain unchanged, the majority of the mechanical and electrical subsystems had to be substantially modified to satisfy stringent launch, size and weight requirements. Telemetry interfaces for monitoring and control also had to be added to allow remote operation. Some of the more salient features of the final design will be presented in this paper, together with preliminary stability data.

STRUCTURAL DESIGN OVERVIEW

An isometric drawing of the maser is shown in Figure 1. The physics unit is supported at two places by titanium stanchions: at the plenum assembly (which houses the getter and ion pumps) and at the junction of the physics unit with the microwave front-end electronics. These stanchions bolt to an aluminum baseplate, which provides support for mounting to the spacecraft.

To achieve its small size and light weight, the maser employs an electrode-loaded cylindrical cavity with one removable end cap. Four loading electrodes are plated on the outer surface of the teflon-coated maser storage bulb. It is much more difficult to achieve a high cavity Q using plated electrodes than it is with the old technique (used in the HRL design) of affixing copper foil electrodes using epoxy adhesives. However, plating provides mechanical rigidity which is critical to preserving the frequency of the cavity under the shake and vibration of launch. An added benefit of plating is a much smaller temperature coefficient of cavity resonant frequency. To achieve the benefits of plating, a new process of depositing high conductivity silver films on a quartz surface had to be developed, in part because the conventional technique, which employs chrome, cannot be used due to the residual magnetic fields that chrome generates.

The solid stem of the storage bulb is clamped at one end of the cavity by a funnel fitting, while the beam entrance stem is permitted axial movement at the other end. This allows for dimensional changes during warmup. The cavity is cantilevered from one end of the surrounding titanium vacuum chamber using four titanium leaf springs. The patented mounting technique isolates the cavity from force changes that would otherwise be transmitted due to mounting surface expansions or contractions. The leaf springs and the delrin washers provide effective thermal and electrical isolation of the cavity.

Five layers of 14 mil thick concentric hypernom magnetic shields with removable tapered end-caps surround the titanium vacuum chamber.[3] The neck transition of each shield is thickened to reduce vibration induced stresses, and the shields are held in place axially by a series of spacers.

The quartz dissociator is housed in a stainless steel enclosure and is designed to operate in vacuum. The dissociator housing mounts to the plenum assembly using a gold wire seal. The demountable plenum and maser vacuum chambers are joined through a compression seal inside the plenum chamber. A single nut on the threaded tubulation connecting the two chambers is used to compress the gold o-ring.

The microwave front end electronics employs MIC technology. The rest of the clock and the control electronics use standard spacecraft electronic construction. All electronic housings are fabricated from aluminum.

THERMAL SUBSYSTEM

The space maser is expected to maintain a specified frequency stability of $1x10^{-11}/\sqrt{\tau}$ for an averaging time τ in the range of $1<\tau<10^6$ sec when the temperature at the spacecraft interface is within the acceptance range of 15 to 45°C, with a maximum excursion of 4°C per orbit. The maser is allowed to operate with degraded performance over the qualification range of 0 to 60°C. This is a very stringent thermal design requirement.

The design approach is to decouple the microwave cavity from the environment using low emittance surface finishes, multilayer insulation blankets and thermal isolators. This passive design is augmented by proportionally-controlled zonal heaters. The goal is to control the temperature of the microwave cavity to within 1 millidegree C. Changes in cavity frequency which result from this small temperature variation are then servoed out by means of a cavity-control system (to be discussed in a following section).

The temperature control servos employ thermistor sensors in a resistive bridge network. DC heaters are used on the outermost shield, the two necks of the vacuum chamber, and the front end electronics for coarse regulation. AC heaters are used inside the magnetic shields to minimize magnetic perturbations. These 20 kHz fine-zone heaters are located on the surface of the vacuum chamber.

HYDROGEN FLOW SYSTEM

The hydrogen flow system makes extensive use of metal hydrides for compactness, lightweight and reliability.[4] A regulated flow of molecular hydrogen from a metal hydride source is dissociated by a rf discharge to form an atomic beam. Atoms in the undesired atomic states are stripped from this beam by means of a quadrupole magnet, while those in the desired state (the upper level of the maser transition) are deflected into the teflon coated storage bulb inside the microwave cavity. The resonant microwave radiation emitted by the atoms in the cavity provides the stable clock reference signal.

The 0.6 moles of hydrogen stored in the lanthanum nickel aluminum hydride supply will last at least twice the 7 year design life of the maser. Normal maser operation requires a hydrogen flow rate of less than

$3x10^{-5}$ torr-liter/sec. The entrance and exit openings of the dissociator are chosen to provide a dissociator operating pressure of 50 millitorr, a value which was empirically found to provide good hydrogen dissociation efficiency, ease of ignition and reliable operation.

The thin walled palladium-silver alloy tube hydrogen flow regulator in our earlier design was found to lack a positive shut off for baseplate temperatures above 40°C. At temperatures higher than 60°C, the uncontrolled permeation rate was so high that flow regulation became very poor. The design was modified by substituting nickel for the palladium-silver alloy. By properly sizing and annealing the nickel tube, the increase in power consumption was made insignificant. The revised design enabled positive shut-off of hydrogen flow at temperatures beyond 80°C.

The dissociator operates with about 3 watts of rf drive power. To minimize possible radio frequency interference, the dissociator is completely enclosed by the metal vacuum envelope. The rf power is generated by a single transistor oscillator coupled to a starting and sustaining electrode structure. Optimizing the coupling network is a tedious procedure due to the capacitive coupling between the electrodes and the metal walls. Good discharge ignition and reliable dissociator operation has, nonetheless, been obtained.

The plenum assembly houses two getter slugs. Although one getter is more than enough for a 7 year life, a second is provided to reduce the powdering of the getter with hydrogen absorption. The powder is confined by encasing the getters in sintered 316L stainless steel filters which also serve as baffles to prevent excessive thermal radiation from reaching the state selector magnet and the cavity region during getter activation. Two 2 liter/sec ion pumps are attached to the plenum assembly. These pumps are throttled down and operated at a low voltage to reduce hydrogen pumping.[5] Their function is to pump the small amount of non-getterable residual gases. The pump current during normal maser operation is typically a few microamps.

CLOCK AND CONTROL ELECTRONICS

A block diagram of the maser receiver electronics is shown in Figure 2. It is basically a triple conversion coherent heterodyne receiver phase-locking a slave voltage-controlled crystal oscillator (VCXO) operating at the GPS standard frequency of 10.23 MHz. The buffered VCXO system output is adjustable in steps of $2x10^{-13}$ over a range greater than $7x10^{-10}$. Since the natural Q of the compact cavity used in this maser is too low to sustain maser oscillation, the design uses external gain and positive feedback to raise, or enhance, the cavity Q. A phase shifter and an attenuator, each independently programmable, are contained in the Q-enhancer circuit to enable setting the desired gain and phase shift.

A cavity stabilization servo system is an integral part of the receiver. The servo system operates by alternately injecting test signals at the half power points of the Q-enhanced cavity. The test signals are produced by upconverting the output of a switched synthesizer (alternating between 11.809 and 11.779 MHz at a 52 Hz rate) with the 1432.199 MHz local oscillator. The transmitted test signals are synchronously detected for any asymmetry in cavity transmission. Any imbalance forms the error signal for the servo system controlling the bias voltage of the varactor reactance tuner.

The microwave front end and the cavity stabilization servo, both of which critically affect maser performance, are located with the physics package in a controlled environment. The remainder of the maser electronics is contained in the side lobe package (Figure 3). The relationship between the contents of the side lobe electronics unit and other maser components is shown in Figure 4. To increase packing density, the majority of the boards are multilayer (4 to 8 layers). The boards are heat sunk and low signal level boards are isolated from higher signal level boards.

STABILITY DATA

Since the dominant perturbation on a satellite borne atomic clock is ambient temperature variation, the preliminary testing of the maser has concentrated on thermal vacuum effects. The stability of the maser has been measured in a vacuum chamber. The maser baseplate was bolted to an aluminum heat exchanger plate through which a temperature-controlled ethylene glycol solution was circulated. The temperature of this solution, which was controlled by a computer-driven heater-chiller, could be raised, lowered, or made to follow a predetermined temporal profile. Stability data were collected on a dual-mixer-time-difference system with a conventional hydrogen maser, the VLG11 P10, as reference.[6]

The data shown in Figure 5 were taken at a constant baseplate temperature of 30°C. As shown by the phase data, the phase variation is, after subtracting a fitted drift of $-4.66\text{x}10^{-15}$ per day, less than 1 nanosecond over the 5.9 days interval. The drift rate is consistent with the normal observation for the VLG11 P10. The Allan variance plot shows that the stability is almost an order of magnitude better than the design requirement. As indicated by the insert in Figure 6, a stepwise baseplate temperature change from 30 to 37°C during the run caused no observable effect. In an earlier experiment, the baseplate temperature was sinusoidally modulated between 21.5 and 30°C with a 12 hour period; Figure 7 shows the synchronously collected phase and temperature data for the first 3 days of this run. Phase data and the computed Allan variance for the complete run are shown in Figure 8. These results demonstrate the effectiveness of the design and excellent stability performance of the maser.

SUMMARY REMARKS

A laboratory design for an oscillating compact hydrogen maser has been completely re-engineered for space application. Careful attention was paid to the structural design to meet vibration criteria, to the thermal subsystem to meet projected spacecraft temperature variations, to the hydrogen flow system to maintain proper operation in excess of the 7 year mission, and to the electronic subsystems by incorporating space qualifiable electronic components.

Stability tests were performed on an EDM which was fabricated from components which had survived vibration testing. The clock has shown excellent immunity to baseplate temperature variations and exceptional long term stability.

The EDM is significantly smaller and lighter than a conventional hydrogen maser, but does not represent a limit in maser size and weight reduction. Indeed, a subcompact maser, CHYMNS-IIIb, has been fabricated and tested at HRL. This maser, displayed and operated at the 1987 PTTI meeting in Redondo Beach, California, has a physics unit having only 1/3 the volume and about 2/3 the weight of the EDM. Although there is slight degradation in short term stability, the electronics limited long term stability is unchanged. It is therefore not unrealistic to expect that a hydrogen maser with far superior stability can be packaged as a drop-in substitute for a cesium clock on board GPS satellites.

REFERENCES

1. This work has been supported by US Naval Research Laboratory under contract number N00014-83-C-2120.

2. H.T.M. Wang, "Characteristics of Oscillating Compact Masers", Proc. 36th Ann. Symp. on Freq. Control (1982), pp. 249-254.

3. D.U. Gubser, S.A. Wolf and J.E. Cox, "Shielding of longitudinal magnetic fields with thin, closely spaced, concentric cylinders of high permeability material", Rev. Sci. Instrum., 50, 751 (1979)

4. H.T.M. Wang, "Application of Metal Hydrides For Gas Handling in Hydrogen Masers", Proc. 37th Ann. Freq. Contr. Symp. (1983), pp. 7-11.

5. D.U. Gubser, S.A. Wolf, A.B. Jacoby and L.D. Jones, "Magnetic Shielding and Vacuum Test for Passive Hydrogen Masers", Proc. 13th Ann. PTTI (1981), pp. 791-799

6. The measurement system was furnished by NRL and we are grateful to NRL for making it available. The system was developed by Mr. A. Gifford of NRL who also wrote the program for data acquisition and analysis.

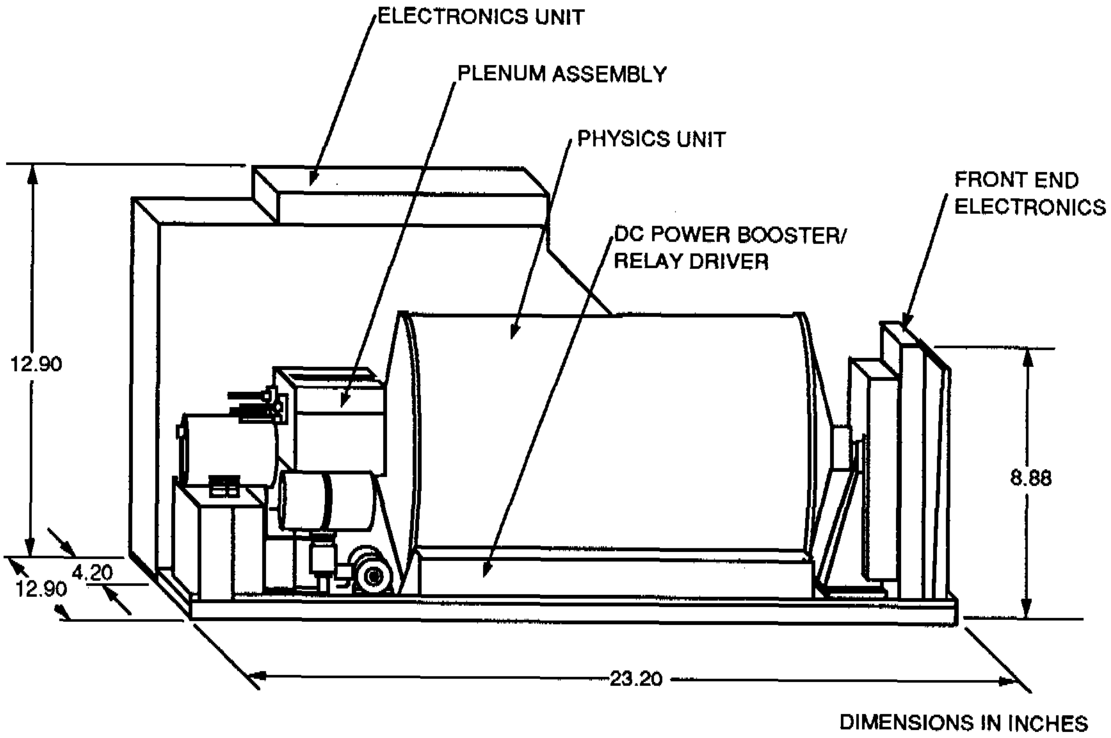


FIGURE 1. OUTLINE DRAWING

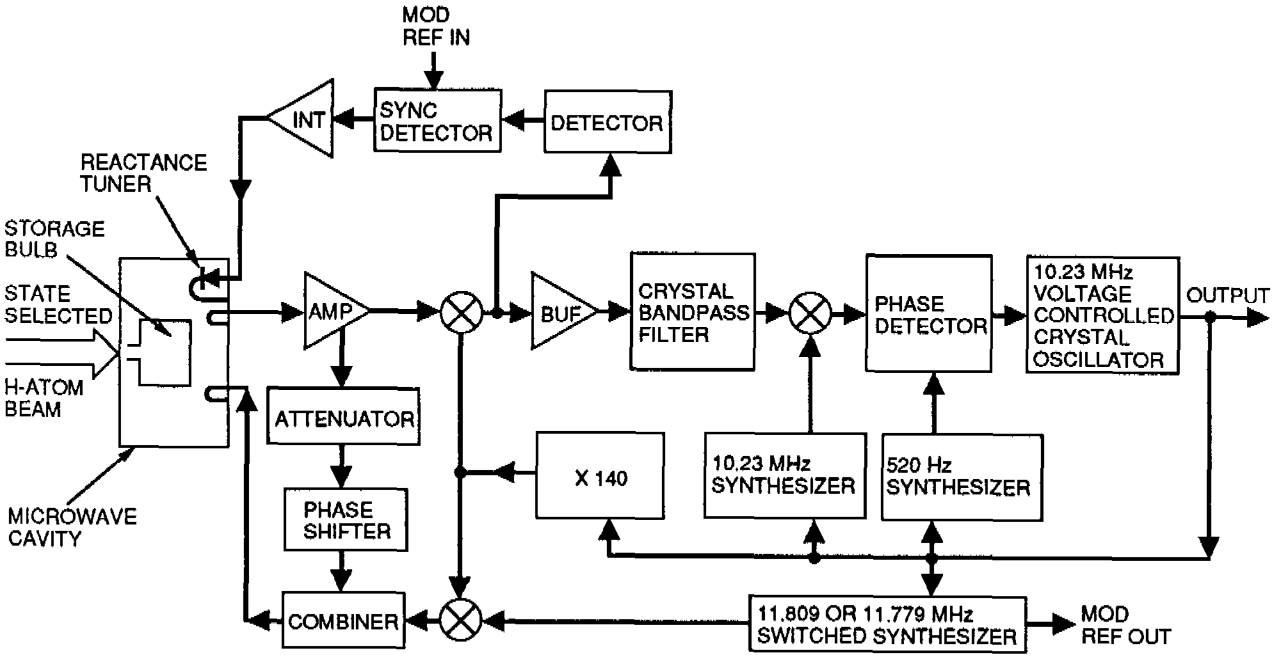


FIGURE 2. RECEIVER BLOCK DIAGRAM

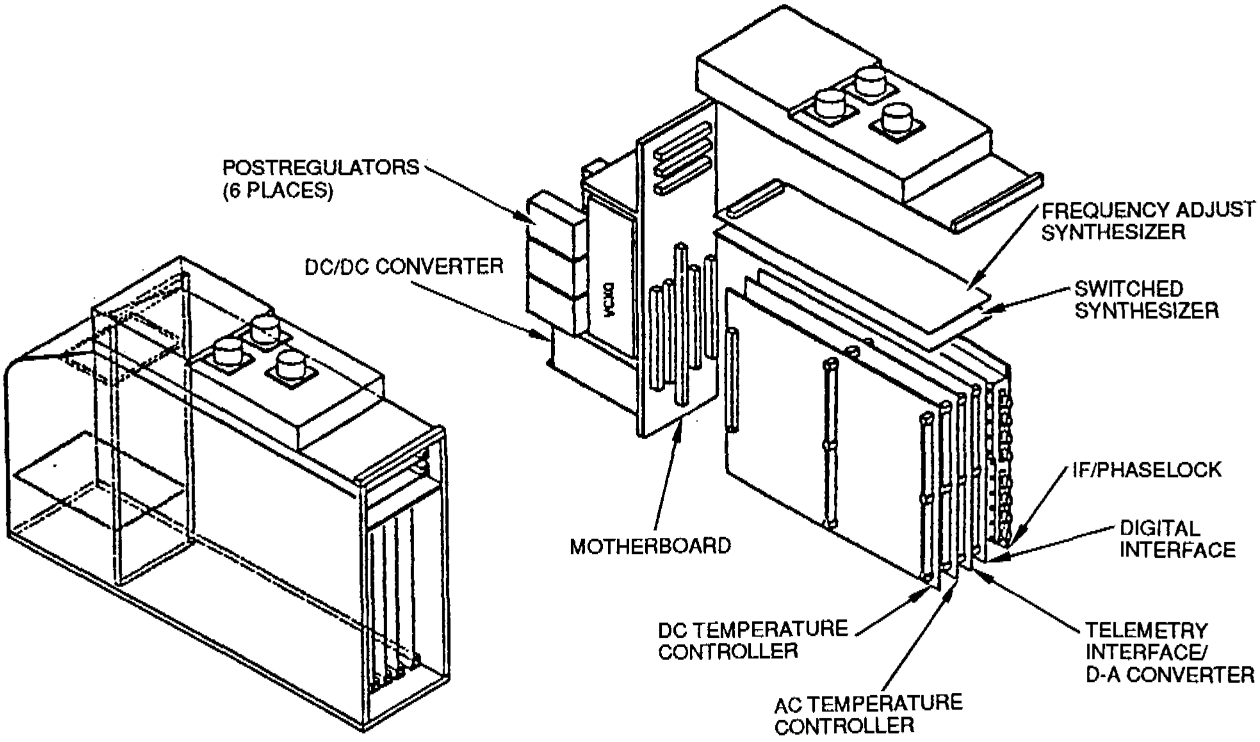


FIGURE 3. ELECTRONICS UNIT LAYOUT

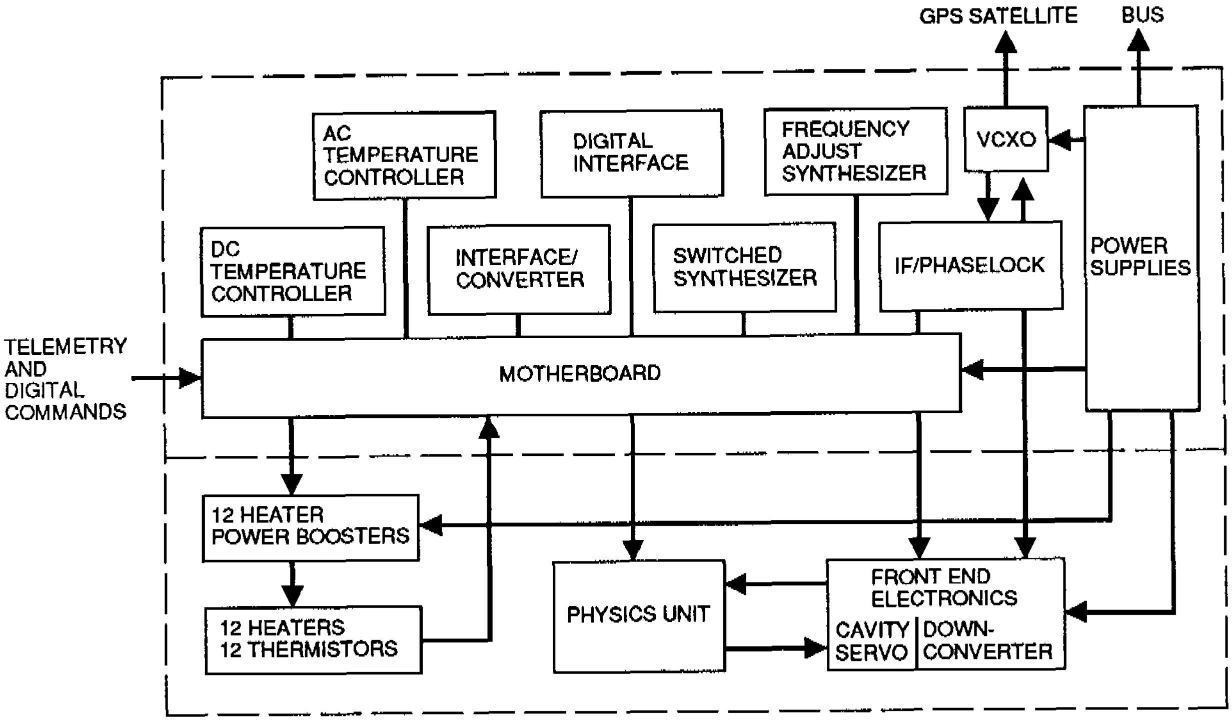
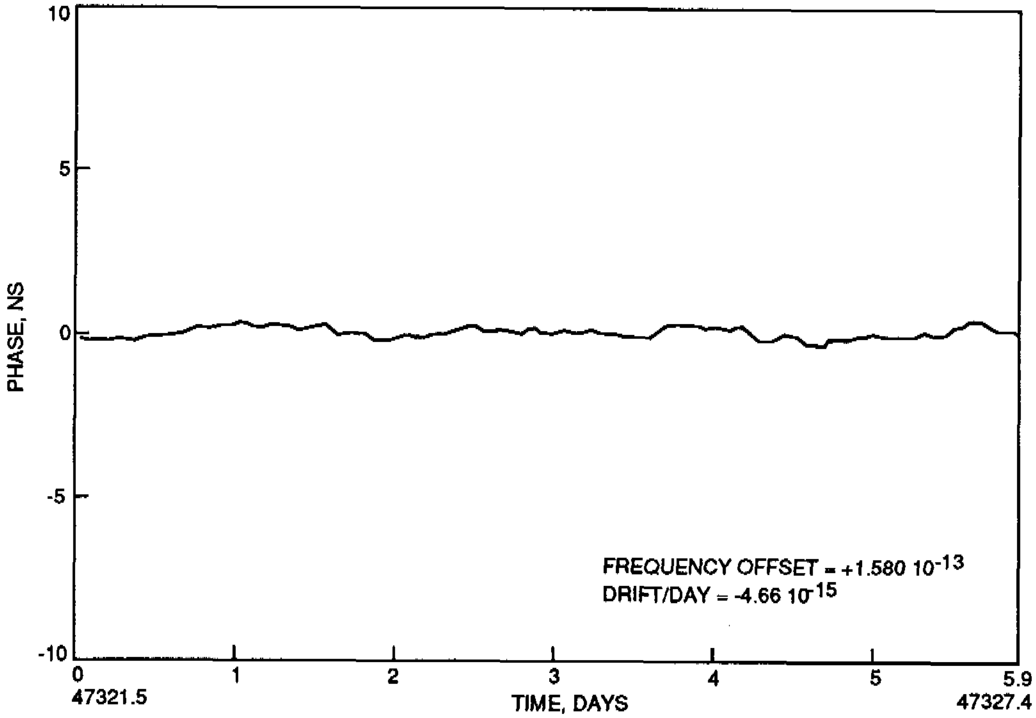


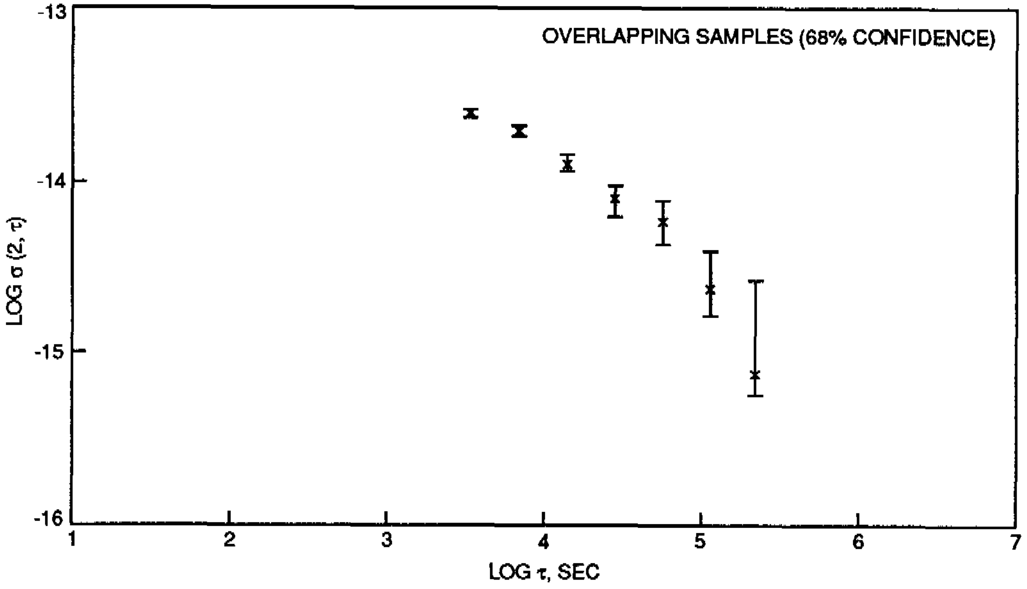
FIGURE 4. ELECTRONICS UNIT BLOCK DIAGRAM



FREQUENCY OFFSET = +1.580 10^{-13}
DRIFT/DAY = -4.66 10^{-15}

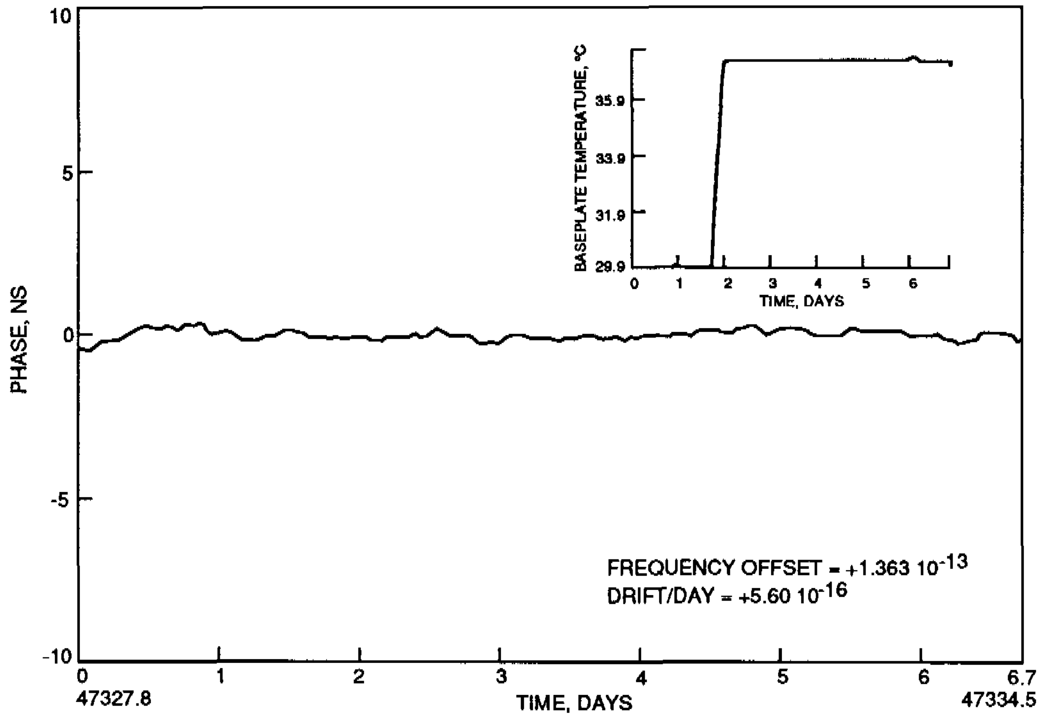
a) PHASE (DRIFT REMOVED) EDM-SM VERSUS VLG11 P10

SIGMA	PAIRS	TAU	LOWER BAR	UPPER BAR
2.34 10^{-14}	139	1H	2.22 10^{-14}	2.52 10^{-14}
1.83 10^{-14}	137	2H	1.72 10^{-14}	2.00 10^{-14}
1.20 10^{-14}	133	4H	1.10 10^{-14}	1.38 10^{-14}
7.62 10^{-15}	125	8H	6.20 10^{-15}	8.92 10^{-15}
5.63 10^{-15}	109	16H	4.30 10^{-15}	7.46 10^{-15}
2.22 10^{-15}	77	32H	1.59 10^{-15}	3.87 10^{-15}
7.44 10^{-16}	13	64H	5.34 10^{-16}	2.58 10^{-15}



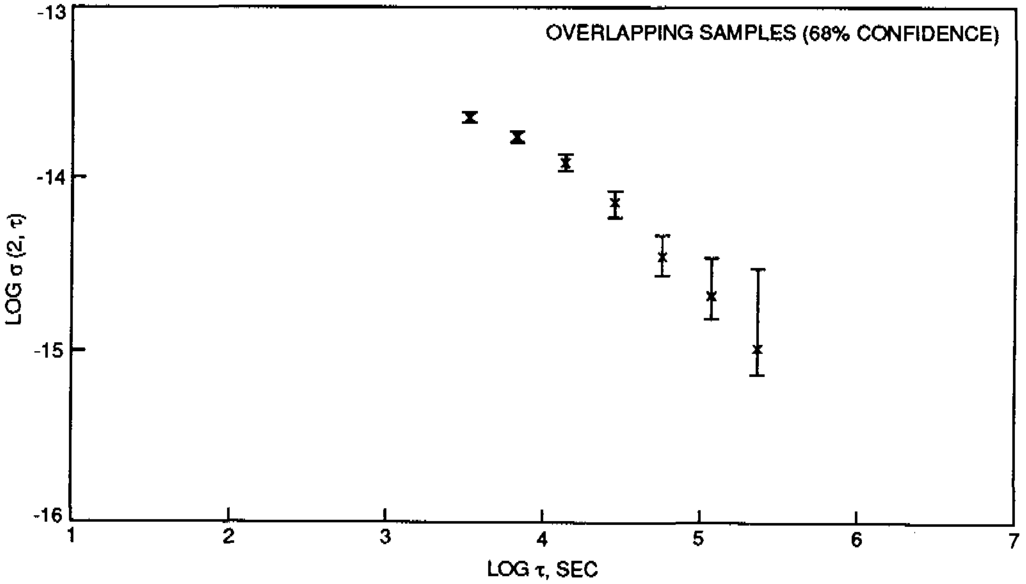
b) CLOCK STABILITY EDM-SM VERSUS VLG11 P10

FIGURE 5. ENGINEERING DEVELOPMENT MODEL IN VACUUM - BASEPLATE TEMPERATURE AT 30°C



a) PHASE (DRIFT REMOVED) EDM-SM VERSUS VLG11 P10

SIGMA	PAIRS	TAU	LOWER BAR	UPPER BAR
$2.05\ 10^{-14}$	159	1H	$1.95\ 10^{-14}$	$2.20\ 10^{-14}$
$1.58\ 10^{-14}$	157	2H	$1.49\ 10^{-14}$	$1.72\ 10^{-14}$
$1.12\ 10^{-14}$	153	4H	$1.03\ 10^{-14}$	$1.27\ 10^{-14}$
$6.93\ 10^{-15}$	145	8H	$5.70\ 10^{-15}$	$8.02\ 10^{-15}$
$3.53\ 10^{-15}$	129	16H	$2.73\ 10^{-15}$	$4.54\ 10^{-15}$
$2.11\ 10^{-15}$	97	32H	$1.53\ 10^{-15}$	$3.42\ 10^{-15}$
$1.03\ 10^{-15}$	33	64H	$7.38\ 10^{-16}$	$2.91\ 10^{-15}$



b) CLOCK STABILITY EDM-SM VERSUS VLG11 P10

FIGURE 6. ENGINEERING DEVELOPMENT MODEL IN VACUUM - BASEPLATE TEMPERATURE RAISED 7°C (2°C/HOUR)

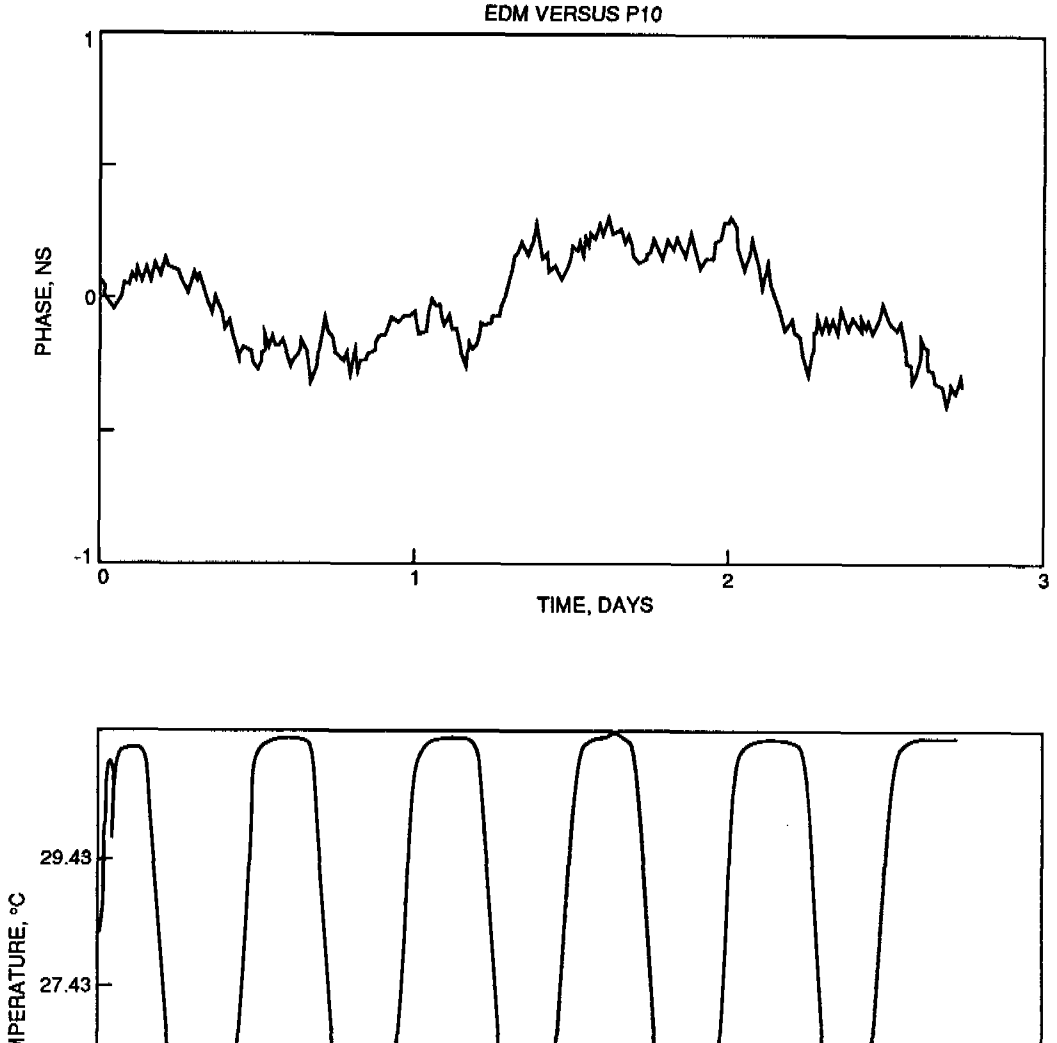
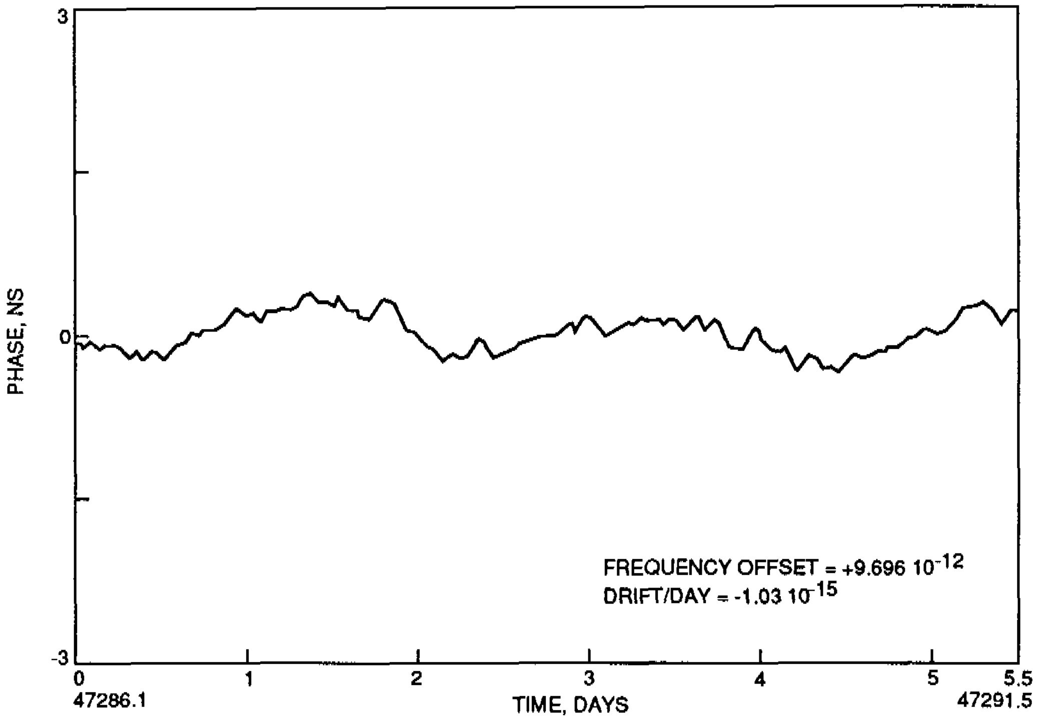
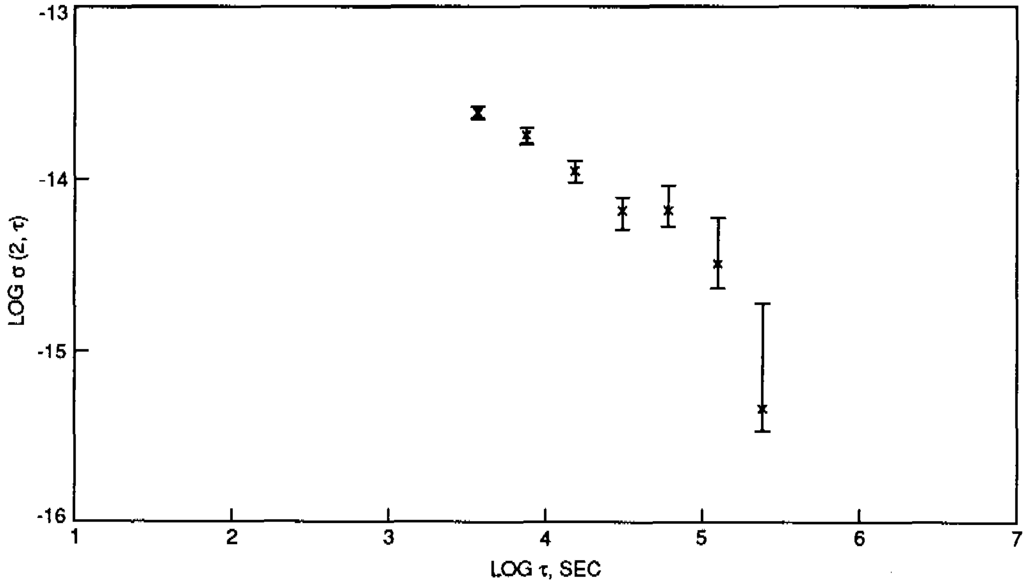


FIGURE 7. ENGINEERING DEVELOPMENT MODEL THERMAL TEST



a) PHASE (DRIFT REMOVED) EDM VERSUS P10



b) CLOCK STABILITY EDM VERSUS P10

FIGURE 8. ENGINEERING DEVELOPMENT MODEL STABILITY WITH 10°C BASEPLATE TEMPERATURE MODULATION