GALILEO QUARTZ CLOCK

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ABSTRACT

Frequency Electronics has developed and tested a quartz oscillator for use in the Galileo experiment (orbiter and Probe) for Jupiter mission 1982. This oscillator has achieved significant performance breakthroughs by the use of an "SC" cut, double rotated, crystal in a titanium Dewar flask. Some of the performance parameters are:

Radiation Sensitivity:	2×10^{-14}/rad
"g" Sensitivity	2×10^{-10}/g
Optimum Deceleration Sensitivity:	2×10^{-10}/425 g
Power Dissipation:	1.2 watts
Size:	1.8" dia. by 5.5"lg
Operating Pressure:	vacuum to 20 torrs
Short Term Stability:	3×10^{-12}/second

The quartz oscillator uses a double proportional control oven to achieve a temperature coefficient of less than 1×10^{-10}/10 degrees C. The results obtained on other "SC" cut crystals indicate the possibility of significant performance improvements in airborne, shipboard, missile timing, navigation and high speed communication systems.

INTRODUCTION

Jupiter, appropriately named for the most powerful god in the Roman Pantheon, is the largest planet in the solar system. Located 770 million km from the sun, Jupiter has an equatorial diameter of 140,000 km, approximately 10 times that of Earth. The planet, which is almost entirely liquid, takes nearly 12 years to complete a solar orbit, but a Jovian day is only of 10 hours duration.

The Pioneer 10 and 11 missions of the National Aeronautics and Space Administration (NASA) flew by the planet in 1973 and 1974 and verified that Jupiter emits more than twice as much energy as it receives. Thus it is a source of high energy particles accelerated into space. In March 1979, Voyager 1 transmitted photographs of the planet's satellites and multicolored atmosphere, including the famous red spot. The photographs revealed a ring of material in equatorial orbit around Jupiter, a phenomenon previously observed only with the planets, Saturn and Uranus.

Scientists believe that Jupiter holds many clues to the origin and development of the solar system and that studies of its atmosphere, magnetic field, satellites, and radiation belts will be important keys in unlocking those secrets. To make these and other important observations, NASA has scheduled Project Galileo for launch on the Space Shuttle in early 1982. The program is named after Galileo Galilei, the Italian Renaissance founder of experimental physics and astronomy, who is credited with discovering four of Jupiter's 13 known satellites in 1610.

The program consists of an orbiter spacecraft which will arrive at Jupiter in 1985 and circle the planet for 20 months, and an entry probe that will descend into the planet's turbulent, hydrogen-rich atmosphere to a pressure of about 20 Earth atmospheres after withstanding an entry speed of 48 km/sec (107,000 mph).

The orbiter will accommodate eleven scientific investigations which will measure the magnetic, gravitational, and thermal properties of Jupiter and its satellites; determine their surface composition and morphology; and study their ionospheres, atomospheres, and gas emissions. The spacecraft will also study the magnetosphere-satellite interaction; define the topology and dynamics of the magnetosphere, magnetosheath, and bowshock; describe the nature of the magnetospheric particle environment; determine the distribution composition, and stability of trapped radiation and conduct a synoptic study of the Jovian atmosphere.

The interplanetary flight phase of the mission will take about 1290 days, or 3-1/2 years. The probe, which consists of a deceleration module and a descent module, will separate from the orbiter 150 days prior to Jupiter encounter. A timer will initiate probe operation about 6 hours before entry into the planet's atmosphere. During high speed entry, acceleration and heatshield performance data will be collected. No telemetry is planned prior to or during entry; all relevant information will be stored for playback during subsonic descent.

During the 60-minute descent the seven scientific instruments on the probe will determine Jupiter's atmospheric structure and composition, location of clouds and their structure and physics, hydrogen/helium ratio, lightning and radio emissions, energy absorption and radiation and energetic particle distribution. The probe mission will be completed at an altitude where the pressure is approximately 20 times that of Earth's sea level.

There will be stable oscillators located on both the probe and Orbiter spacecrafts. These stable oscillators will be used by the scientists to obtain data about the atmosphere of Jupiter as well as to transmit information. Both oscillators have been designed to be virtually identical although they will see somewhat different environmental conditions.

Design

The oscillator is housed in a 1.8" diameter by 5-1/2" long stainless steel enclosure. Stainless steel was chosen to allow the entire package to be a vacuum sealed welded enclosure capable of withstanding the vacuum to 20 bar pressure variation. The outline and mounting dimensions are shown in Figure 1. The internal construction is shown in Figure 2. The oscillator and amplifier printed circuit boards are located inside a titanium dewar flask. Titanium was chosen for the dewar flask for its low thermal conductivity and light weight to minimize both power consumption and weight and yet have the strength to withstand the 425 g deceleration force.

Figure 3 shows the construction for this Dewar flask. Inside the Dewar flask, we have a double proportional controlled oven. The quartz crystal and oscillator circuit are inside the inner oven. The output amplifier and oven control boards are located in the outer oven. The entire assembly is foamed in place to maintain stability during shock, vibration and deceleration. Figure 4 is a photograph of the first engineering model of this oscillator next to a larger Fltsatcom oscillator. The connectors used are ceramic to metal seals to withstand the large pressure variation. A special weldable r.f. connector was constructed by Tek-Wave, Inc. an FEI subsidiary to perform this function.

Figure 5 is the schematic of the oscillator circuitry. A Colpitts oscillator configuration was chosen for ease of use and minimization of components. The quartz crystal is an "SC" cut, 5th Overtone at approximately 24 MHz. The

"SC" cut was chosen because it is stress-free, and will give excellent warm-up repeatability. Q1 is the oscillator transistor, and both a fundamental and B Mode trap are used in the emitter. An output transformer couples the signal to the rest of the circuitry. Figure 6 is a circuit block diagram of the entire unit. The inner oven controller has an additional booster heater which is slaved to provide additional power during warm-up. Once the oven has reached its normal operating range, this booster heater is no longer functional. The A1 area represents all circuitry located inside the Dewar flask. The voltage regulator board A2A1 is located on the base of the unit. All of the components used in this oscillator are space qualified and goes through additional screening and burn-in requirements.

Performance

The oscillator was able to meet all of the specification requirements and performed considerably better than specified in some significant areas. Table 1 is a summary of these performance characteristics. The performance was such that under all conditions of environment, during the 30 minute descent phase of the probe, the oscillator was capable of maintaining the desired frequency accuracy. A composite curve is shown in Figure 7 which shows a total uncertainty of $\pm$ 3 x 10^{-10} at the end of this 30 minute interval. The warm-up characteristic of this oscillator is shown in Figure 8. The smooth and rapid warm-up is indicative of the SC cut crystal performance. The warm-up time to PP10^{-9} occurred within 6 to 7 minutes and no overshoot or ringing was apparent in the frequency curve. This type of overshoot-free warm-up curve has been found in other oscillators which also used the SC crystals.

The oscillator performance in a radiation environment showed an improvement over typical AT crystal performance of 1 to 2 orders of magnitude. A typical AT cut crystal would exhibit a sensitivity of 1 - 2 x 10^{-12}/rad whereas the SC cut crystals showed a sensitivity of 1 - 2 x 10^{-14}/rad in the best case and 3 x 10^{-13} in the worst case. Radiation tests were performed using a Cobalt 60 radiation source. Figure 9 is a typical radiation response curve that was obtained from these oscillators. The radiation applied was at the rate of 10 rads/sec for 700 seconds. The initial response shows a positive offset which varied from 1 to 5 x 10^{-9} and was independent of radiation rate. After this initial positive offset a negative slope was obtained which was directly proportional to the radiation rate and whose sensitivity became less as the crystal was further preconditioned.

TABLE I

GALILEO QUARTZ CLOCK

TABLE OF CHARACTERISTICS

PARAMETER	OBJECTIVE	ACTUAL
SIZE:	1.75" DIA X 5.5"	1.75" DIA X 5.5"
WEIGHT:	14 OZ.	20 OZ.
INPUT POWER:	7 WATTS PEAK	7 WATTS PEAK
WARM-UP TIME:	300 MIN.	< 300 MIN.
FREQUENCY STABILITY:		
AGING:	1×10^{-10}/30 MIN.	$< 1 \times 10^{-10}$/30 MIN.
VOLTAGE:	1×10^{-10}/VOLT	$< 1 \times 10^{-11}$/VOLT
TEMPERATURE:	$1 \times 10^{-10}/10°C$	$1 \times 10^{-10}/10°C$
MOTION:	1×10^{-9}/G	2×10^{10}/G
SHORT TERM:	5×10^{-11}/SEC	1×10^{-11}/SEC
PHASE STABILITY:	0.016 DEGREES	0.003 DEGREES
RADIATION SENSITIVITY:	-2×10^{-12}/RAD	-2×10^{-14}/RAD

Figure 10 shows a radiation level of 150 rad/sec for 24 minutes. During this radiation exposure the change of slope as a function of radiation level is apparent. The retrace characteristic at the conclusion of the radiation exposure was random in nature and no conclusions have been drawn as yet.

Figure 11 shows an accumulated radiation exposure of 1 megarad after the initial 25 krad preconditioning. The variation was approximately 1×10^{-8} for 1 Mrad. Figure 12 shows the effect of radiation on the orbiter engineering model. Radiation levels of 10 rad/sec for 700 seconds was applied after initial preconditioning of 25 krads and shows a slope of 3.3×10^{-12}/rad. After a further preconditioning of 200 krads and with the same radiation level (as shown on Figure 13), we obtain a sensitivity improvement to 7×10^{-13}/rad. Data taken on these oscillators indicated that with a preconditioning of 500 krads to 1 megarad, radiation sensitivity of PP10^{-14}/rad are obtained.

The two engineering models built on this program will be used to further determine radiation sensitivity and warm-up as a function of time. These units will be retested at 6 month intervals for the next two years to further characterize these parameters.

Conclusions

Tests on the engineering models of the Galileo oscillator have indicated that the SC cut crystal has acheived considerable improvements in both warm-up characteristics and radiation sensitivity. Five to ten minutes warm-up to within 1PP10^{-9} was achieved without overshoot and an order of magnitude improvement in radiation sensitivity was obtained. The use of the titanium Dewar flask has permitted the achievement of low power drain and high stability equivalent to that obtainable with glass, but has provided the capability to withstand the harsh environmental atmosphere that will be encountered during the mission.

Acknowledgment

We would like to thank both Ferdinand Euler and Lester Lowe of RADC for their help and assistance in making available both equipment and facilities to obtain the radiation data presented here. The experimental results in the paper were developed under the Galileo Probe Spacecraft subcontract with the Hughes Aircraft - Space and Communication Group and NASA/Ames Research Center. Special thanks are due to Al Kahane of RADC, Dr. T. A. Savo of HAC, and John Vig of ERADCOM for their technical support and encouragement in preparing this paper.

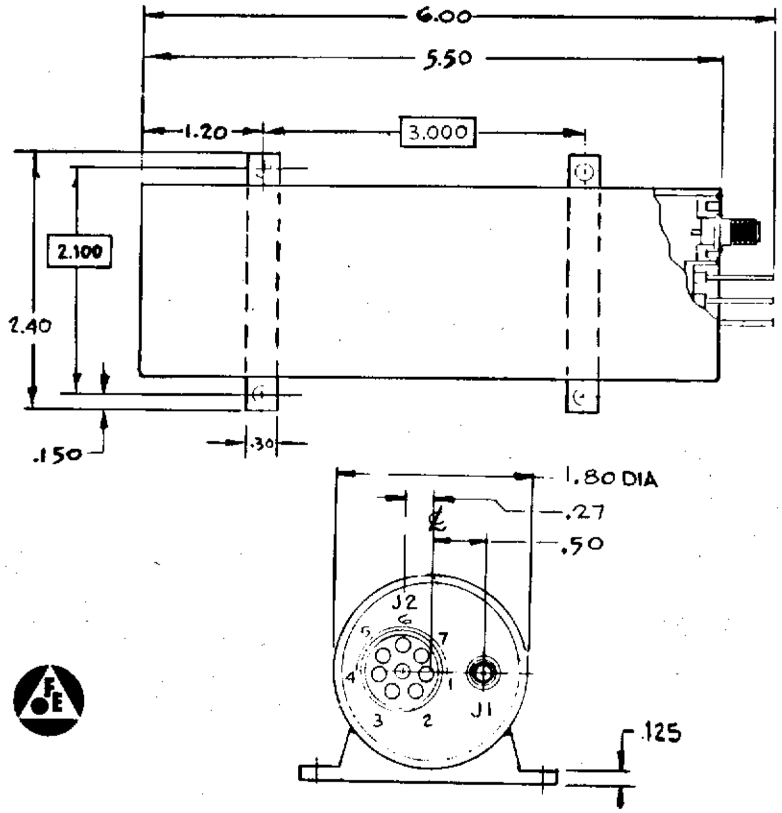

Figure 1. Outline Details

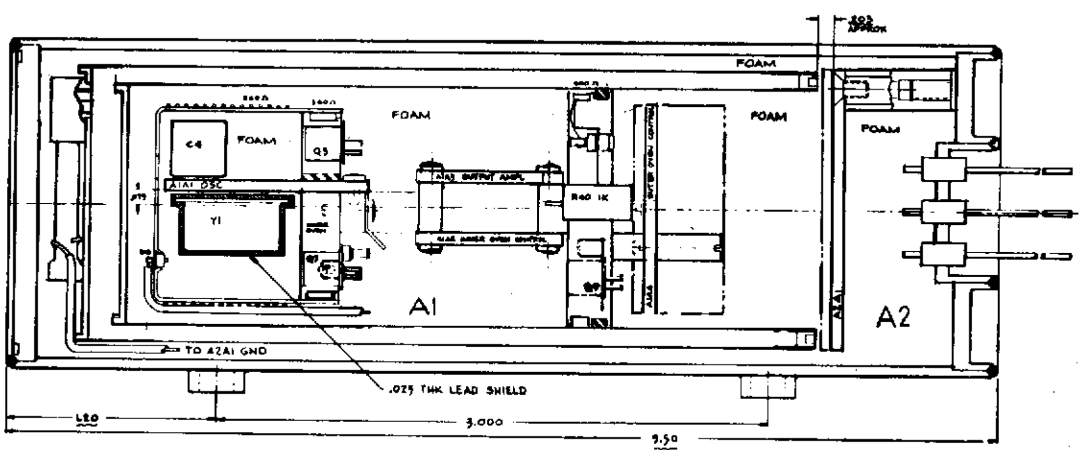

Figure 2. Unit Assembly

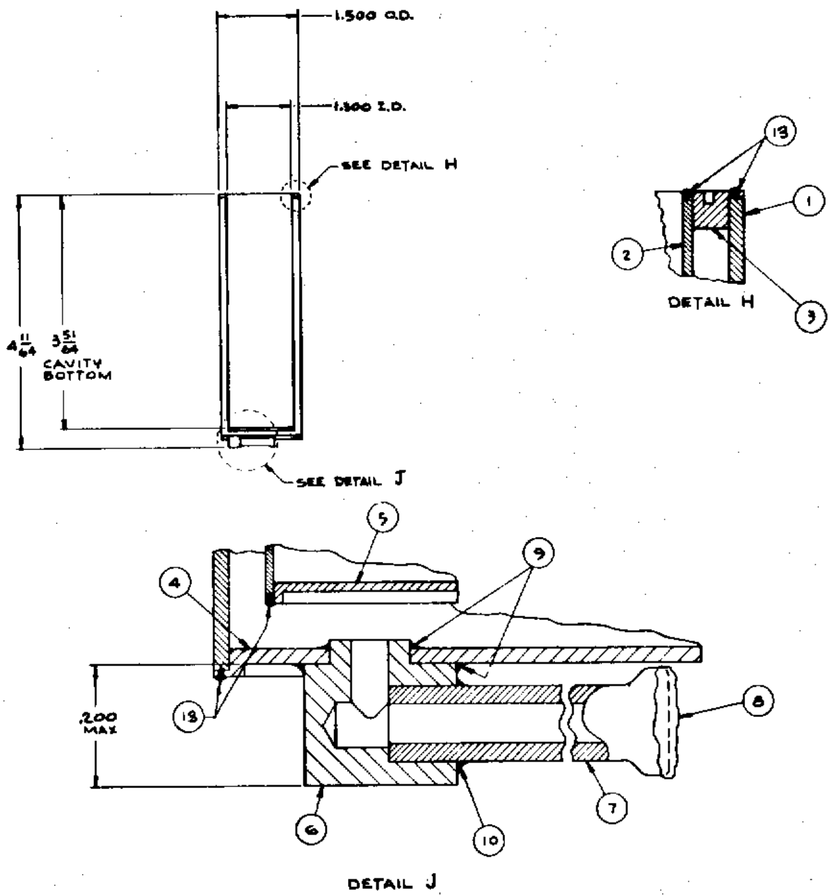

Figure 3. Dewar Flask Construction

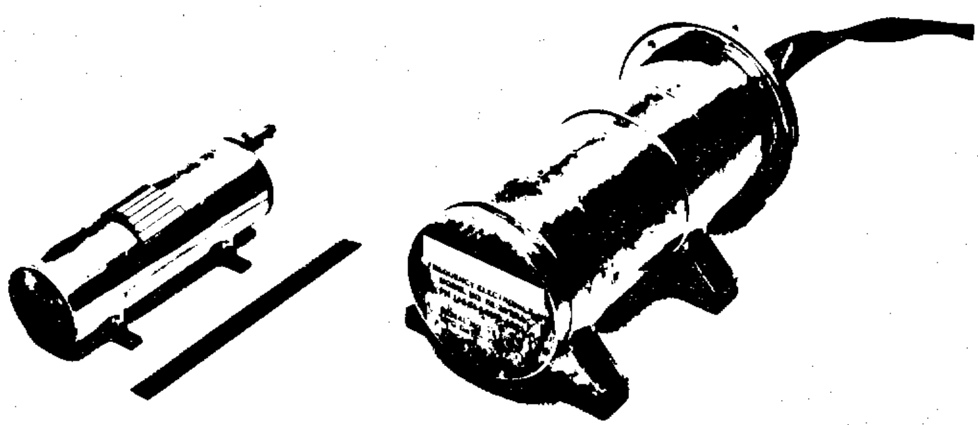

Figure 4. First Engineering Model

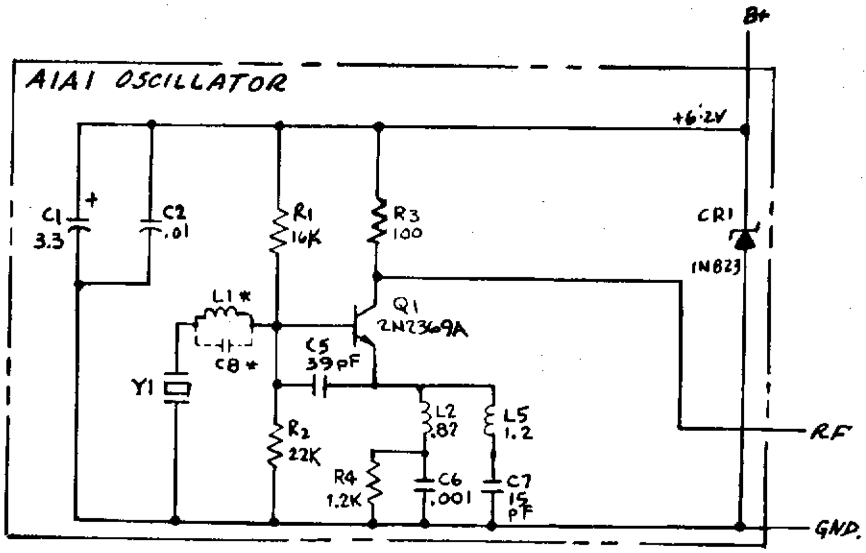

Figure 5. Oscillator Schematic

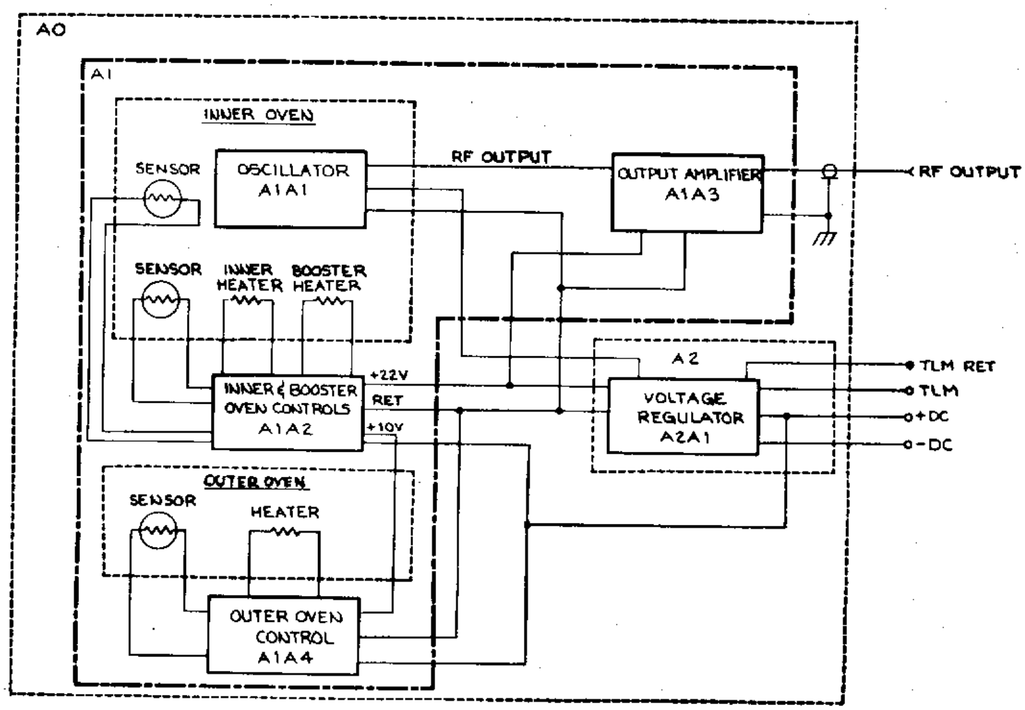

Figure 6. Circuit Block Diagram

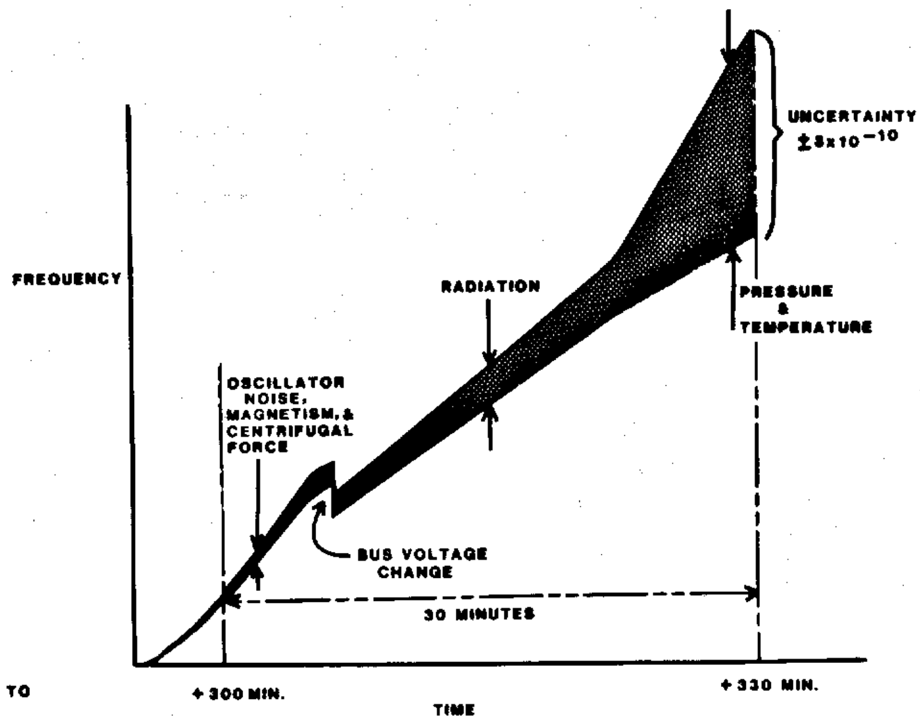

Figure 7. Typical Oscillator/Drift

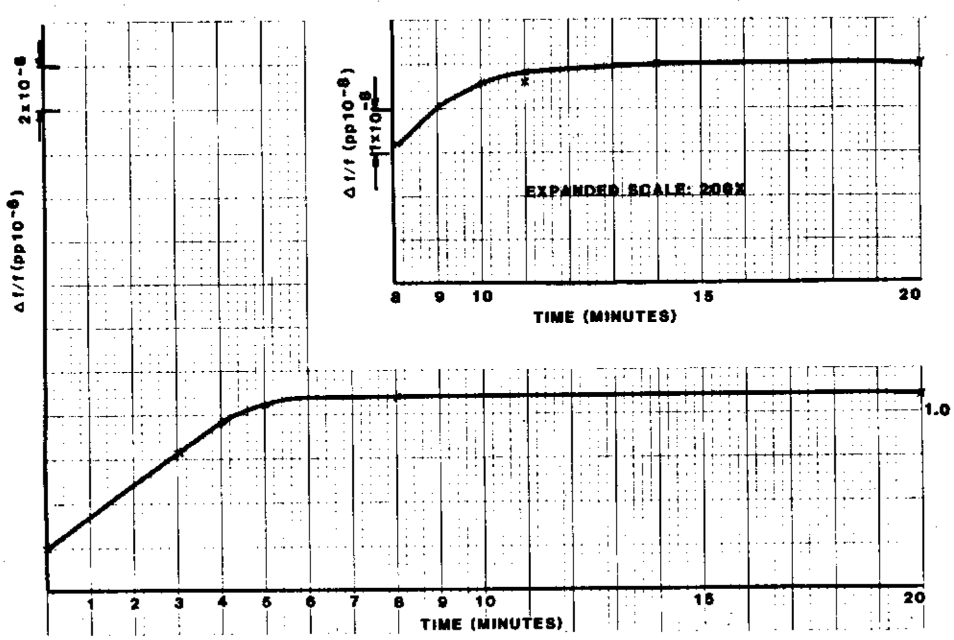

Figure 8. Galileo Warmup Curve

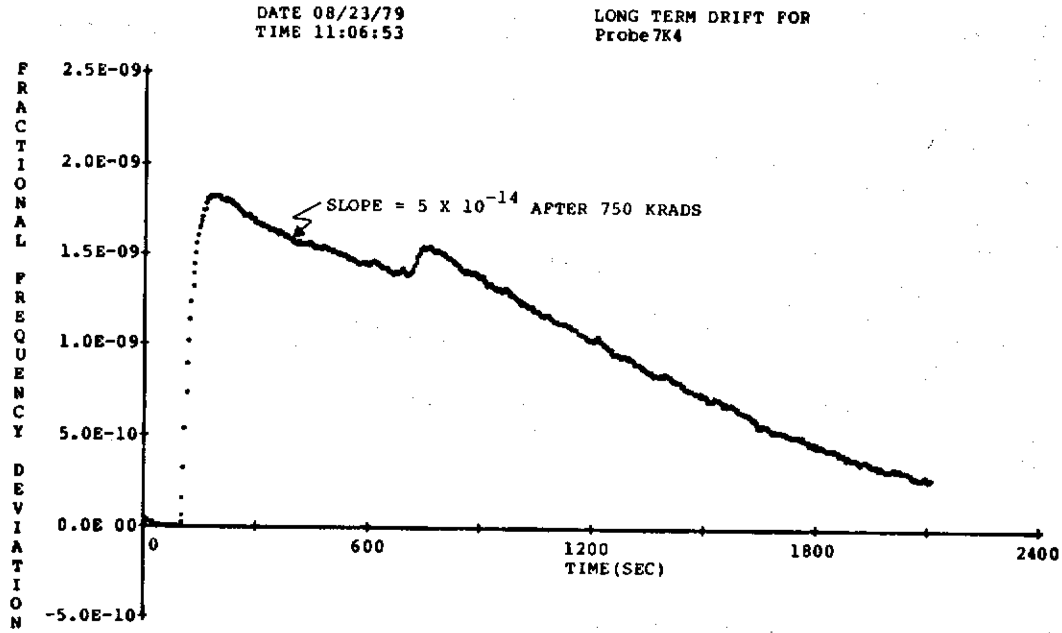

Figure 9. Probe Radiation, 10 RAD/Sec for 700 Seconds

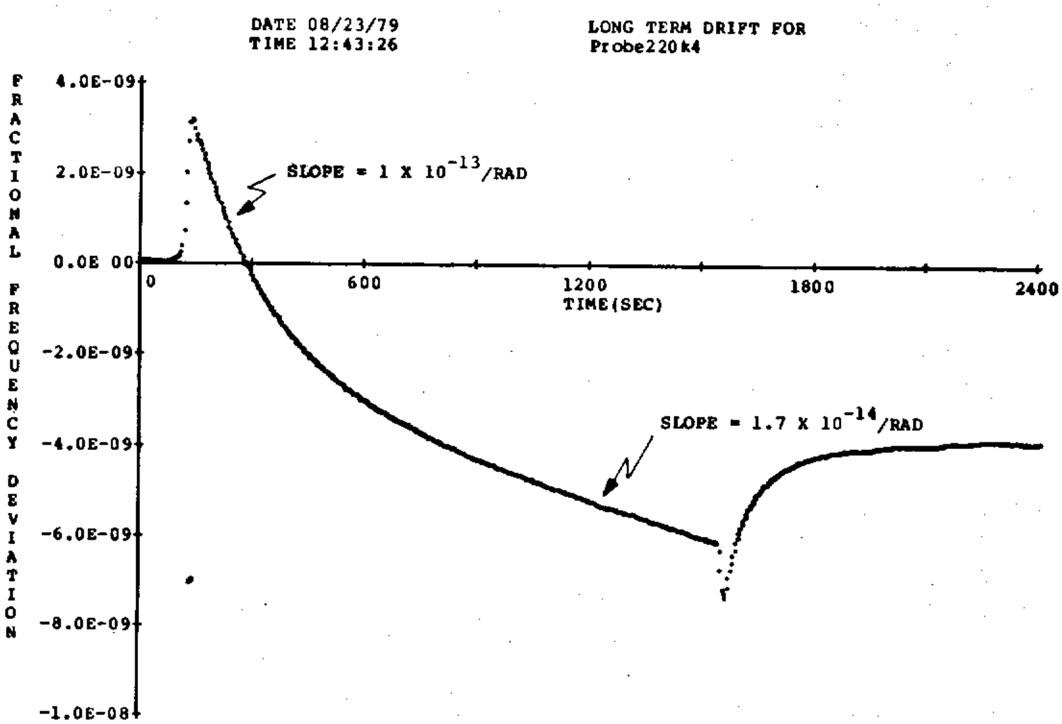

Figure 10. Probe Radiation, 150 RAD/Sec for 24 Minutes

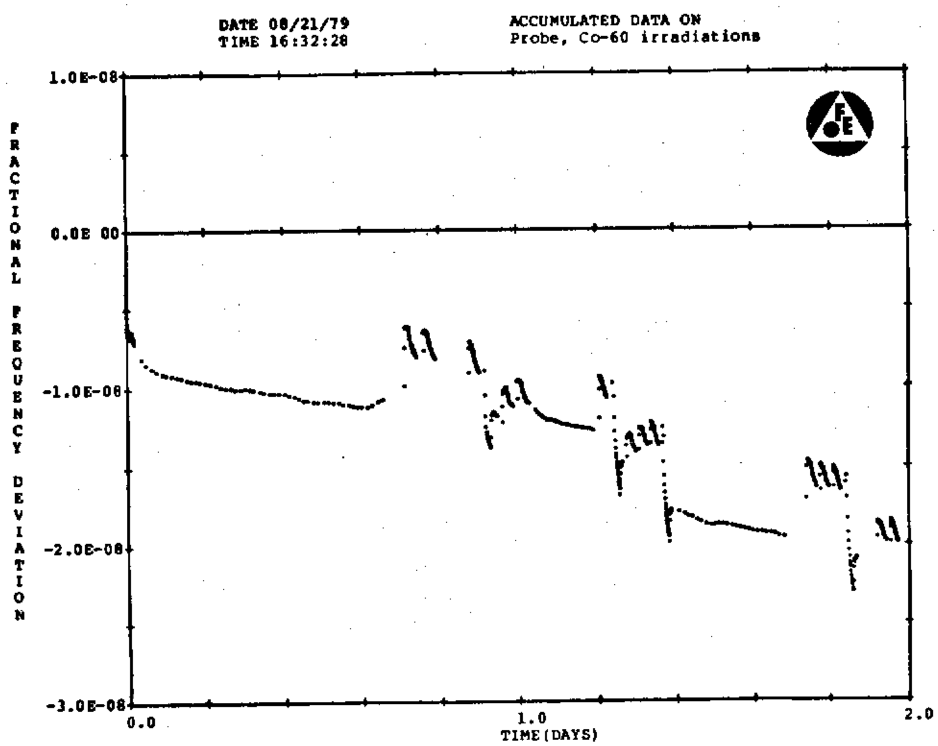

Figure 11. Accumulated Probe Radiation, 1,000,000 RADS

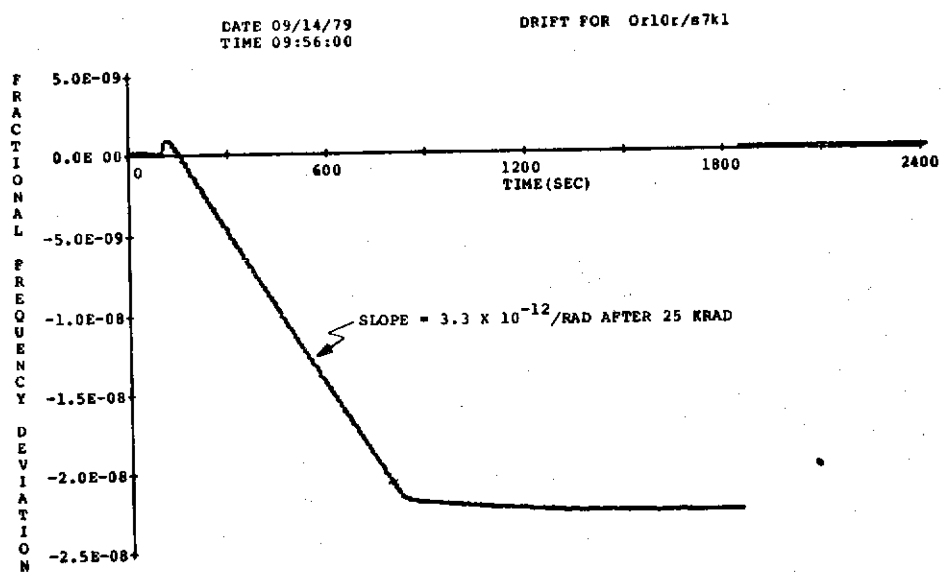

Figure 12. Orbiter Radiation, 10 RADOSEC for 700 Seconds, 25 KRAD Preconditioning

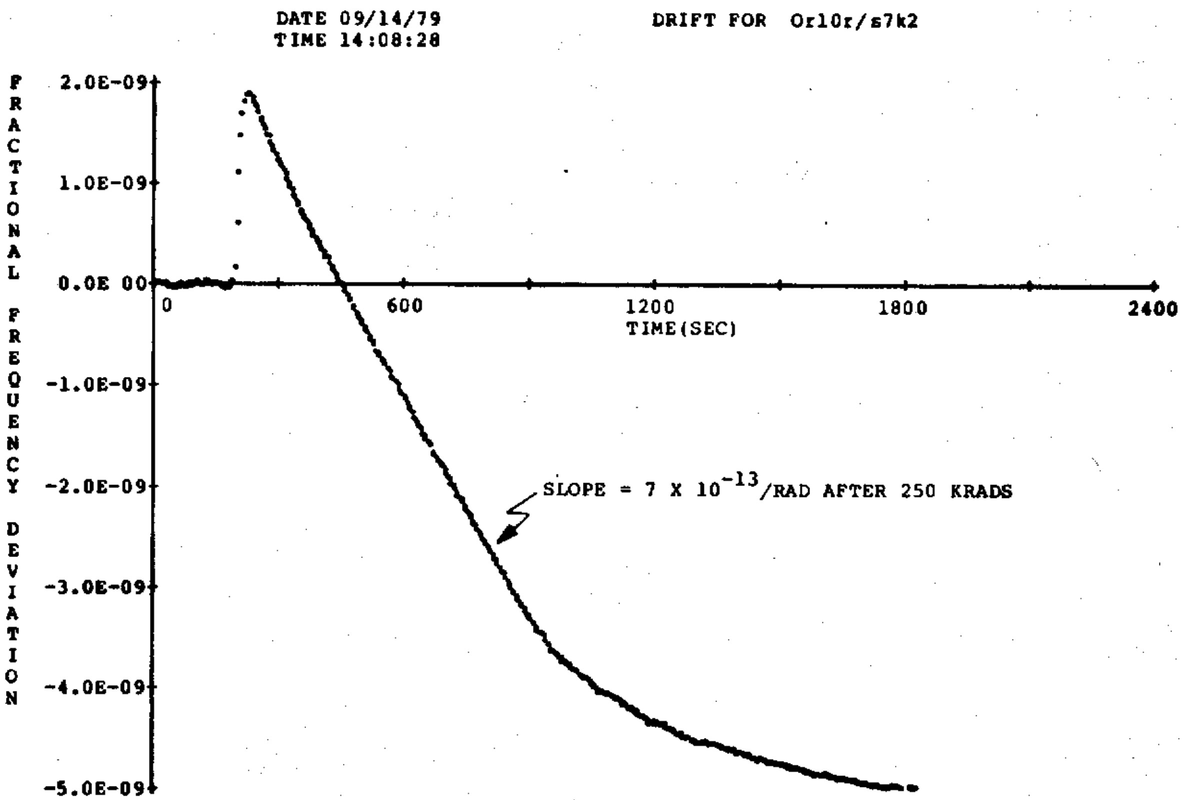

Figure 13. Orbiter Radiation, 10 RADOSEC for 700 Seconds, 250 KRAD Preconditioning

QUESTIONS AND ANSWERS

DR. WALLS:

Have you or do you plan to investigate the effect of chemical polishing versus mechanical polishing on radiation sensitivity because that may in fact involve some changes in the stress level of the surface?

DR. BLOCH:

No Fred. We did not intend to, but we have a study contract now on SC cut crystals and that might be a test that would be there. I have a feeling that it is something more simple. Unfortunately we didn't have the luxury to take apart the resonators, but we have seen in cutting quartz that the late vintage premium Q swept quartz there aren't two resonators cut right next to each other that have the same defects.

And another possibility Fred, it might be that one has more severe defects than the other. The quartz has been really a problem to us in handling.

MR. PLEASURE:

You seem to have a small resonator that is peculiar to the crystal itself. You showed a little L and a dotted little C, is that what you used to tweek in the final set of frequencies, the operating frequencies?

DR. BLOCH:

Yes. We use either inductance of capacitance to set nominal.

MR. PLEASURE:

And isn't that a temperature sensitive device?

DR. BLOCH:

It is really not, if you make an error budget analysis, it contributes less than a part in 10 to the 11th to the error budget. The SC cut crystal has a very low value of C-1, so the external effects, if you shift the frequency of a part in a million of let us say 20 picofarads, the effect of that capacitor is negligible, also with the inductor.

QUESTION:

Is it made on an air core so that it won't stretch and have a hysteresis in its characteristics?

Have you tried this?

DR. BLOCH:

Are you talking about the inductor? The inductors that we use for setting are all air core inductors so they have a very low temperature coefficient and the capacitors that we are using are all glass capacitors with about 20 parts per million per degree C. Since this is in an oven with about a 50 millidegree temperature control under the worst condition, it produces negligible effects.

QUESTION:

So you have a bad form, it will knock it silly.

DR. BLOCH:

It really doesn't, the glass capacitors do what we need. We have them to repeat to within a part per million and if you visualize a 20 picofarad capacitor changing by more than a part, that is far fetched change for a precision glass capacitor.

We have not experienced any such problem in the regime of parts in 10 to the 10th and 10 to the 11th. Maybe in 10 to the 14th.

QUESTION:

What is the error then?

DR. BLOCH:

There is an air core which has very similar retrace characteristic. It has very little hysteresis and again there is a large tolerance. You are talking many microhenries for one part per million change. It is a very stiff resonator. So there is a large tolerance on the effect of those parts.