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THERMAL VACUUM TESTING TECHNIQUES FOR SPACECRAFT

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ABSTRACT

Cesium frequency standards are to be flown on the NTS-2 satellite which is part of a program conducted at the Naval Research Laboratory (NRL) to develop technology and time standards for NAVSTAR Global Positioning System (GPS). Mission requirements for the thermal design of this frequency standard called for a low nominal temperature (15°C) and the removal of most of the heat generated by the standard from the spacecraft. This paper describes the test program run at NRL to determine the thermal properties of the frequency standard. Since it was necessary to run tests before delivery, a simulator was constructed for these tests. Special mathematical analysis techniques were developed to obtain the thermal coefficients required for the spacecraft thermal analysis. These coefficients are then used to predict the thermal environment for different orbital conditions. Thermal vacuum tests of the flight frequency standard and the integrated spacecraft demonstrated the validity of this technique.

INTRODUCTION

A Cesium Beam Frequency Standard is being flown on the Naval Research Laboratory developed Navigation Technology Satellite Two (NTS-2), as part of the NAVSTAR Global Positioning System (GPS).¹ This standard was developed especially for NTS-2 and, as a part of that program, a thermal analysis was made of the standard. This paper will present the test techniques, data analysis methods and results of the thermal characteristics of the standard.

Frequency Standard Testing

Due to time constraints, the flight qualification model of the frequency standard was not available for

testing when data was required to complete the satellite thermal design, therefore a simulator was constructed and tested first.

The complete testing program, which was conducted at NRL, consisted of testing the simulator, testing the effects of changes on a simulator (different thermal coatings and conductivity paths) and testing flight qualification models. Tests were also run by another group at NRL on a mockup of the satellite and on the flight model satellite.

The frequency standard as seen in Fig. 1, is a box, 25 cm x 41 cm x 20 cm high, weighing 13 kg and

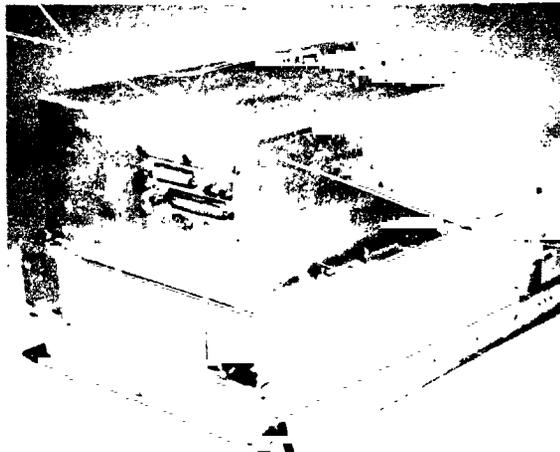


Fig. 1 - Flight Frequency Standard



Fig. 2 - NRL Simulator

dissipating approximately 23 watts of DC power. The simulator as seen in Fig. 2, was constructed to have as nearly as possible, the same size, weight, and DC power. Most of the weight was simulated by a one inch thick aluminum plate. Boxes were added top and bottom to simulate the size and the mounting brackets were constructed in a shape similar to the standard. A large electric heating blanket simulated the DC load. It is to be noted that the standard design allowed the use of vibration isolators. Early tests on both the simulator and the standard were made with the vibration isolators, but in the spring of 1976 the isolators were replaced with solid aluminum blocks and another set of test data was taken on both the simulator and the flight model frequency standard.

Frequency standard and simulator thermal vacuum tests were run at NRL in a chamber which has a 17 inch diameter cylinder, 21 inches deep, with a temperature controlled plate. A vacuum pressure of 1×10^{-5} torr and lower was achieved with the use of a diffusion pump. Temperature control was achieved with a recirculating bath which was proportionally controlled. The capacity of the heating and cooling equipment allowed a rapid change of the temperature controlled plate (less than an hour) and temperature stability was better than $\pm 0.1^\circ\text{C}$. The temperature range of the chamber is -15°C to $+50^\circ\text{C}$. The walls of the chamber were lined with aluminized mylar early in the test series, and were changed to polished stainless steel late in the test series, due to maintenance problems of the aluminized mylar.

The test procedure consisted of placing the object in the chamber; setting the temperature controlled plate, and the DC power load; and allowing the object to stabilize. Normally four temperature sensors were used. Fig. 3 shows typical locations of the temperature sensors. Temperature stabilization was monitored by observing the rate of change of the sensor mounted on the object under test. A complete test series consisted of three different temperatures with three different DC power settings at each temperature, but due to time limitations, it wasn't possible to obtain a complete data set for each series.

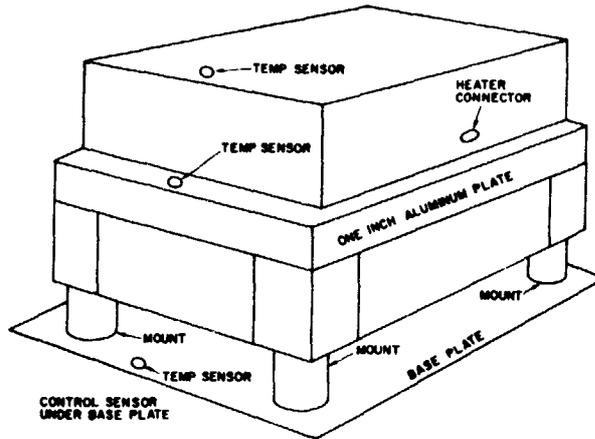


Fig. 3 - Sensor Locations on Standard

Data Analysis

At the equilibrium temperature, the DC power is dissipated by radiation and conduction to the controlled plate and the chamber walls.² The energy balance equation is

$$P = A_1(\sigma T_s^4 - J T_p^4) + C_1 (T_s - T_p) + C_a (T_s - T_a)$$

where

- P = DC power (watts)
- A_1 = Effective radiating area (cm^2)
- σ = Stefan - Boltzmann constant ($\text{w}/\text{cm}^2 \text{ } ^\circ\text{K}^4$)
- C_1 = Conductivity between the unit under test and temperature controlled plate ($\text{w}/^\circ\text{C}$)
- C_a = Coupling to the ambient room temperature
- T_s = Temperature of unit under test ($^\circ\text{K}$)
- T_p = temperature controlled plate temperature ($^\circ\text{K}$)
- T_a = Ambient temperature ($^\circ\text{K}$)

The purpose of this test program was to determine the parameters A and C_1 . By changing the terms T and T_p , it was possible to generate a data set that could be used to calculate A and C_1 . The coupling coefficient must be determined and includes the effects of

instrumentation wiring and radiation to the wall which is assumed to be approximately linear.

The problem in data analysis is to separate the radiated and conducted coefficients. A plot of the plate temperature vs. the temperature of the unit under test is nearly linear. An inspection of the methods of solving simultaneous equations shows that small temperature variations cause large coefficient variations.

To illustrate the problem³, a group of three data sets were chosen which were characteristic of conduction coupling to the baseplate and to ambient. Conduction and radiation parameters were then derived from these data sets assuming no conduction to ambient. Then the frequency standard temperature in the middle data set was incremented by plus and minus one degree and the effect of the increment on the parameter solution was determined. The results are plotted in Fig. 4. The small temperature increment on one data point produced widely varying solutions.

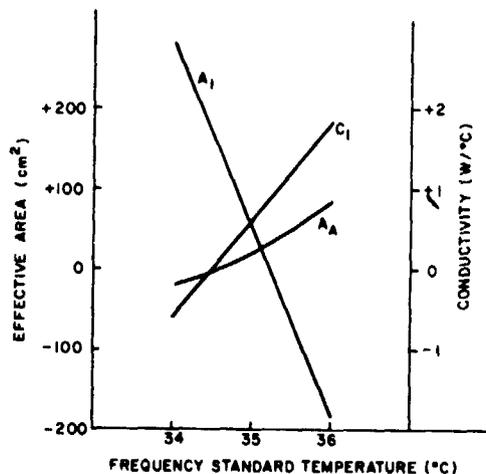


Fig. 4 - Simulated Parameter Solution

A combination of test and analytical techniques yielded a consistent set of coefficients. Since the standard was mounted on four legs, it was possible to run tests using two and then four legs. The energy balance formula is then used to calculate the conductivity coefficient. Once the conductivity coefficient is known, the other coefficients may be calculated from the data set. A complete test run consists of nine lines of data (3 temperatures with 3 DC power levels at

each temperature) the resulting nine energy balance formulas were then analyzed on a desk top calculator using a multiple linear regression technique. It was noted that varying the temperature and not the power yielded a data set, that did not give consistent results using the multiple linear regression.

Test Results

Six major tests were run between October 1975 and July 1976. Table I lists the characteristics of the six units tested. The manufacturer made available for a short time a thermal simulator which used many of the frame components of the flight standard. When that simulator was returned, another simulator was constructed at NRL of approximately the same size and weight of the flight standard. Initial tests indicated that the thermal coupling between the standard and the

Table I
Characteristics of Units Tested

Unit Tested	Coating		Legs	Thermal Straps
	Bottom	Top		
MFG Sim.	Black	Alum	Isolators	No
NRL Sim.	"	"	"	Yes
FLT Std.	"	"	"	Yes
NRL Sim.	"	"	Isolators & Blocks	Yes
NRL Sim.	"	Black	Blocks	No
FLT Std.	"	"	"	No

base plate was lower than desired. Therefore a series of tests were run to determine the feasibility of adding flexible copper braided straps. The formula used to estimate the conductivity coefficient is $C = W/PL^2/K$ where W = weight (2.6 gms/in), L = length, P = density (.22 lb/in³ for copper), K = conductivity (9.7W/oC - in for copper). Test results gave a coefficient half that of the calculated value, probably due to the difficulty of bonding the braid to the aluminum box.

In the spring of 1976, as the result of the analysis of vibration tests, it was decided to replace the vibration isolation mounts with aluminum blocks to lower the gradient between the frequency standard and the base

and to provide a number for the satellite thermal system design. The value listed in Table II is the 10% to 90% response to a step change in temperature.

The thermal coefficients generated in Table II can now be used to predict operating temperatures in the satellite. The temperature of the baseplate is controlled by the area of the optical surface reflectors on the outer surface of the baseplate panel. Fig. 5 shows expected temperature performance for four different cases, three with the simulator and one with the flight standard, assuming no coupling with the inside of the spacecraft. The temperature difference between the standard and the baseplate was 28°C with a baseplate temperature of 0°C in the original design. The straps reduced the differential by 5.4°C, and the switch to solid blocks reduced the temperature difference to 14.6°C. The flight standard agreed with the simulator within less than one degree. This error could be attributed to differences in the quality of the black paint of the radiated area.

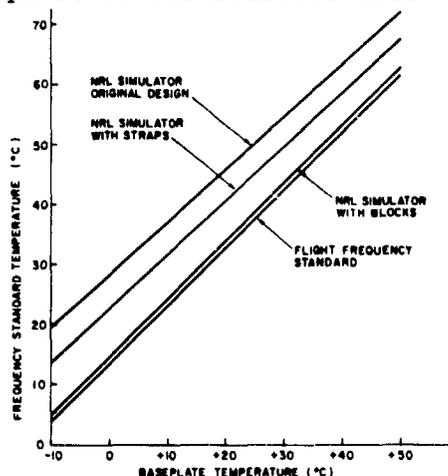


Fig. 5 - Temperature Performance of Simulators and Standard

Conclusion

This testing program was successful in generating a set of thermal coefficients for use in the spacecraft thermal system design, before the flight frequency standard was delivered to NRL. The NRL - conducted simulator was shown to be an accurate model of the flight standard and the technique chosen to separate the conducted and radiated terms produced coefficients which were used to predict performance of the flight standard.

References

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4. Model 10 Hewlett Packard Calculator Model 9810A Stat Pac