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Design and Ground Test of the NTS-1 Frequency Standard System

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The NRL TIMATION III satellite, redesignated as GPS Navigation Technology Satellite I (NTS-1) was successfully placed into a medium altitude orbit, 7,300 mi, on July 14, 1974. One of the major experiments performed with the satellite is the investigation of the space-environment performance of two rubidium controlled frequency standards and a specially developed quartz oscillator. System design, ground testing, and flight qualification modifications were performed at NRL. This included modifying commercial-quality rubidium standards to levels acceptable to the flight environment; the design and construction of power control, RF switching, and remote digital

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tuning circuits; and ground testing the candidate frequency standards in terms of short-term stability (Allen Variance), aging, warmup, tuning characteristics, DC power consumption and environmental effects due to vacuum, radiation, vibration, and temperature.

CONTENTS

DESIGN AND GROUND TEST OF THE NTS-1 FREQUENCY STANDARD SYSTEM

INTRODUCTION

The Navigation Technology Satellite One (NTS-1) is part of a program conducted at the Naval Research Laboratory (NRL) to develop new navigation and time transfer techniques. This satellite was conceived as the third satellite in the NRL TIMATION series. It has since been incorporated into the NAVSTAR Global Position System (GPS) development program. With the TIMATION program's combination into the NAVSTAR GPS program, the satellite was renamed NTS-1. The objectives of the satellite remained the same, so past frequency-standard experiments are relevant to the new program. A principal objective is to demonstrate new techniques in the application of frequency standards for satellite use.

The two earlier satellites launched in the TIMATION program in 1967 and 1969 [1, 2] each used a quartz oscillator [3] as the frequency standard. Similarly, NTS-1 uses a quartz oscillator [3] as its primary frequency standard. However, late in the satellite's fabrication process, it was possible to incorporate two experimental atomic frequency standards. This possibility was brought about by recent developments in the atomic frequency standard state of the art [4,5] and by the availability of space in the satellite. The satellite configuration for ground testing is shown in Fig. 1, and the orbit configuration is shown by Fig. 2. NTS-1 was successfully launched from Vandenberg Air Force Base on July 14, 1974.

SYSTEM DESCRIPTION

The frequency standard system for NTS-1 [6] can be divided into three parts: the frequency standards, tuning and control logic, and regulators. There are three frequency standards; one Frequency Electronics (FE) quartz oscillator, and two Efratom rubidium frequency standards. The quartz oscillator is hard wired to the spacecraft battery. The important specifications of the quartz oscillator system are listed below.

DC power consumption	4.7 W
Aging	-2.5×10^{-11} per day
Radiation effect	-5×10^{-11} per day
10,000-sec sigma	4.4×10^{-12}
Tuning range	$\pm 0.8 \times 10^{-8}$
Smallest increment	3 to 9×10^{-11}
Estimated tuning life	3 years

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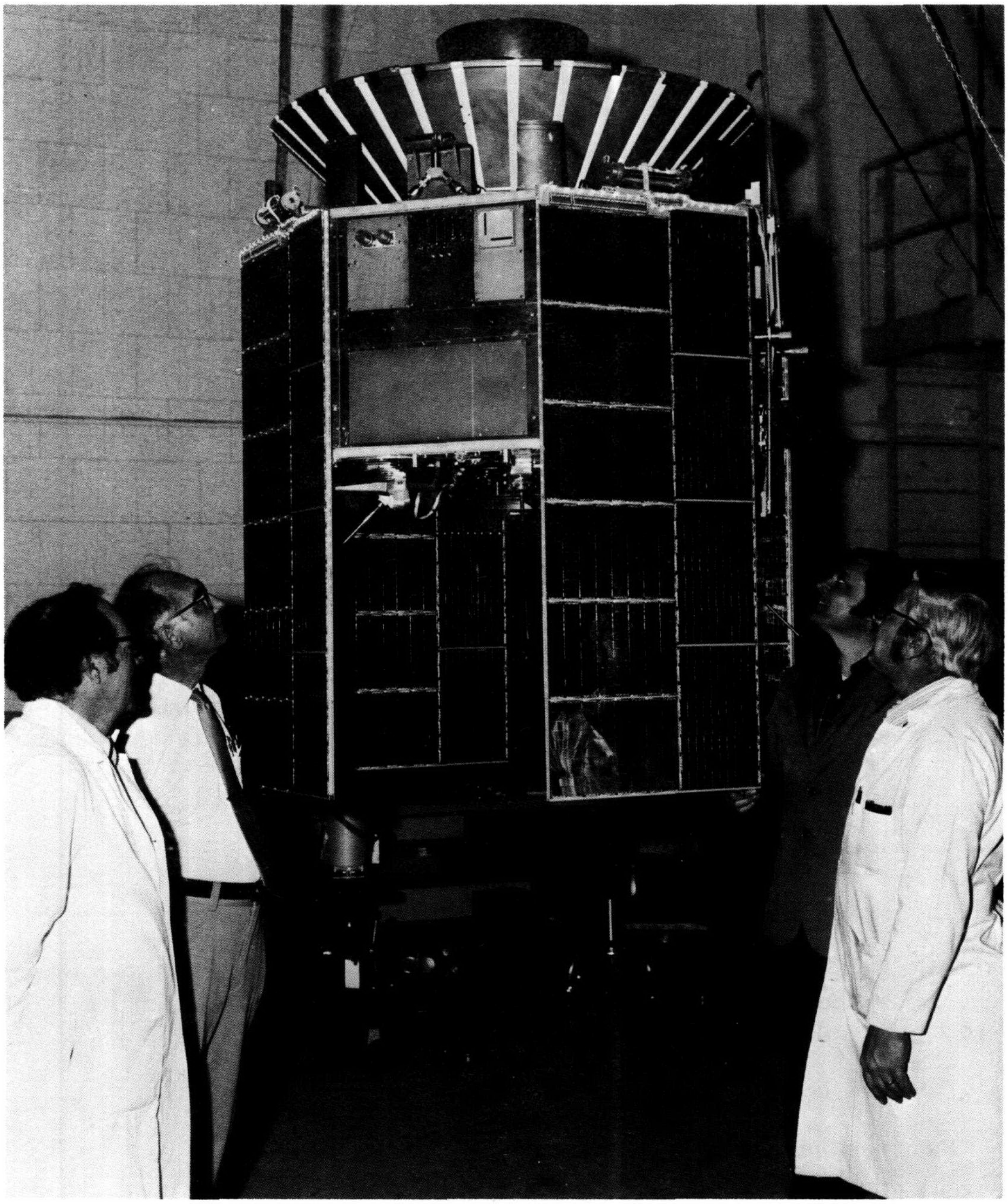


Fig. 1 — Ground test setup for NTS-1

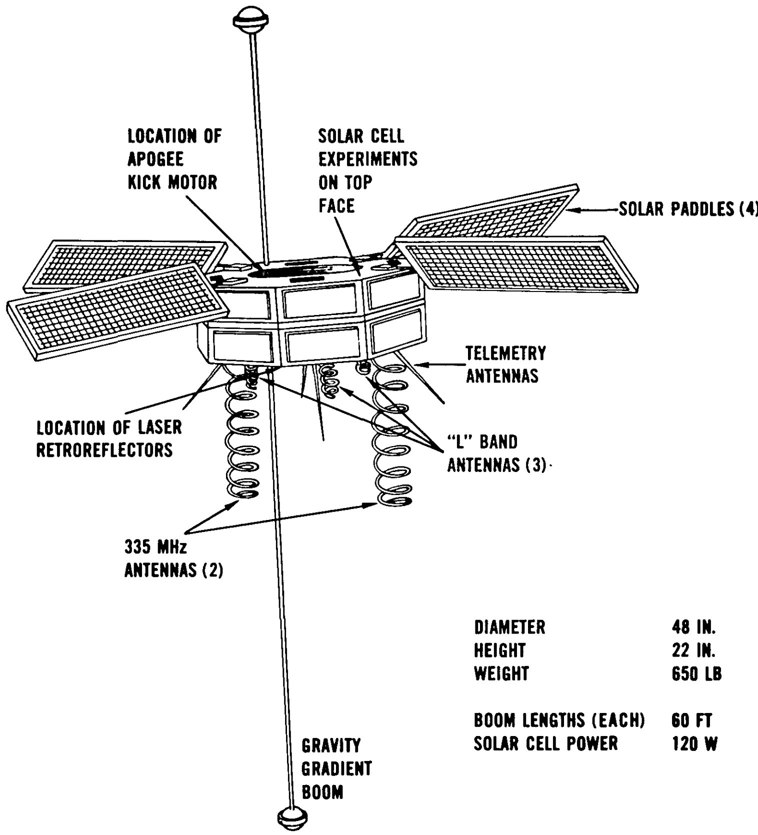


Fig. 2 — NTS-1 Artist's concept with details

Two rubidium frequency standards are being flown. These can be turned on individually, but only one rubidium unit can be turned on at one time. The important specifications are listed below.

Additional DC power consumption	14.6 W
Aging	0.6 to 2×10^{-12} per day
10,000-sec sigma	1 to 5×10^{-12}
Tuning range	$\pm 3 \times 10^{-9}$
Smallest increment	8×10^{-12}
Estimated tuning life	5 years

The tuning and control logic box accepts commands, controls the RF output to the experiment, and tunes the appropriate frequency interface between the rest of the satellite and the components of the frequency standard system. All power, command, telemetry, and RF connections are made through the tuning and control logic box.

Seven regulators are used in the frequency standard system. Figure 3 is a block diagram of the system. Figure 4 shows the equipment deck of the satellite including the frequency standards and the tuning and control logic box.

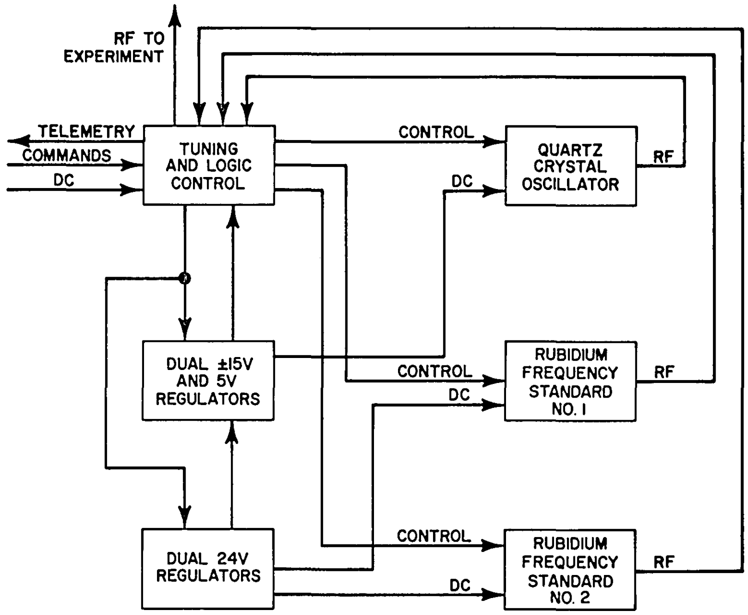


Fig. 3 — Frequency standard system

Quartz Oscillator

Five quartz oscillators were produced by Frequency Electronics for potential application in NTS-1. These oscillators were the continuation of a series of oscillators especially designed for the TIMATION program. Figure 5 shows the oscillator, which uses a fifth overtone AT-cut quartz crystal mounted in a double oven. The oscillator, buffer amplifier, and frequency control varactor are located inside the inner oven. This entire assembly is mounted inside a dewar flask with another amplifier, oven controls, and the second oven. As originally delivered, the oscillator also had an electromechanical tuning control, similar to those of TIMATION I and II, which allowed tuning in increments by sending pulses to the oscillator.

Modifications to Quartz Oscillator—A year after these units were delivered, a plan was developed to fly more than one frequency standard, the other standard to be a rubidium vapor frequency standard. Several modifications were required to integrate the quartz oscillator into this system, the most important change being in the tuning circuitry. The oscillators used for TIMATION I and II were tuned by glass piston capacitors which were controlled by a stepping motor. They had the advantage of consuming no power except during tuning, and the requirement of a relatively simple command control. The oscillator supplied for NTS-1 is tuned by changing the DC voltage to a varactor diode. This change has allowed a more efficient oven design to be used. The modification, added by NRL, was a digital-to-analog (D/A) converter, which converts a 12-bit digital word to an oscillator-frequency DC control voltage. Figure 6 shows the new printed circuit (PC) board. Figure 7 is a block diagram of the modified unit. A special high-stability voltage reference was used with the D/A converter. This reference voltage changes less than 1 mV for a 10-V output from 10° to 40°C. The output amplifier was also changed so that there would be two independent 5-MHz outputs.

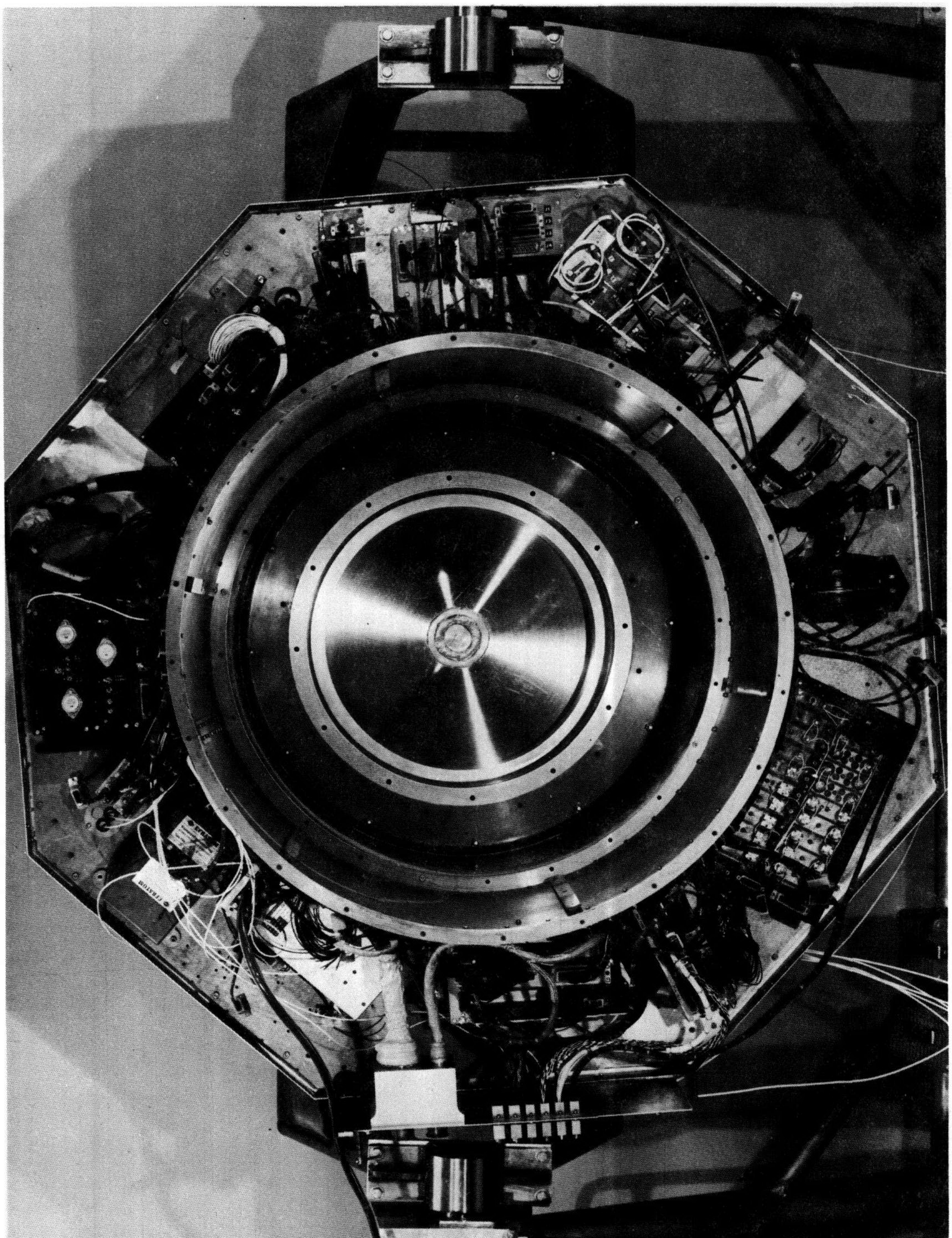


Fig. 4 — Satellite equipment deck showing frequency standard system

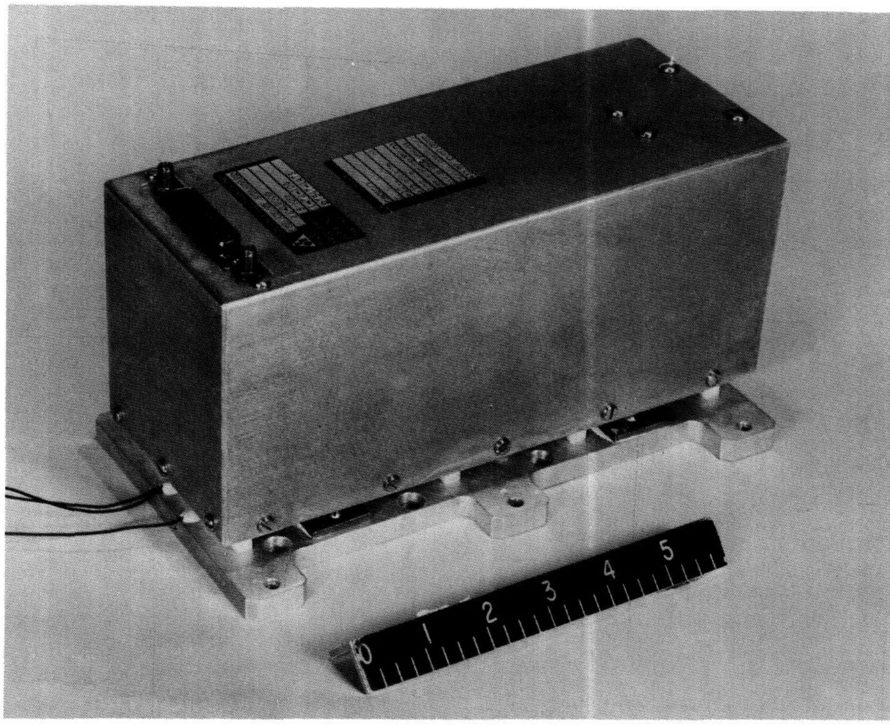


Fig. 5 — FE quartz oscillator

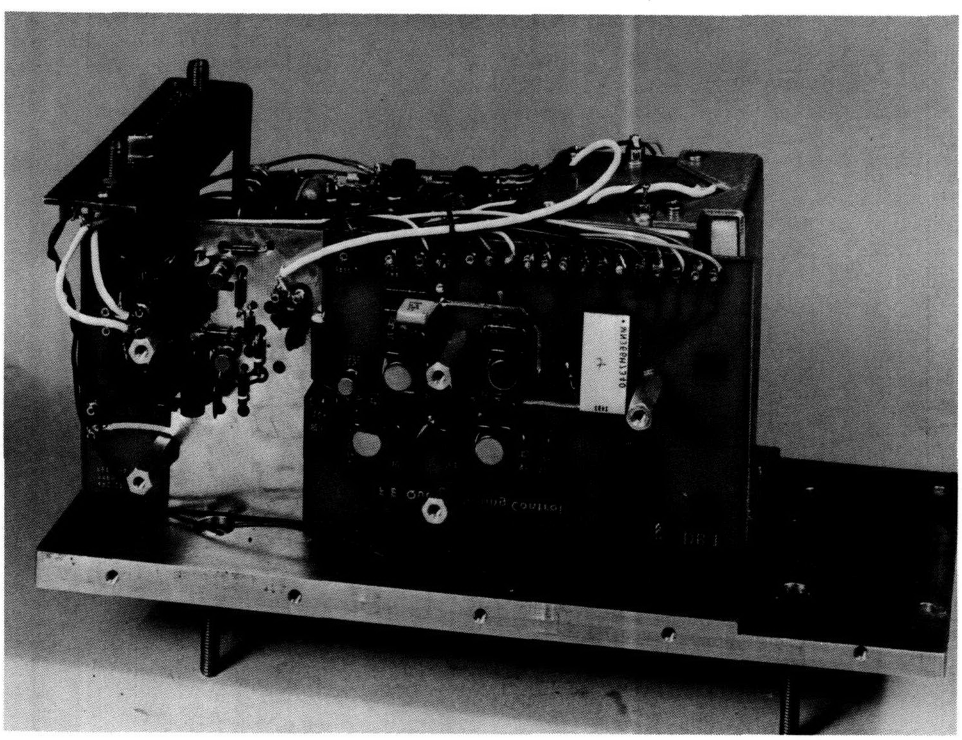


Fig. 6 — FE quartz with cover removed

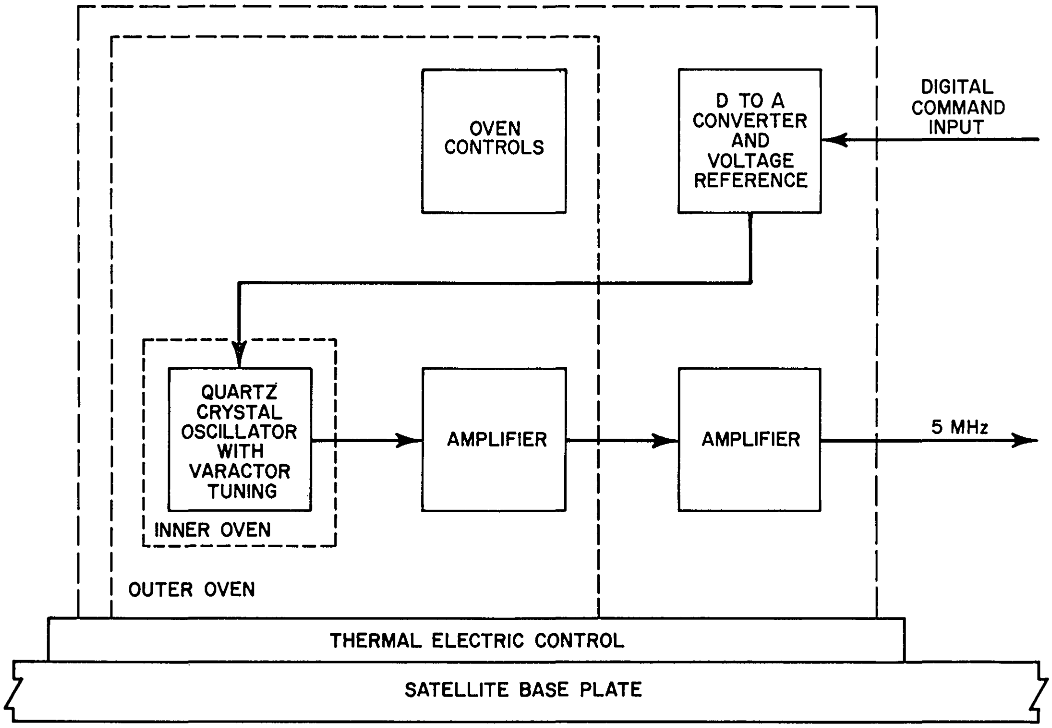


Fig. 7 — FE quartz oscillator functional diagram

The modifications changed the power requirements for the oscillator. The D/A converter required a ±15-V supply, so the oscillator was connected to +15 V through a small dropping resistor. The power consumed by the modified oscillator is 2.9 W in air and 2.5 W in vacuum. Table 1 lists the oscillators received and their status.

TABLE 1
Status of Quartz Oscillators

Serial No.	Date Received	Test Program Use	Final Use
6589	Apr. 1971	Prototype	Disassembled
101	Sep. 1971	Flight use	Laboratory tests
102	Oct. 1971	Evaluation	Exchanged
103	Jan. 1972	Evaluation	Backup units
104	Feb. 1972	Evaluation	Laboratory tests
105	Mar. 1974	Evaluation	In satellite

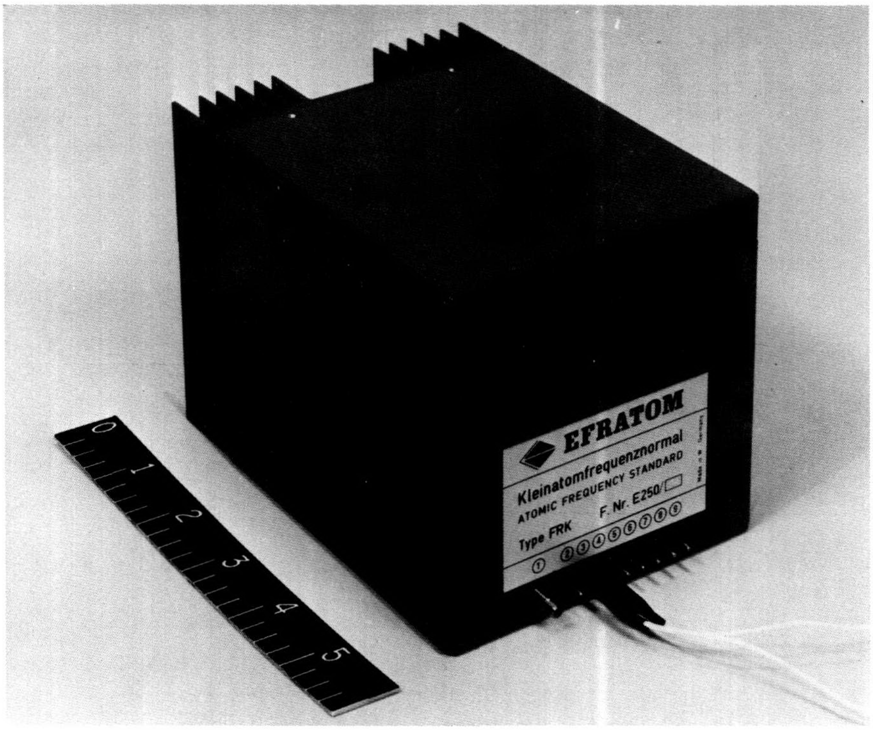


Fig. 8 — Efratom rubidium frequency standard

Rubidium Frequency Standard

A commercial miniature rubidium vapor frequency standard, shown in Fig. 8, was introduced by Efratom Elektronik Gmbh., Munich, Germany in 1972. Four of these units were purchased late in 1972 for evaluation for spacecraft use. An analysis of these units showed that their electronic characteristics were compatible with spacecraft use, but several modifications were needed to allow remote control operation and to meet launch vibration requirements [7,8]. Six additional units were purchased in the summer of 1973 for possible spacecraft use. All six were tested. Four were selected for modification, two for flight use, and two for backup units. The units were tested again after being modified. Of the four original units, two were used as prototypes for the planned modification, one was transferred to another agency, and one was kept as a benchmark standard. Table 2 lists the units received and their status.

The features of this unit are light weight (2.9 lb), small volume (4 by 4 by 4.5 in.), and low power (13 W). The fractional frequency standard deviations (0) between 1 and 10,000 sec and also the frequency stability over one month show that this unit can provide significant stability improvements over quartz oscillators.

The Efratom rubidium standard is employed as shown in Fig. 9. This is an abbreviated block diagram of the flow of NTS-1 frequency (time) data. Only one of the three available frequency standards will provide a reference signal at any one time. The several frequency sources have been integrated into the satellite in order to investigate the performance characteristics of both quartz and rubidium standards and also to assure a reliable redundancy for operation.

TABLE 2
Status of Rubidium Frequency Standards

Serial No.	Date Received	Test Program Use	Final Use
116	Dec. 1972	Prototype	Laboratory tests
120	Jan. 1973	Prototype	Disassembled
124	Jan. 1973	Benchmark standard	Life test
129	Jan. 1973	—	Exchanged
140	July 1973	—	Sent to Naval Observatory
163	Aug. 1973	Evaluate for flight use	Exchanged
164	Aug. 1973	Evaluate for flight use	Laboratory tests
165	Aug. 1973	Evaluate for flight use	In satellite
189	Aug. 1973	Evaluate for flight use	Backup unit
196	Aug. 1973	Evaluate for flight use	In satellite
198	Aug. 1973	Evaluate for flight use	Backup unit

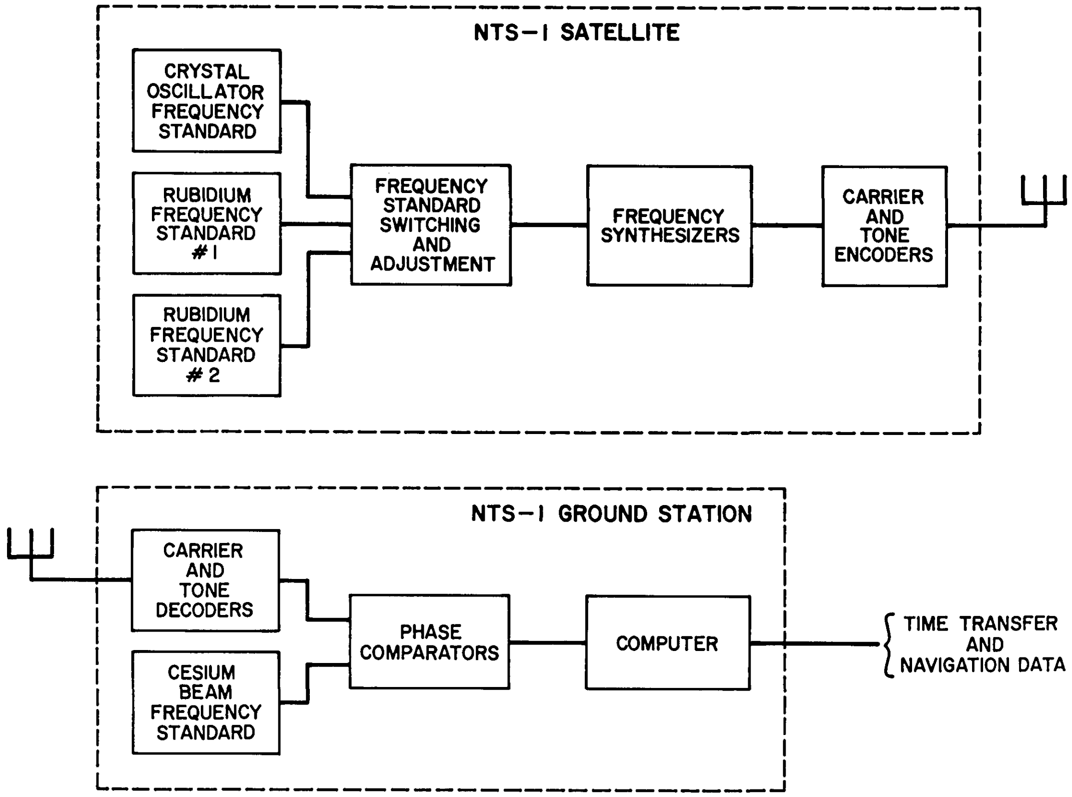


Fig. 9 — NTS-1 data flow

Modifications to Rubidium Standard—Both electrical and mechanical modifications were made to the Efratom standard to convert it to a space-qualified unit. The electrical modifications were mainly in the quartz oscillator circuit; the mechanical modifications were made to strengthen the unit so it could pass the launch vibration specifications.

In the quartz oscillator circuit as seen in Fig. 10, the coarse tuning was originally made by glass piston capacitor CV1. This was replaced with varactor diode D4 and associated circuitry (C17 and R32) to permit remote tuning. The rubidium output connector was also modified for remote operation. Figure 11 is a block diagram of the modified rubidium frequency standard.

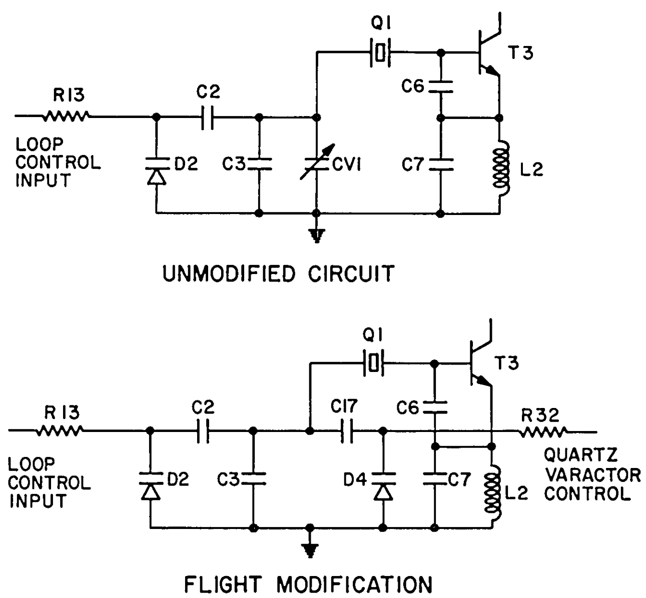


Fig. 10 — Modifications to rubidium quartz oscillator

Digital Frequency Control

The digital frequency control is a circuit that converts digital information to analog signals to control the frequency of the standard [9,10]. For effective frequency control, the output level changes must be low compared with the frequency sensitivity of the frequency standard control. Extensive use was made of components and techniques that have been developed and refined in the past few years. Figure 12 shows the main components and their interconnections.

The digital frequency control has four main functions: DC power control, digital word control, D/A conversion [11], and analog control-voltage processing. As the primary frequency source, the quartz oscillator has DC power applied at all times. It uses +15 V for oscillator, ±15 V for the D/A converter and operational amplifiers, and 5 V for the logic control. The rubidium unit can be turned on at any time. Separate regulators are used for these voltages, except the logic supply, to provide redundancy. The command

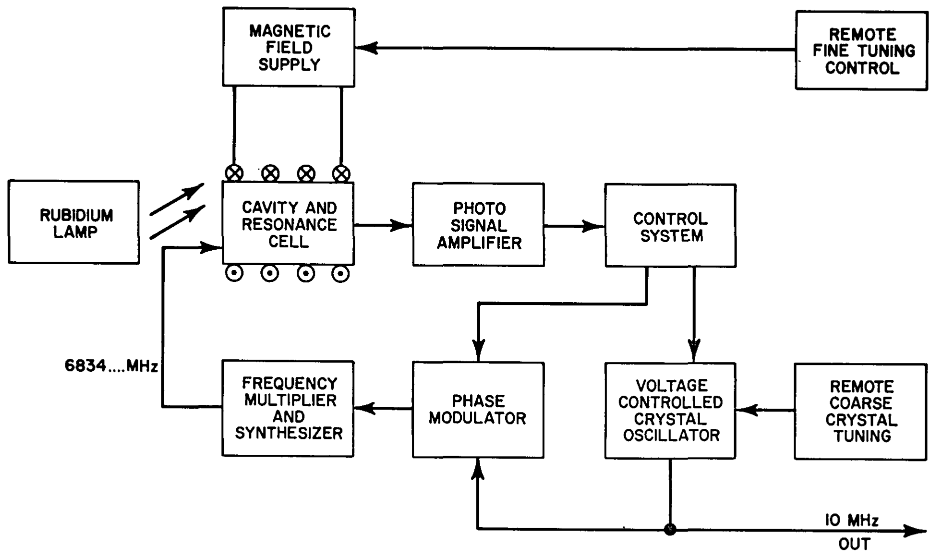


Fig. 11 — Rubidium unit

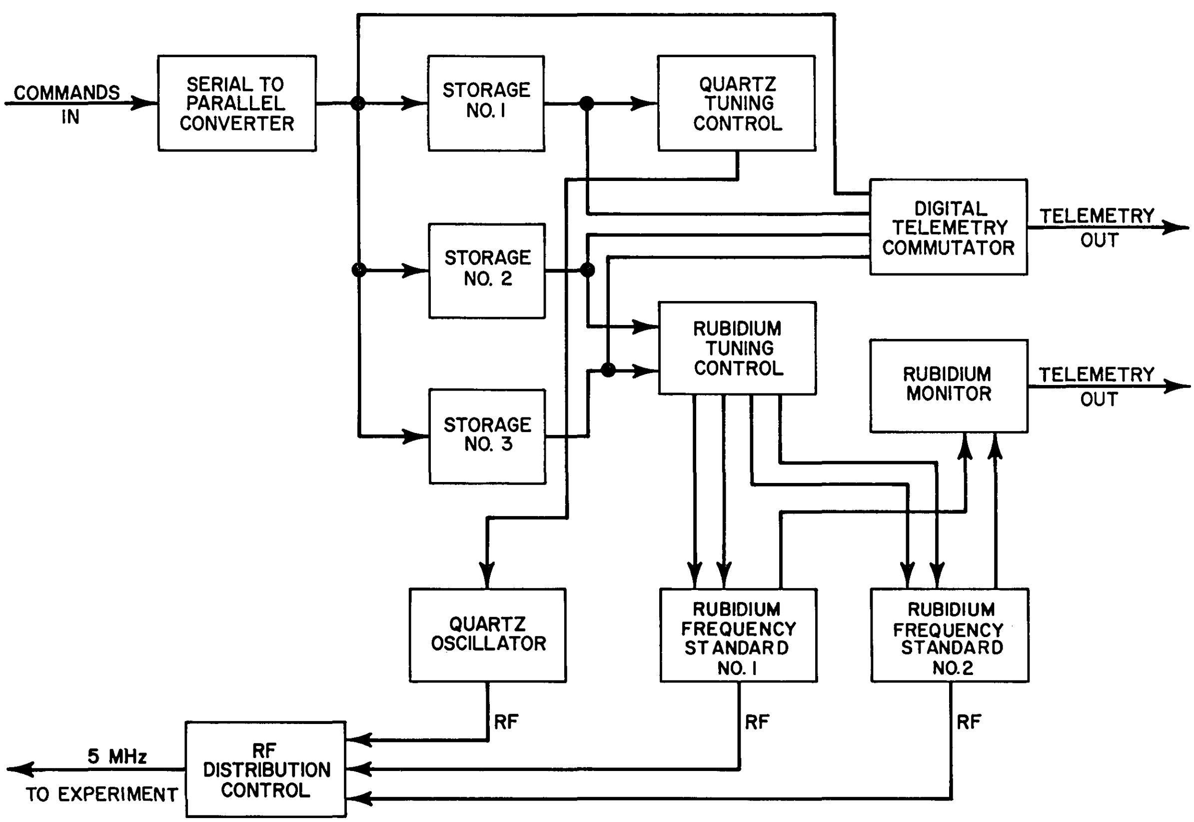


Fig. 12 — Digital frequency control

system and associated log circuitry are not redundant. The frequency standard system will continue to run in the event of a command system failure, but there will probably be a frequency shift. The digital frequency control has four switches to control these voltages. The satellite command system switches power to the rubidium units. In addition, there is a precision 10-V regulator in the control to supply the reference voltage for the D/A converters.

Tuning the digital frequency control is accomplished by sending a 14-bit serial word. The command word consists of 14 bits, of which the first 12 comprise the data word and the last two the address. The format below shows that bit 1 is the most significant bit, which is sent first; the least significant bit is bit 12, and the bit to be sent last is the second bit of address, bit 14. The address bits and their functions are also shown.

Bit number	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Binary word	←											→		
Address													←	→
MSB	X													
LSB												X		
First bit sent	X													
Last bit sent														X

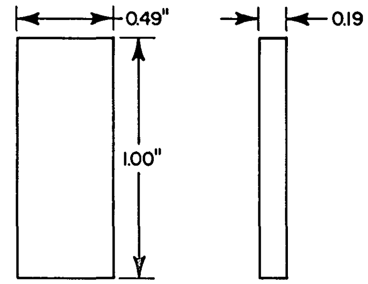
Addresses

Bit 13	Bit 14	Function
0	1	FE quartz
1	0	Rb C-field
1	1	Rb crystal
0	0	Not used

The OSR Execute signal enables the simultaneous reading of the address bits and parallel transfer of the 12-bit data word into one of three registers, as determined by the address.

This word can then be loaded into one of three registers as determined by two of the bits. A 12-bit storage register tunes the quartz crystal oscillator, a 10-bit storage register controls the fine tuning of the rubidium frequency standard (C-field adjust), and an 8-bit storage register keeps the rubidium crystal oscillator within the locking limits of the control circuitry. The loading of the 14-bit word can be verified by digital telemetry before it is transferred to the appropriate storage register. There are also several provisions made to keep spurious signals from entering the digital frequency control by disabling the input circuitry when it is not needed.

The D/A converter used for all three tuning commands is a 12-bit, thin-film, hybrid, low-power module. Its specifications are shown in Fig. 13. The pins have the same spacing as a dual, in-line, integrated circuit package. The connector uses the external voltage reference mentioned earlier. Tests of this voltage regulator showed a voltage change of about 0.7 mV with temperature changes from 10° to 40°C. This circuit was designed to be insensitive to supply voltage changes. In the satellite, the regulator is temperature stabilized to within 0.2°C and supply voltage regulation within 0.2 V will be



12 BIT DIGITAL TO ANALOG CONVERTER

POWER CONSUMPTION:	570 mW
LINEARITY:	± 1/2 LSB
TEMPERATURE RANGE:	-25°C TO +85°C
CONSTRUCTION:	HERMETICALLY SEALED DIP PACKAGE
INPUT:	TTL COMPATIBLE
OUTPUT:	0 TO -2 mA

Fig. 13 — Digital-to-analog converter specification

available. The 12-bit D/A converter is also temperature stabilized to provide the necessary voltage stability to the quartz oscillator varactor control. An operational amplifier circuit is used to convert the 0 to -2 mA D/A converter output to the 1- to 6-V output required by the oscillator. The output voltage of this D/A converter is expected to be stable to within 1 mV. The requirements for the D/A converters to be used for controlling the rubidium units are not so stringent, and therefore these units are not temperature stabilized. They do, however, use the same precision voltage reference. The output voltage range of the 8-bit rubidium crystal D/A converter is 0 to 5 V, and the 10-bit, rubidium C-field D/A converter output is 7 to 8.5 mA for rubidium frequency standard 2 and 10 to 11.5 mA for frequency standard rubidium 1.

Provision has also been made to exercise the rubidium units independently of the command system on the ground. In addition, several monitoring points have been brought out to the satellite skin to allow performance monitoring during system checks. Figure 14 is a block diagram of the system.

Figure 15 shows the prototype tuning and logic control box, which weighs 2.5 lb.

Telemetry

When the satellite is in orbit, there are three monitoring signals from the frequency standard system. The rubidium loop control voltage is monitored. This voltage can range from 0.5 to 18 V and is divided by 4. On the ground it will be read out as a 0 to 5 V signal once every 8 sec with a ±0.5% deviation. There is also to be an on-off indication of the status of the oscillator (OSR) tuning system. Digital telemetry will provide the status of the serial-to-parallel converter (load register) in the frequency standard system.

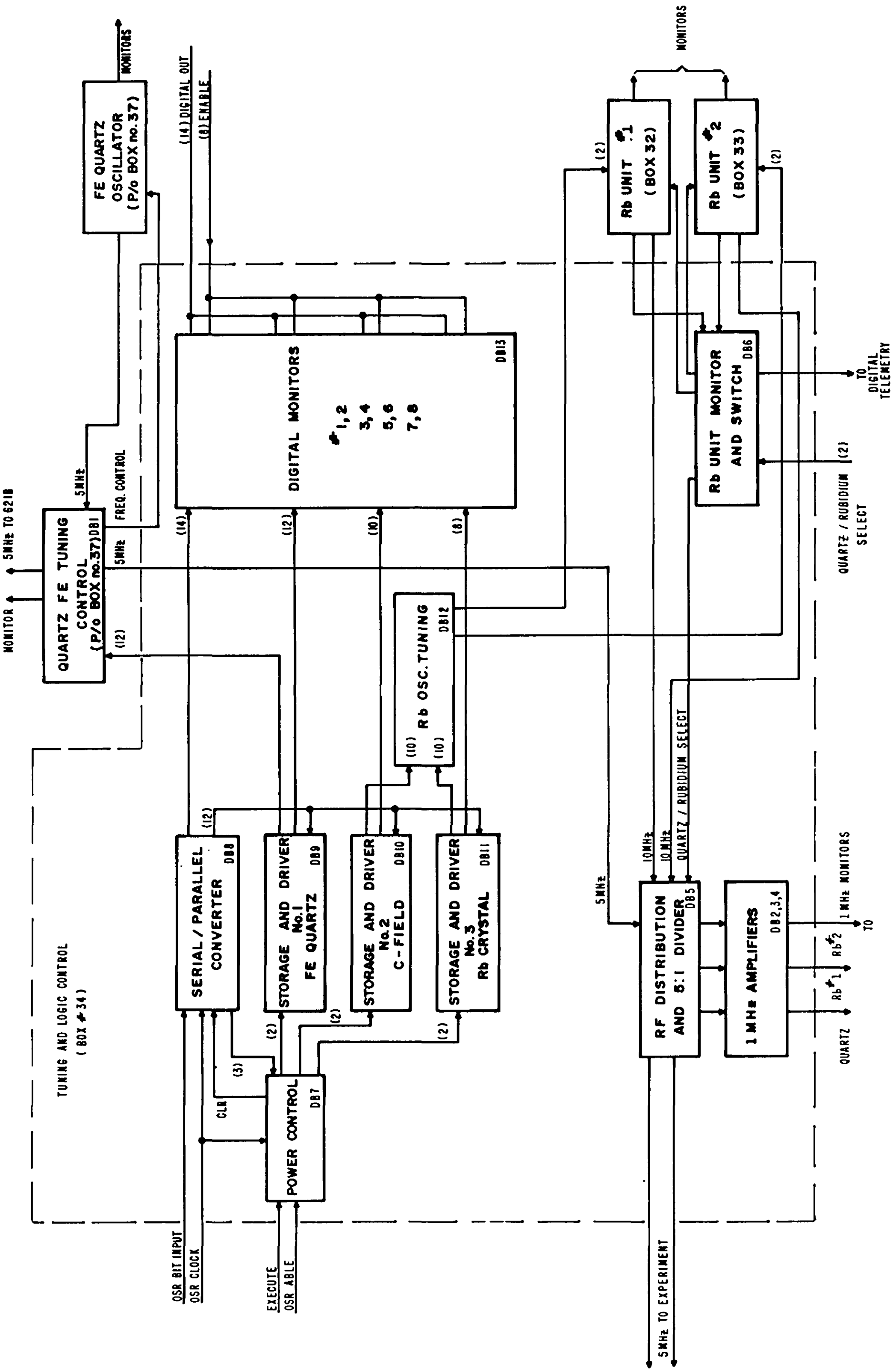


Fig. 14 — Tuning and logic control

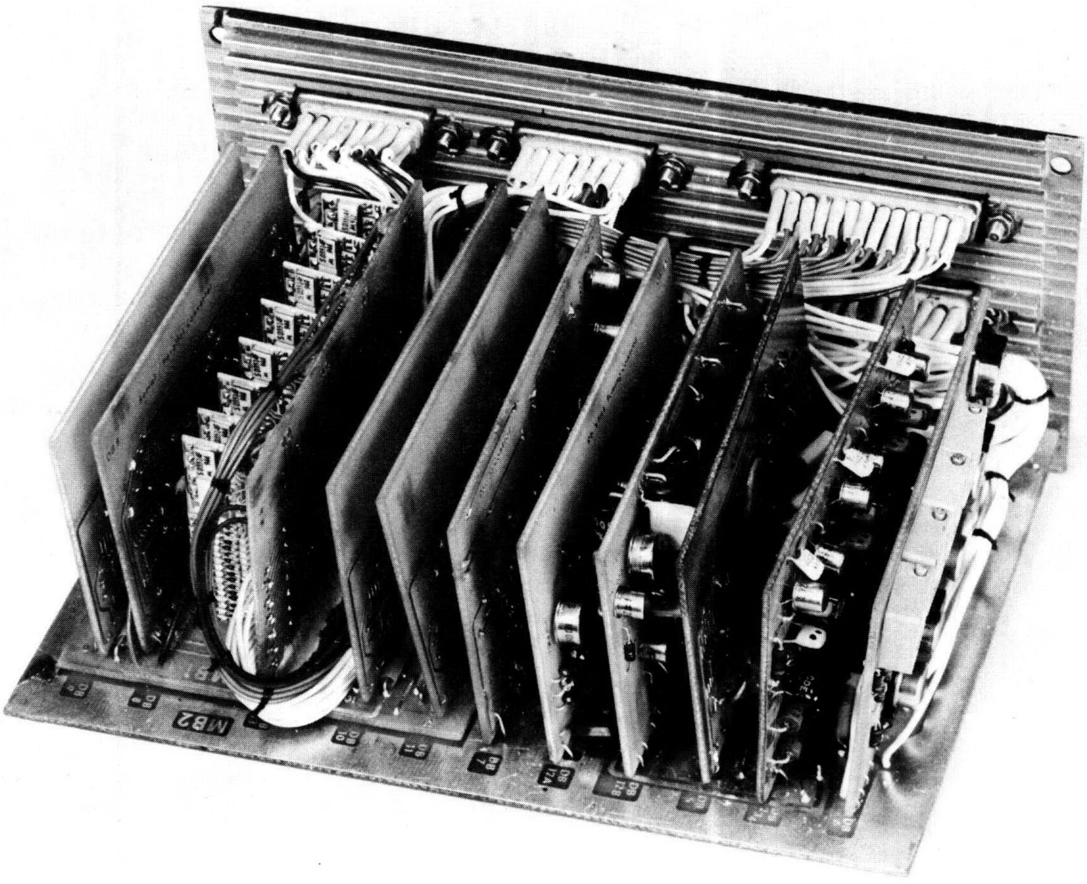


Fig. 15 — Tuning and logic control

COMMANDS

Eleven commands are provided for the frequency standard system; they can be separated into power commands and digital commands. The power commands turn the DC power to the rubidium standards on and off. The digital commands select the RF output to the experiment and control the tuning of the various units. An OSR enable signal must be sent and verified before a digital command can be sent. Four commands are used for tuning and two commands are used to control the RF. Table 3 gives a list of these commands with an explanation of each one.

Figure 16 is a set of curves showing the relation of the tuning control with the frequency for the quartz and rubidium frequency standards in NTS-1.

CONSTRUCTION

The frequency standard system is designed as a modular subassembly. All DC and control functions are on one connector on the tuning and control logic box. All boxes except the FE quartz oscillator (which is connected directly to the equipment deck for thermal control) are mounted on easily removable pallets. Figure 17 shows the boxes mounted on one of the pallets which includes the rubidium regulators, 5-V regulator and

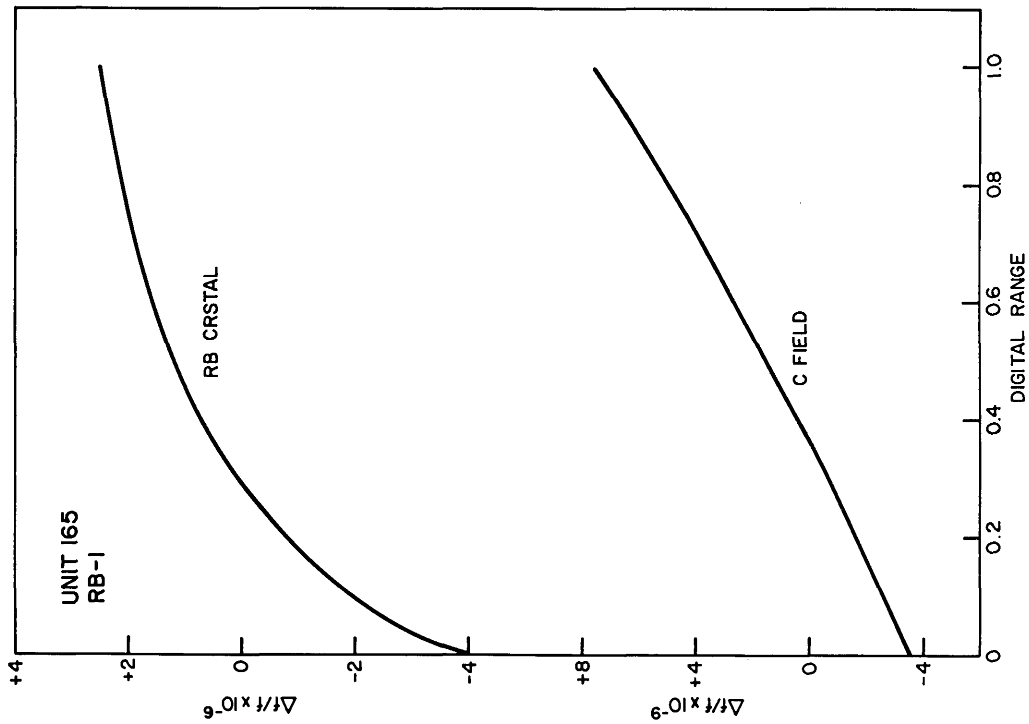
TABLE 3
NTS-1 Frequency Standard System Commands

Command	Number	Action	Special Conditions
Timation ON	81	Turns on interface	Necessary for Commands 109, 110, 111, 127, 143
OSR Enable	95	Allows 14 bits to be loaded	Also necessary to read digital monitor and for commands 109 and 110
OSR Bit Input/OSR Clock	127/143	14 bits, two levels "1" or "0" with delay increment pulse/(bit) 127 is "1", 143 is "0"	12-bit tuning word + 2-bit control. Rb tuning cannot be done unless "Rb ON" has been sent.
OSR Execute	111	Transfer function; register and disables tuning circuit	Also disables digital monitor information.
OSC FE Select	109	Allows RF from FE quartz to experiment	OSR enable must be sent first
OSC Rb Select	110	Allows RF from Rb to experiment	Only one Rb can be on. Automatically selects output from correct unit
Rb 1 Select	93	Allows DC power to Rb 1	This command should not be sent when Rb power is on.
Rb 2 Select	94	Allows DC power to Rb 2	This command should not be sent when Rb power is on.
Rb ON-OFF	91-92	Applies DC power to selected Rb	Also applies power to Rb tuning control

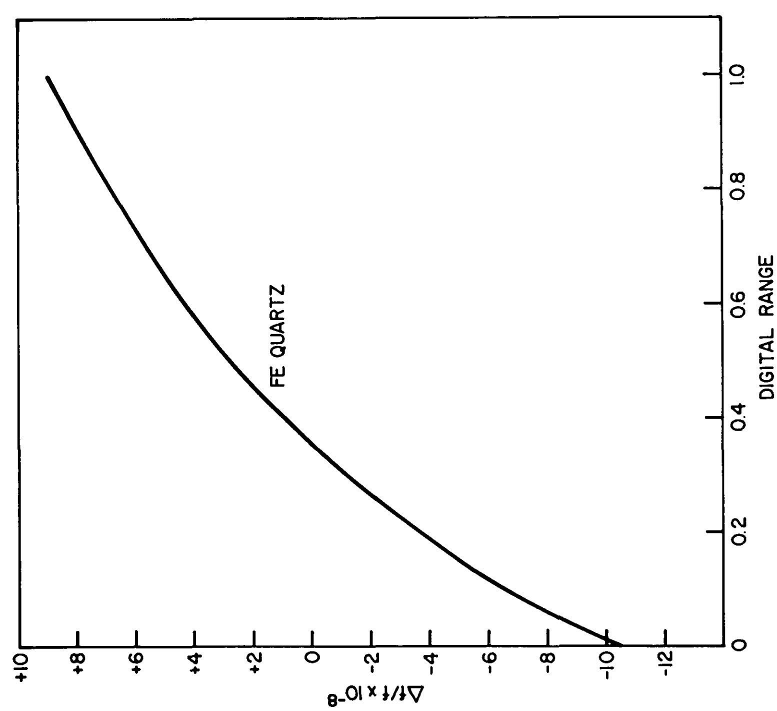
tuning, and control logic box. Figure 18 shows the rubidium frequency standards as they are mounted in the satellite with their lead shield. Figure 19 shows the volume and weight of the major components of the frequency standard system.

LABORATORY PERFORMANCE

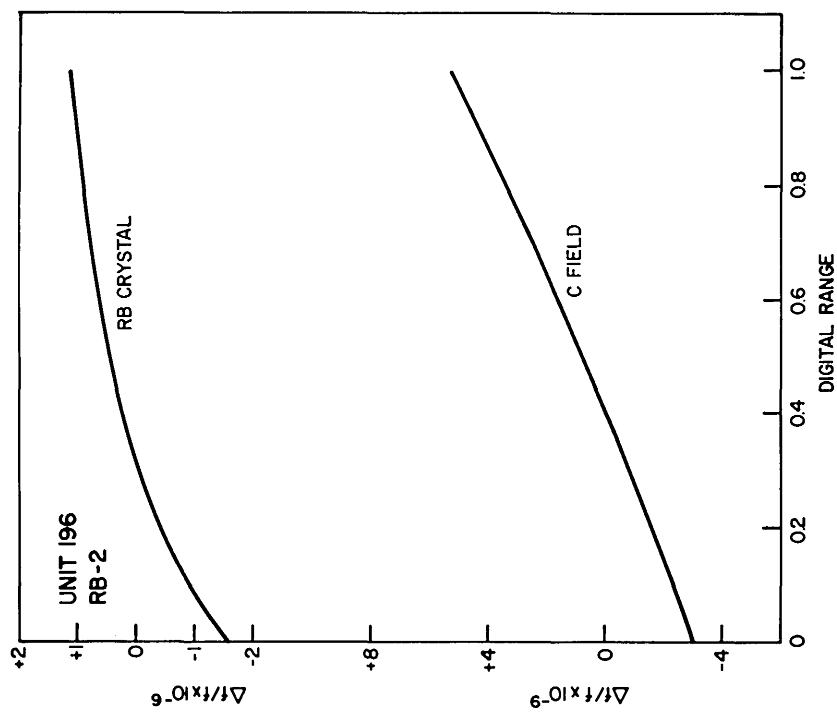
Before modifications were begun, all candidate frequency standards were extensively tested under controlled laboratory conditions as a means of predicting performance and as a preselection process to ensure that a unit with marginal performance would not be modified for flight use.



(b) Rb 1 (Unit 165)



(a) FE Quartz Oscillator



(c) Rb 2 (Unit 196)

Fig. 16 — Satellite tuning curves

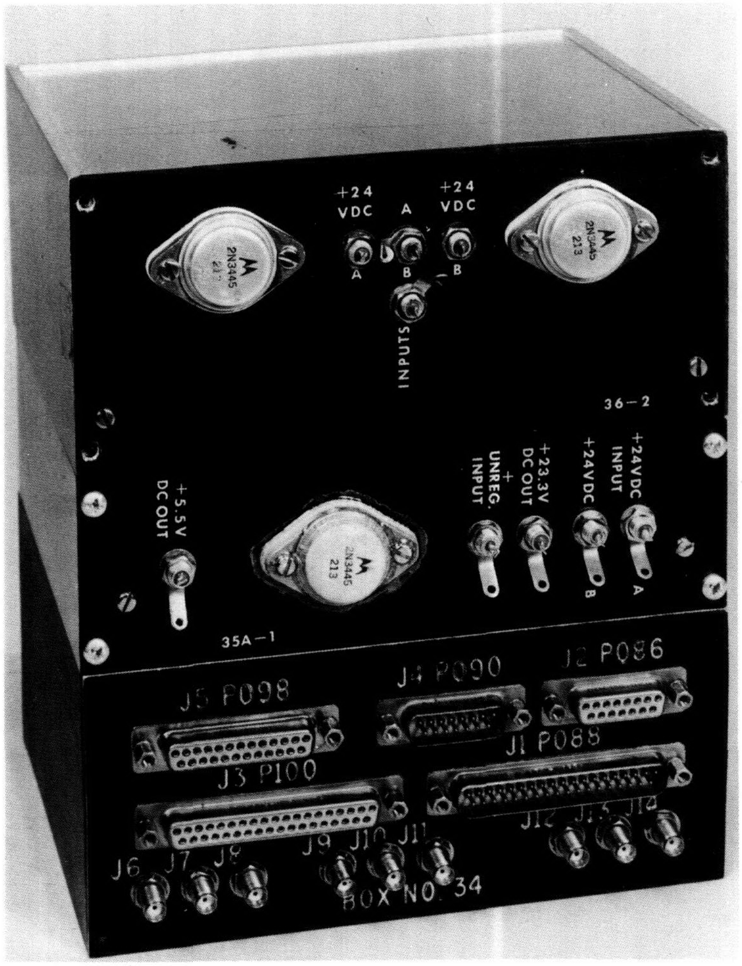


Fig. 17 — Frequency standard system boxes

For convenience of identification, the rubidium units tested are referred to by the last three digits of the serial number, as listed in Table 2. Two of the units, 124 and 129, were incorporated into FRT units, which include a power supply and frequency divider circuits. They were, however, tested independently of the FRT unit. Not all tests were conducted for each unit. In some cases this was because units were not available because of failure or concurrent testing, and in other cases it was felt that the additional data would provide no new information. Where possible, tests were run on two or more oscillators to check sample variation. Table 4 lists the test results of all units.

Short-Term Stability and Aging

Quartz Oscillator—A series of short-term stability and aging measurements was made under controlled laboratory conditions. The experimental configuration is shown in Fig. 20. The synthesizer is used to provide a reference frequency offset. The resulting mixer output was about 1 Hz. The counter was then used to measure the period of the 1-Hz output. This technique allows resolution of period differences of less than 1 μsec. The

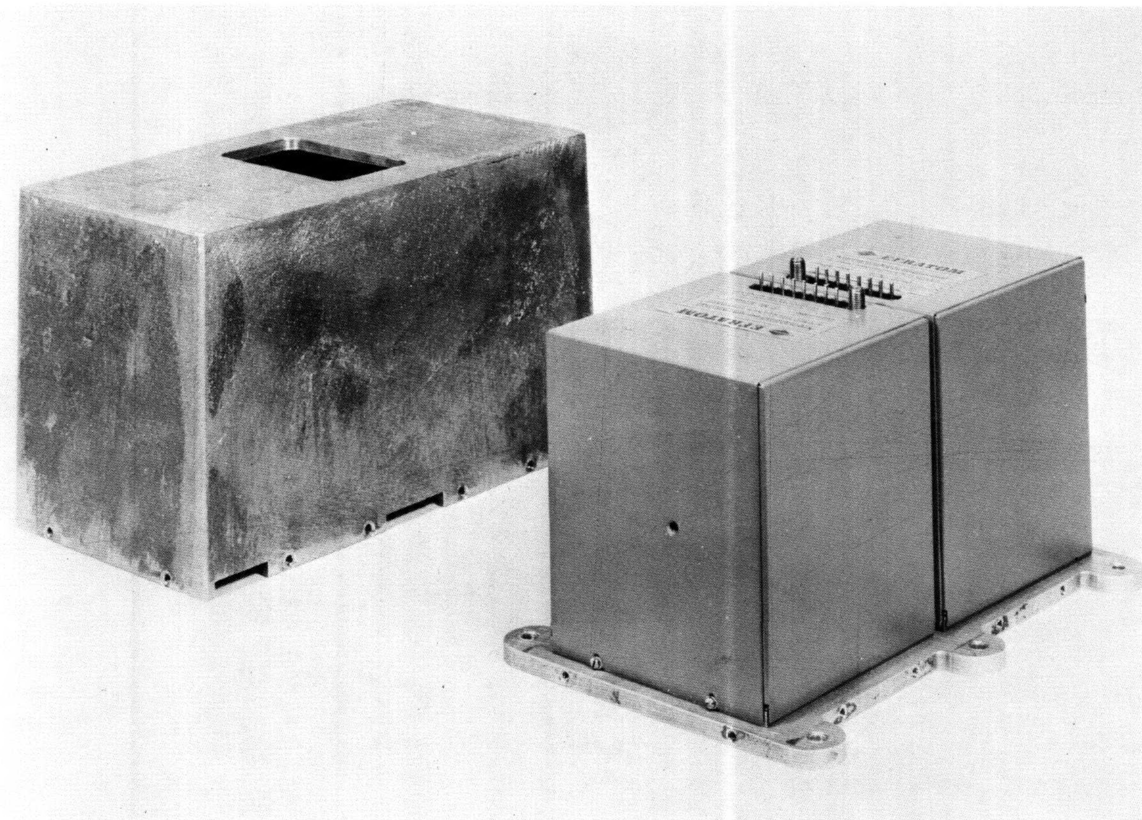


Fig. 18 — Rubidium units as positioned in the satellite

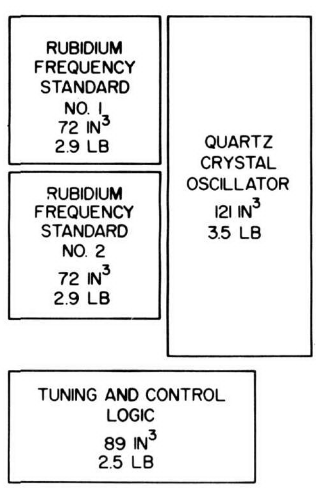


Fig. 19 — Sizes and weights of units in the frequency standard system

TABLE 4
Summary of Laboratory Aging and Temperature Tests

Rubidium Frequency Standard Ser. No.	Short-Term Stability				Aging		Temperature (X 10^{-10})				Total Range
	1 sec	100 sec	1000 sec	5000 sec	Date	Rate* (10^{-12})	10°C	20°C	30°C	40°C	
116	17.6	0.89	0.42	0.29	Dec. 1972	+1.7	-0.2	Ref	-0.2	-0.4	0.4
120	—†	—	—	—	Jan. 1973	-1.0	+0.7	Ref	+1.5	+3.7	3.7
124	19.3	1.28	0.50	0.37	Mar. 1974	-0.3	-0.2	Ref	+0.4	+0.5	0.5
129	—	1.47	0.59	0.58	Mar. 1973	-0.8	—	—	—	—	—
140	19.8	0.90	0.24	—	July 1973	-1.4	+0.2	Ref	+0.1	+0.3	0.3
163	21.2	0.70	0.64	—	Sept. 1973	+2.6	+1.0	Ref	+2.7	+7.2	+7.2
164	18.7	1.01	0.44	—	Sept. 1973	-0.3	-1.6	Ref	+1.2	0	+2.8
165	33.3	0.96	0.37	—	Sept. 1973	-0.8	-2.3	Ref	-1.8	+0.2	+2.5
189	15.2	0.55	0.24	—	Oct. 1973	+2.2	-3.4	Ref	+3.0	+4.4	+7.8
196	21.1	1.20	0.25	—	Sept. 1973	-0.6	+3.6	Ref	-1.7	—	+6.6
198	11.7	0.67	0.41	—	Oct. 1973	-2.7	-7.2	Ref	0	+4.4	+11.6
Quartz Oscillators FE Ser. No.											
101	8.17	2.72	2.95	3.77	July 1973	+13.0	-0.6	Ref	+1.5	+0.8	2.1
102	6.35	1.38	1.76	3.32	Feb. 1973	+17	-0.2	Ref	0	+0.5	0.7
103	5.14	1.13	1.14	3.21	Aug. 1973	- 3.6	-1.2	Ref	+0.4	+0.5	1.7
104	9.00	1.33	1.46	3.84	May 1973	-20	-2.0	Ref	+1.6	+3.2	5.2
105	4.8	2.13	—	—	Apr. 1974	-13.0	—	—	—	—	—

*Best number for each unit.
†Dashes indicate no data taken.

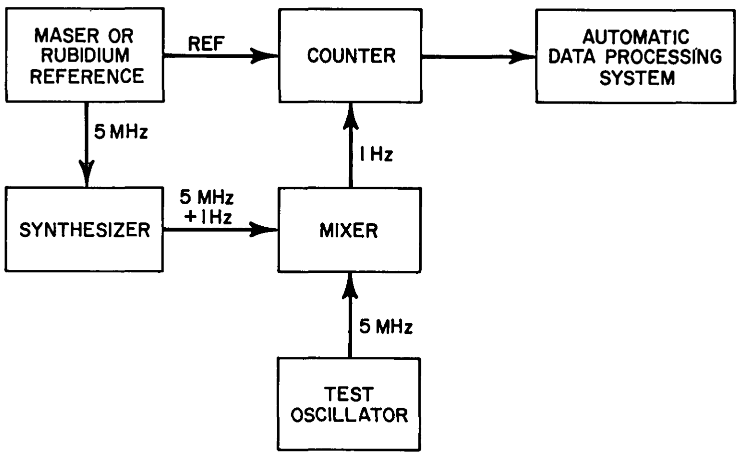


Fig. 20 — Short-term stability test

counter's digital output is coupled to an automatic data processing system. The fractional frequency fluctuation was computed using the Allan variance formula [12,13]

$$< \sigma \left(\frac{\Delta f}{f}\right), 2, \tau > = \frac{1}{f_0} \left[\frac{1}{2N} \sum_{i=1}^{N} (f_{2i} - f_{2i-1})^2 \right]^{1/2}$$

where N is the number of data pairs. Short-term stability tests were run several times on each oscillator for averages from 1 to 10,000 sec. Typical results are shown in Fig. 21. All of the oscillators have been run as nearly continuously as possible since their delivery.

Each oscillator's frequency is compared with a cesium-beam frequency standard and readjusted when the difference is greater than 5 to 10 pp 10^{10}. One of the best oscillators, Ser. No. 103, had a high positive aging rate when delivered and now has an aging rate of less than 5 pp 10^{12} per day. Figure 22 shows the changes in aging rates of the two best oscillators. The variation in aging rates of the fourth oscillator was erratic and therefore was not included.

Rubidium Standards—An extensive series of short-term stability measurements was made on the Efratom units before they were modified for space flight using the same experimental configuration used for the quartz oscillator program. The frequency stability of more than 10 rubidium frequency standards has been measured. Typical performance features are as follows: For short term stability, sigma varies from 2×10^{-11} at 1 sec to 1×10^{-12} at 100 sec, and from 200 to 10,000 sec, sigma is 5 to 7×10^{-13}.

Similar measurements were made on the unit's crystal oscillator with the atomic control loop open. Figure 23 shows the short-term stability results with the loop open and closed.

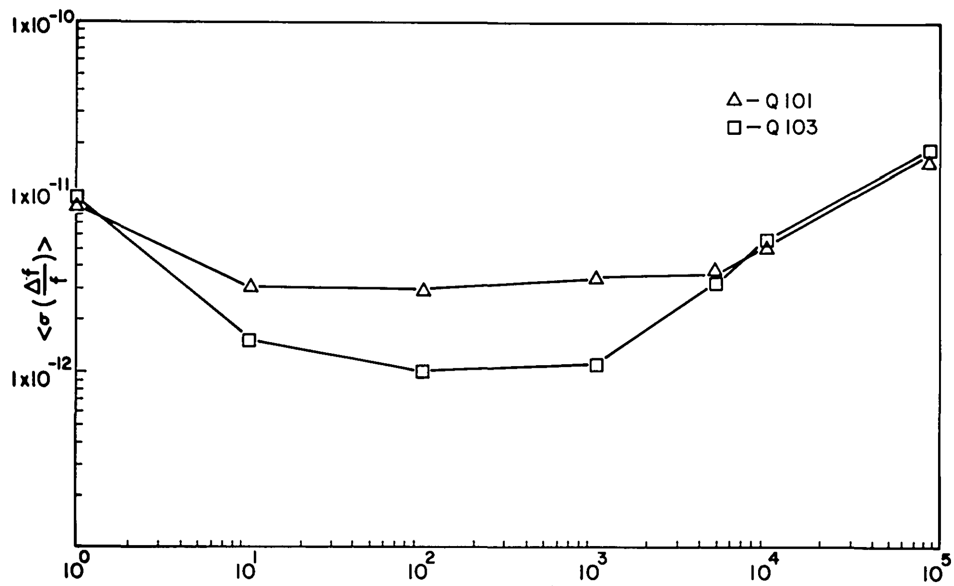


Fig. 21 — FE quartz short-term stability

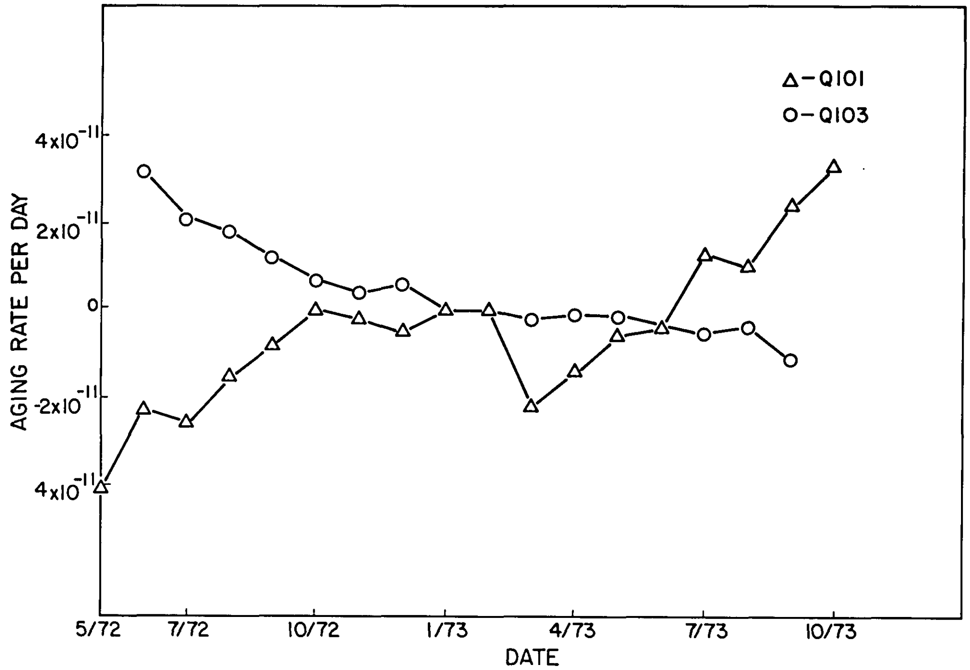


Fig. 22 — FE quartz aging rate

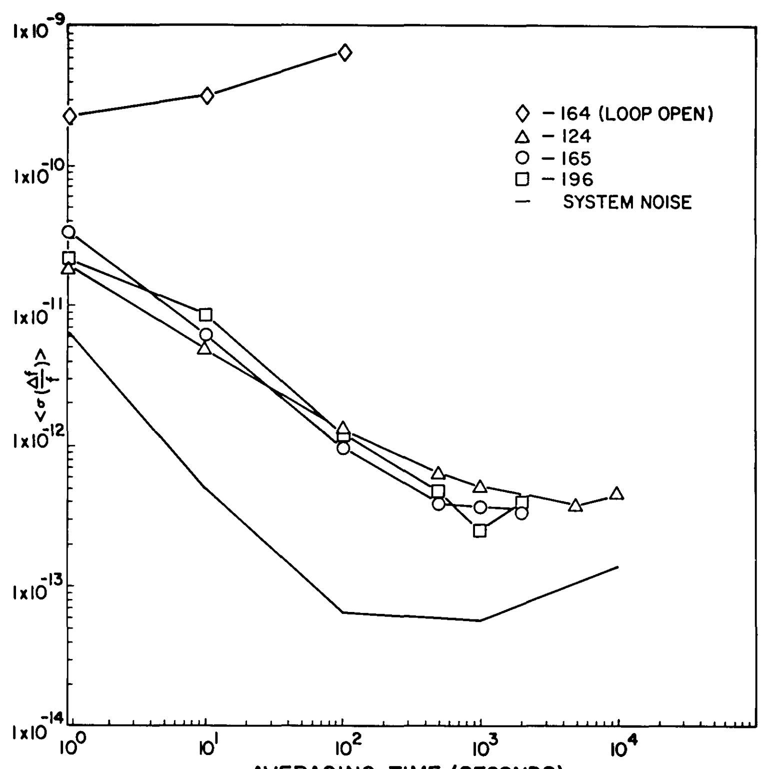


Fig. 23 — Rubidium short-term stability

Since NTS-1 has an orbital period of 8 hr and one pass lasts approximately 2.5 hr, short-term stability for averaging times of 10^4 to 10^5 sec was of interest. Figure 24 shows the long-term performance of three Efratom units and the Hewlett-Packard rubidium, type 5065. Unit 140 was measured by the Naval Observatory [14]; all other measurements were made at NRL.

One hundred independent data pairs were used for each calculation. Figure 25 shows a running calculation of the variance for unit 124 when averaged for 10,000 sec. In our data collection it has been observed that oscillators with smooth aging curves such as this tend to show less fluctuation in the short-term measurements.

Aging data were recorded for each of the rubidium units. Figure 26 shows the aging of several oscillators over typical selected periods. The fluctuations shown by unit 129 were found to have a correlation with laboratory temperature and also with unit 120. In view of the measured temperature effects on units 120 and 124, these results are to be expected. It is also interesting to note that the aging rate of unit 124 changed. When the unit was delivered in January 1973, the aging rate was -3.7×10^{-12} per day. After five months, aging was less than -1×10^{-13} per day, and after one year, aging had settled to approximately -3×10^{-13} per day. Figure 27 shows this aging rate. Unit 124 ran nearly continuously after it was received and was completely unmodified.

In addition to frequency aging, lamp aging is of concern in rubidium frequency standards. A measure of the darkening of the glass is the DC voltaic output of the photocell detector. In unit 124, this voltage is decreasing at an approximate rate of -0.39 V/yr. If this rate remains constant, lamp darkening would not cause failure for 5 to 7 years.

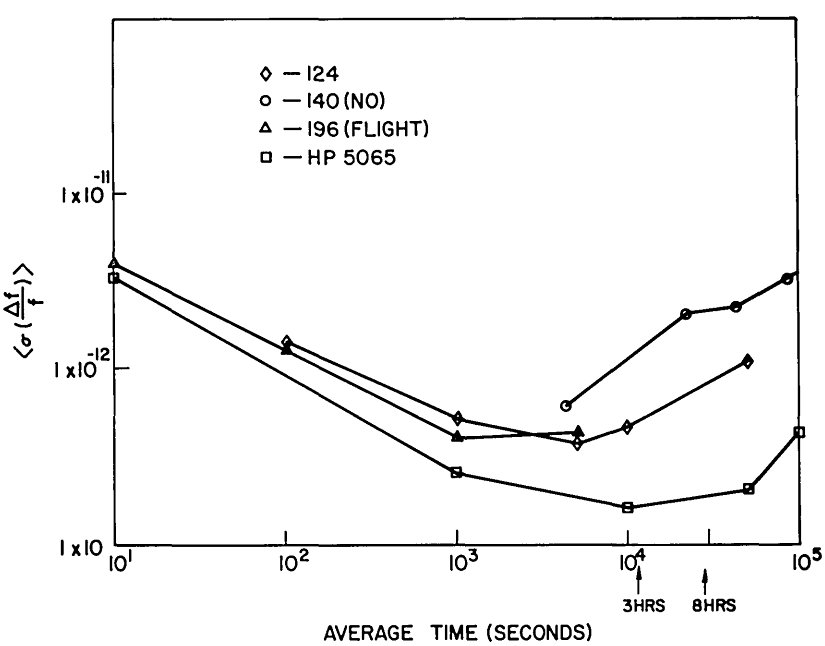


Fig. 24 — Rubidium short-term stability to 10^5 sec

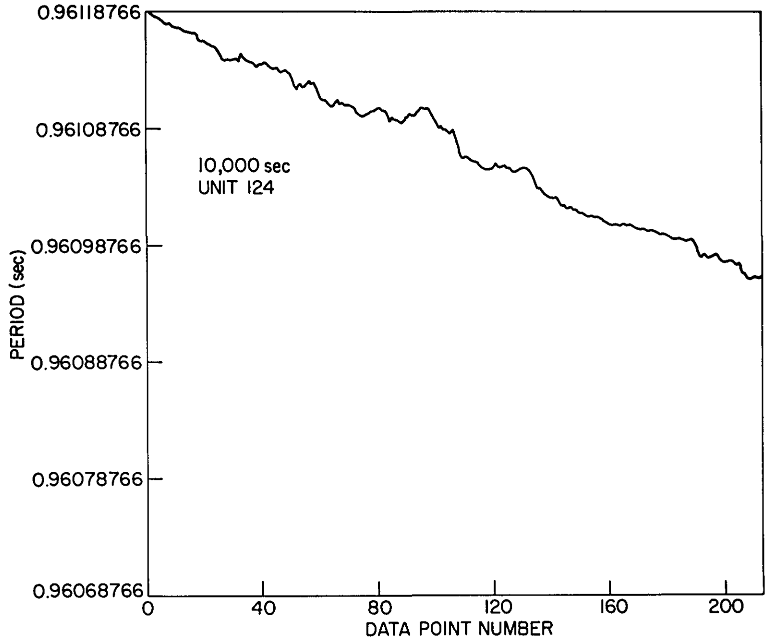


Fig. 25 — Rubidium 10,000-sec period average

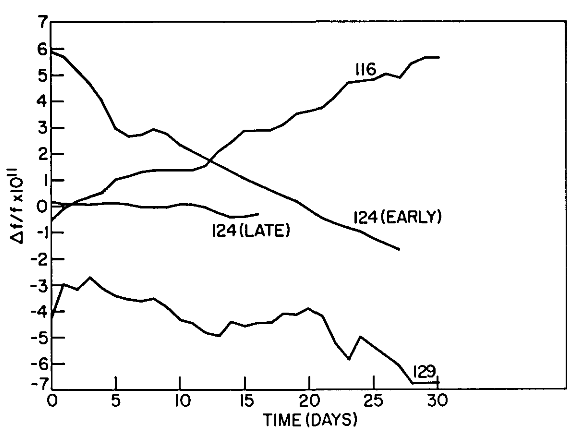


Fig. 26 — Rubidium aging

Output Spectrum

Quartz Oscillator—The 5-MHz output was 2.5 V p-p into 50 ohms with the second harmonic at -43 dBm and all other harmonics -50 dBm or lower. There is a crystal filter in the output amplifier to reduce noise when the frequency is multiplied to L band. Figure 28 shows a typical spectrum.

Rubidium Standards—The 10-MHz output was measured on the spectrum analyzer. The 20-MHz harmonic is 23 dB below the fundamental, and all others are at least 35 dB below the fundamental. The slightly stronger 60-MHz signal is from the 60-MHz output

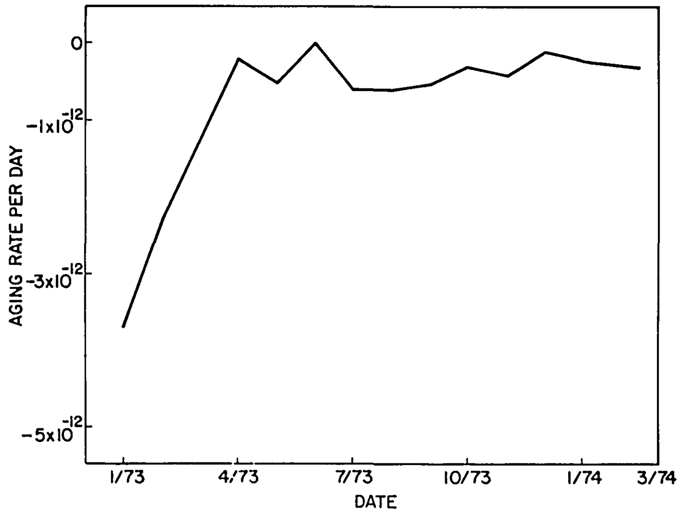


Fig. 27 — Rubidium aging rate

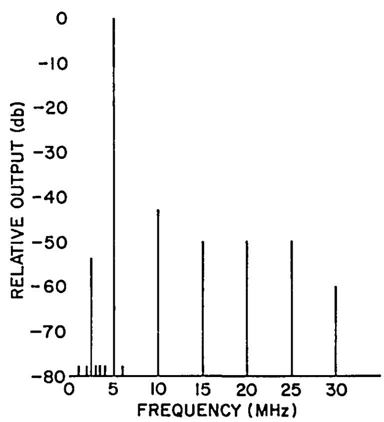


Fig. 28 — FE quartz output spectrum

of the synthesizer. There is, however, no evidence that the other synthesizer-generated frequencies appear in the output. Figure 29 illustrates the spectrum.

Rubidium Microwave Cell Measurements

Inside the cavity is a step-recovery diode which is driven by a 60-MHz signal and a 5.3125-MHz signal. These two signals produce the three large signals seen in the display of Fig. 30, which shows microwave spectrum present inside the cavity. The center signal is at 6840 MHz, the 114th harmonic of 60.00 MHz. The other two are the 5.3125-Hz sidebands. The lower frequency signal is therefore at 6834.68 MHz, which is the rubidium resonance frequency. Monitoring this spectrum gives a good indication of the performance of the frequency control loop.

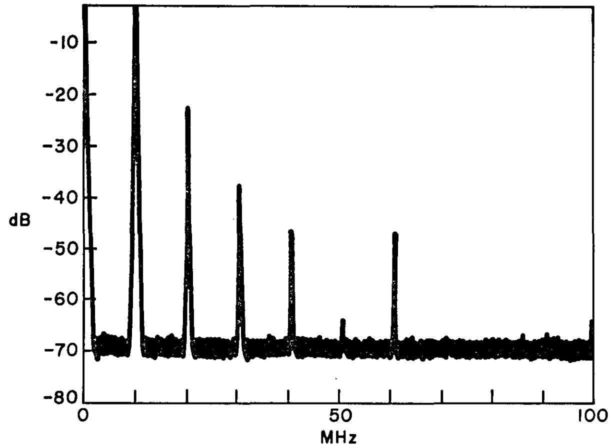


Fig. 29 — Rubidium output spectrum

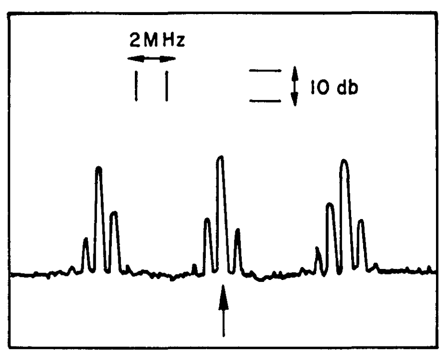


Fig. 30 — Rubidium microwave spectrum

Power Consumed

The DC power consumed by the quartz oscillator was 125 mW at 12.5 V. The major power-consuming circuits are the outer oven and the power amplifier. The oscillator is designed to operate with an input voltage of 11.5 to 14.0 V. The power consumption in a vacuum is about the same as at ambient pressure. The main power change with temperature occurs in the outer oven, which has a coefficient of -0.4 mW/°C. Several tests were run to measure the DC power of the rubidium standard and its variation as a function of voltage, temperature, and vacuum. Figure 31 summarizes these tests.

Direct current power consumption of the rubidium unit is influenced by voltage, backplate temperature, and pressure. In a normal laboratory environment, the frequency standard operated at 24 V with a backplate temperature of 36°C. The unit used 13.8 W in this condition. In a vacuum, the power consumed typically was 10.5 to 11.3 W. As the temperature was raised, the power decreased. Temperature sensitivity was -130 mW/°C at ambient pressure and -20 to -50 mW/°C in vacuum. Power consumed was directly proportional to the voltage. The manufacturer specified an operating range of 22

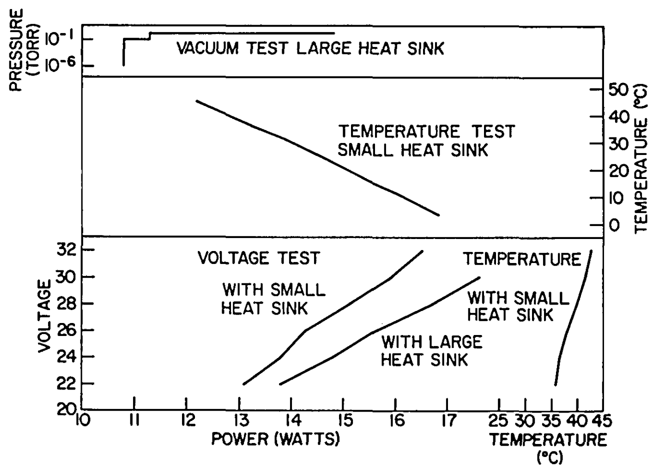


Fig. 31 — Rubidium DC power

to 32 V. When a large heat sink is used, the increase in power is linear, with a value of approximately 0.5 W/V whether in vacuum or at ambient pressure.

The bottom of Fig. 31 shows the effect of varying the voltage. As the voltage is raised, the power is raised and so is the temperature of the base plate. This temperature rise induces a frequency shift. This effect was investigated further by attaching the oscillator to an aluminum block, 1 by 11 by 12 in., which weighed 13 lb. The voltage test was repeated, and, as can be seen in Fig. 31, the frequency standard consumed more power and the effect of voltage change on power was slightly smaller. However, during this test the temperature and therefore also the frequency remained constant.

The temperature of the frequency standard was varied while the input voltage was held constant at 23 V. The results are shown in the middle of Fig. 31. As the temperature increased, the power consumed decreased.

A plot of power consumed during the vacuum test is also shown in Fig. 31. The frequency standard was connected to a large (1 by 11 by 12 in.) heat sink. The power consumption dropped 27% in a hard vacuum. The power sensitivity to temperature decreased in vacuum to 39.2 mW/°C as compared with 132 mW/°C at ambient pressure. Of the 650 mA consumed by the frequency standard at room temperature, 350 mA was used for the electronic circuitry and the rest for the three ovens. In a hard vacuum the oven current was less than half the value at ambient pressure.

The lower input voltage limit was determined by lowering the input voltage while monitoring the regulated output voltage, loop lock indicator, and frequency. With an input voltage of 21.2 V, the regulator voltage changed and a frequency shift occurred. At 18.5 V the control loop unlocked.

ENVIRONMENTAL TESTING

To qualify the frequency standards for use in the NTS-1 system required a series of environmental stability tests. In each test the frequency standard was exposed to a particular environmental condition while its operating parameters were continuously monitored.

Acceleration

Acceleration tests were conducted only for the rubidium standards, the purpose of the acceleration experiment [15] was to determine at what gravity loading level below 5 g the standard would lose lock in the servo loop control. An NRL centrifuge was used to develop the acceleration levels at 17 ft from the axis. After initial examination of the oscillator showed that 5 g along any one of three mutually perpendicular axes would not cause loss of lock, it was decided to examine 10-g loading along one axis.

The average accumulation of time ΔT during the phase comparison interval, divided by the duration of the comparison interval T for the combined runs at 1, 5, and 10-g is plotted in Fig. 32 to indicate the frequency offset ($\Delta f/f$). There is a linear shift of frequency in the order of -4×10^{-12} per g over the interval between 1 and 10 g. The shift between 0 and 1 g is between -4 and -8×10^{-12} per g. In this range the effect of the earth's gravity tends to mask the centrifuge effects.

Vibration

Vibration testing was conducted at the NRL vibration test facility. To qualify for NTS-1, a component is required to withstand the vibration level shown in Fig. 33 for a 2-min period in each of three mutually perpendicular axes. The curve shown is the actual vibration to which the device was subjected.

For this test the optional heat sink was removed from the rubidium standard so it could be mounted on the test stand. Seven units were tested to determine their ability to survive a launch on NTS-1. One prototype unit was tested with the unit running. Figure 34 shows the effects on frequency caused by the vibration. This test was run at a level of 9g, rms. Note that in only one plane did the unit lose lock. Four units that had

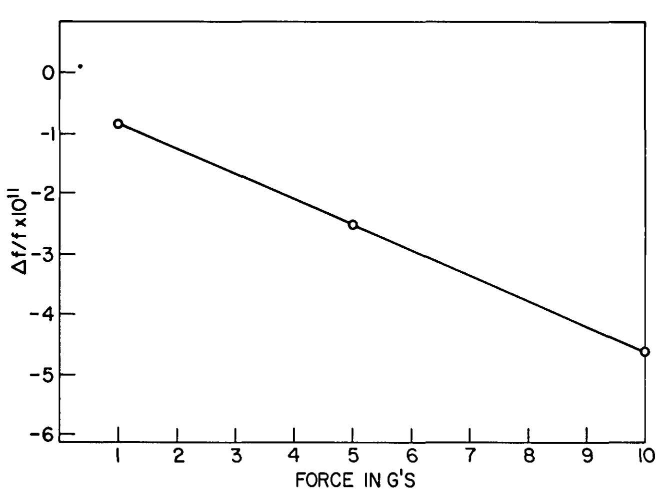


Fig. 32 — Rubidium acceleration test

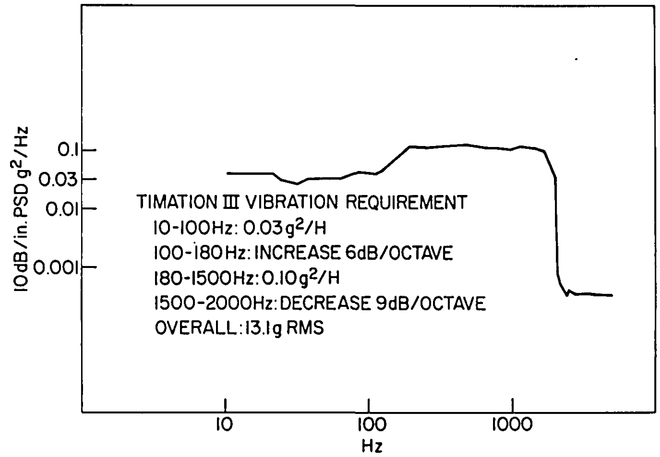


Fig. 33 — TIMATION III vibration specification

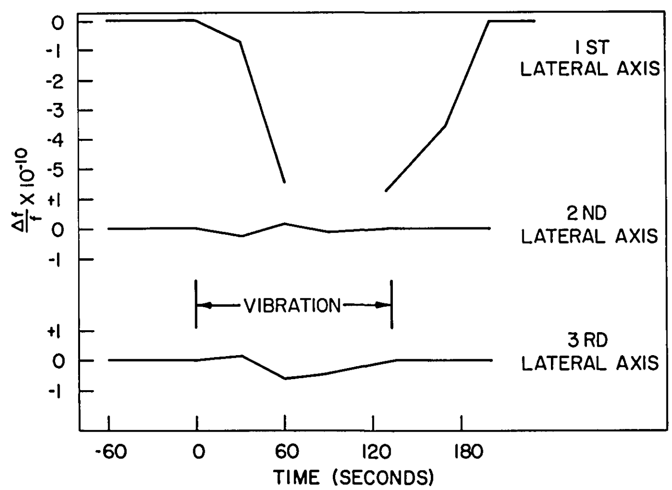


Fig. 34 — Rubidium vibration test, 9 g rms

been specially modified for flight use were tested. The three nonflight units tested and their failures are described by Table 5.

Several modifications were designed and implemented to ruggedize the units as a result of this test series. Undesirable features of the unit for a high vibration environment are the mounting of printed circuit boards only at the corners, use of commercial potentiometers, use of trimmer capacitors, and inadequate support of certain components on the printed circuit board. In addition, it was learned that the resonance cell of unit 120 was held in place with foam strips which allowed sufficient movement during vibration to break the glass. It is believed that, in other units, the resonance cell is held in place with potting compound.

Corrective action taken to ruggedize the units was as follows: Several bakelite blocks were glued on each mounting plate to provide additional stiffening, all four potentiometers were replaced with fixed resistors, two of the three trimming capacitors were

TABLE 5
Vibration Failures of the Rubidium Standards

Serial No.	Date Tested	Type of Failure
Before Modification		
116	Jan. 30, 1973	Synthesizer trimming capacitor
		Synthesizer potentiometer
136	Apr. 17, 1973	Synthesizer transistor lead
120	Aug. 15, 1973	Resonance cell
After Modification		
165	Nov. 7, 1973	Crystal oscillator
189	Nov. 8, 1973	None
196	Nov. 8, 1973	None
198	Nov. 7, 1973	Crystal oscillator
		Transistor in lamp oscillator

replaced with fixed capacitors, and components were potted selectively. Figure 35 shows the printed circuit boards with additional blocks glued on.

A second set of vibration tests was performed on four modified units; the results are as shown in Table 5.

A study was made of the failure of the crystal oscillators. The manufacturer used three different vendors for crystals. A microscopic analysis of the two units that failed shows two problems: the crystal had shifted in its mounting clips, and one lead had broken.

After the purchase of our units the manufacturer obtained crystals from a fourth manufacturer, the Colorado Crystal Company. These crystals have also passed our vibration tests. The flight rubidium units have a Colorado and a Phillips crystal, both of which use heavier leads than the other manufacturers.

The most serious environmental problem encountered with quartz oscillators has been mechanical vibration. In the course of flight qualification testing, severe breakage problems were encountered with the glass dewar surrounding the crystal oscillator assembly. The prototype unit (SN 6589) passed three-axis random vibration testing at the standard qualification level without potting the oscillator in the dewar. Subsequent tests of flight units 101 and 103 produced dewar failures. Apparently a small amount of lead shielding placed around the crystal in the flight units created a situation where the mass of the electronics inside the dewar could vibrate with sufficient energy to break the glass. The use of a heavier dewar and potting the oscillator assembly in the dewar cured the problem.

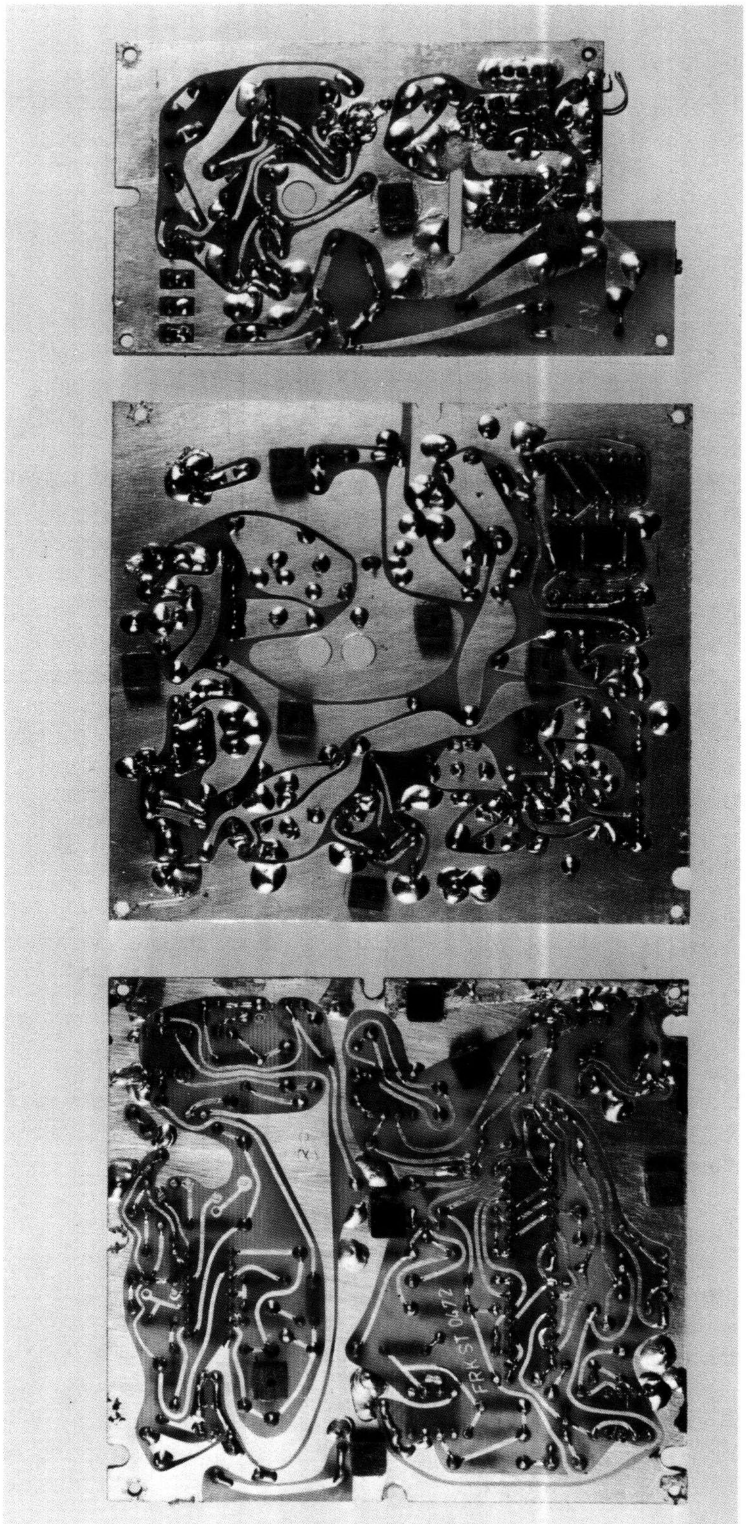


Fig. 35 — Printed-circuit boards with blocks, for rubidium unit

Temperature

The rubidium frequency standard is designed to dissipate heat through its base plate. Major heat-producing electronic components and the mechanical structure are attached to the base plate. The unit is either supplied with an optional heat sink or it can be attached to a large metal surface. In a normal room-temperature environment (25°C) the base plate, with the optional heat sink, will be at about 35° to 40°C.

On several rubidium units, the frequency stability vs temperature was measured on several units. For these tests, each unit was placed inside a temperature chamber with the optional heat sink and a thermistor probe to monitor the backplate temperature. The temperature range of interest for spacecraft applications was from 5°C to 40°C. The chamber temperature was set at approximately 40°C for at least 24 hr and was then stepped down in 10° increments to 5°C, being held at each intermediate temperature for 8 to 20 hr. At the end of the test, the temperature was returned to the starting temperature for at least 24 hr to allow for compensation of aging effects. For two units tested, one had a very small frequency shift vs temperature, with a frequency shift of less than 1×10^{-10} over a 35°C temperature change, whereas the other oscillator had a parabolic temperature response, with a minimum around 20°C and maximum of approximately 5×10^{-10} at the high and low temperature. Figure 36 is a plot of the temperature data points for these two standards, as well as unit 164, which was manufactured about 8 months later than 120 and 124. It is also to be noted that the temperature curve of unit 120 was not smooth. If these units were placed in a laboratory room where the temperature fluctuated ±5°C, the frequency of unit 124 would vary by approximately 2×10^{-12} while unit 120 would vary by approximately 1.4×10^{-10}. These differences are clearly seen in the smoothness of the aging data presented earlier in this report.

In the same manner, three Frequency Electronics quartz oscillators were tested over a range of 10° to 40°C, Figure 37 shows the results of these tests. The TIMATION I oscillator had a temperature coefficient of about 2 pp 10^{11}/°C and the TIMATION II oscillator with a triple oven, had a temperature coefficient of 1 to 2 pp 10^{12}/°C. A typical NTS-1 type oscillator, Ser. No. 103, has a temperature coefficient of 1 to 5 pp 10^{12}/°C. As in TIMATION II there will be a thermoelectric control (TED) 7A to keep

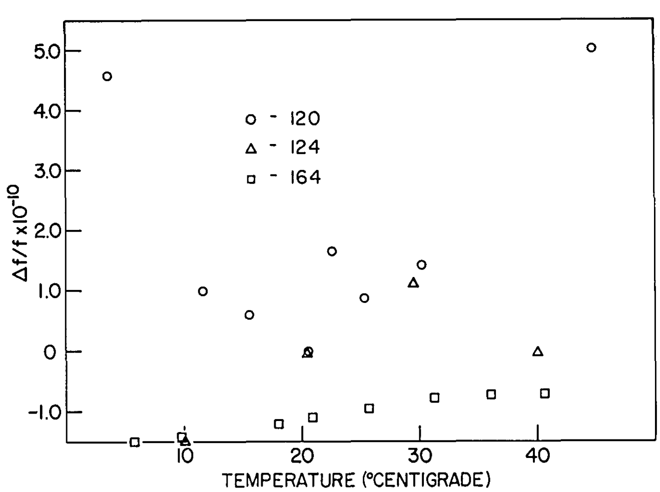


Fig. 36 — Temperature test for rubidium units

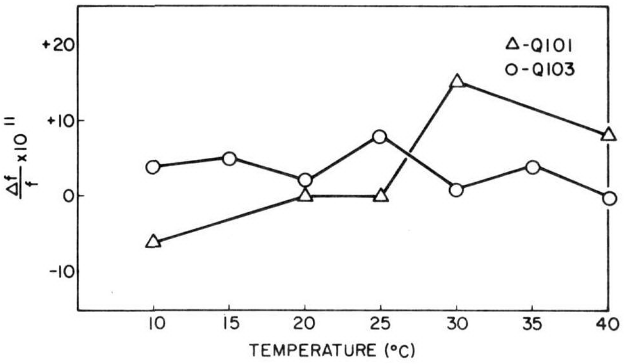


Fig. 37 — Temperature test for FE quartz oscillator

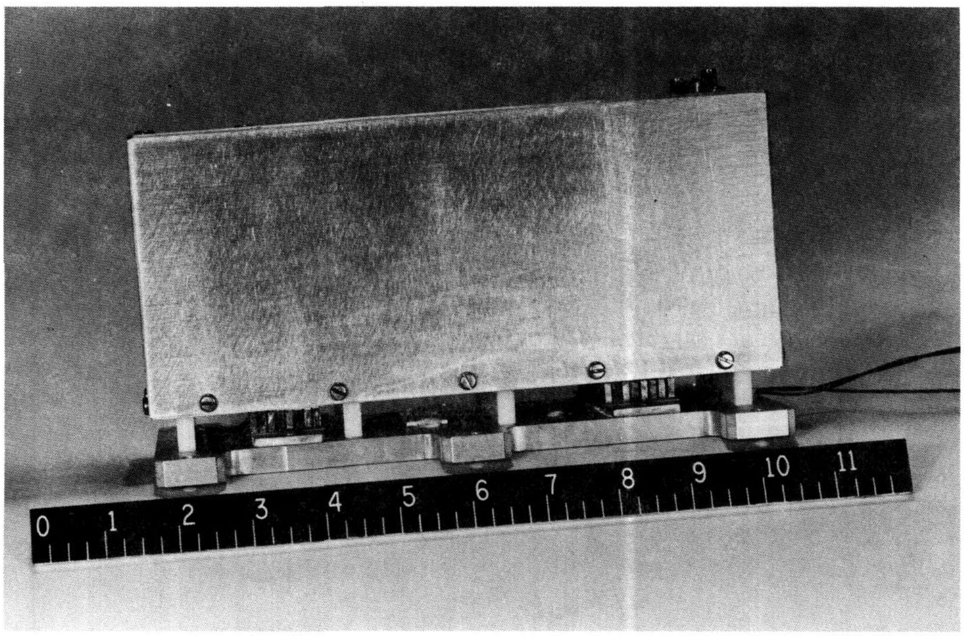


Fig. 38 — FE quartz oscillator on thermoelectric device

the oscillator at 25°C ±0.1°C, which will make performance independent of ambient temperature. Figure 38 shows the oscillator mounted on the TED.

Vacuum

As a simulation of space environment, several rubidium units were placed in a thermal vacuum chamber. For this test the FRK unit was mounted to an aluminum block (1 by 11 by 12 in.) which was in thermal contact with the chamber walls. Primary operating parameters were monitored for the duration of the test. One test lasted 10 days; several others were run for three days. Figure 39 shows the results of the 10-day test; Figure 40 shows test results for two of the units that were tested for three days. The chamber was evacuated in two stages, first to a pressure of 10^{-1} Torr using a mechanical pump and then to the low 10^{-6} Torr range with an oil-diffusion pump. The response to

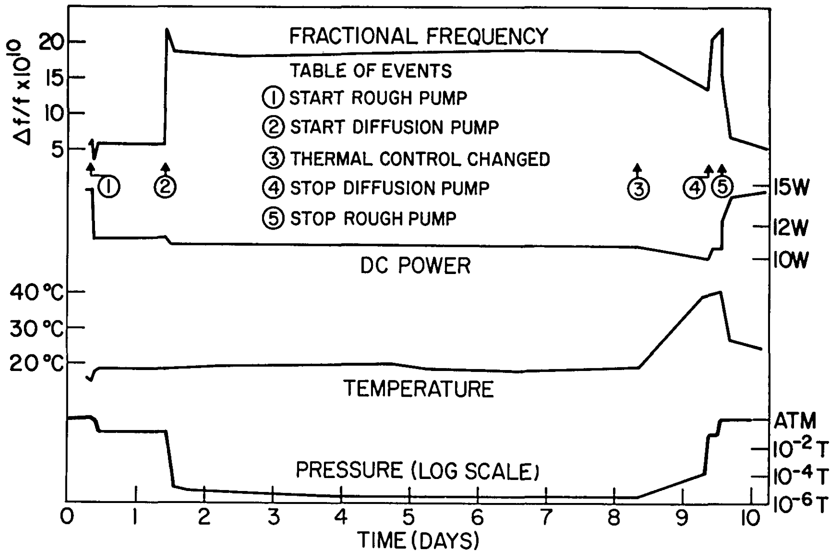


Fig. 39 — Rubidium vacuum test, 10 days

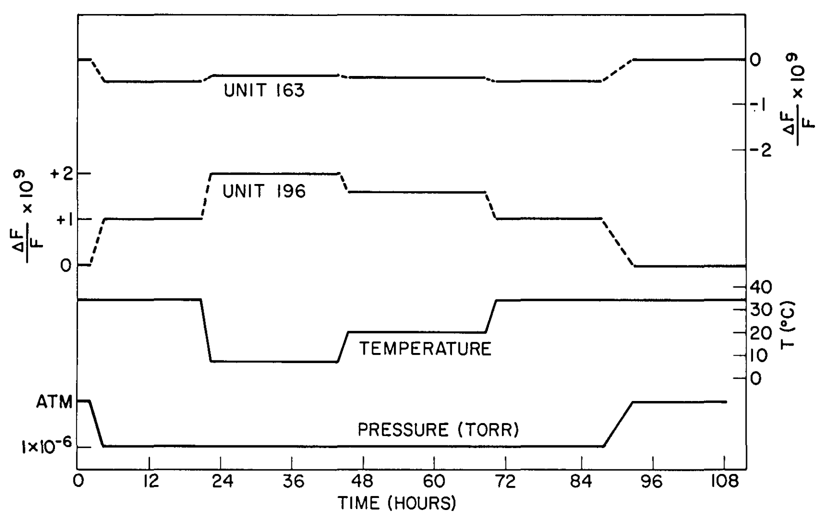


Fig. 40 — Rubidium vacuum test, 3 days

the initial mechanical pumpdown appears to be masked by a corresponding temperature change. A further shift was observed after the diffusion pump was turned on. Table 6 is a record of the responses of several key parameters of six units to a vacuum environment. Note that unit 163 was tested with two lamps to show the effects of changing lamps. Figure 41 compares these results.

It was noted that there was a difference in the temperature behavior of the rubidium units at ambient pressure and in vacuum. Figure 42 shows the differences, which are due to an internal compensation technique that becomes unbalanced because of the vacuum shift.

TABLE 6
Results for Six Rubidium Frequency Standards Tested in Vacuum

Unit Serial No.	Vacuum Shift ($\times 10^{-9}$)	ATM 10-40°C Range ($\times 10^{-11}$)	Vacuum 6-33°C Range ($\times 10^{-10}$)	ATM Photocell (V (DC))	Vacuum Photocell (V (DC))	ATM 2ND Harmonic (V (RMS))	Vacuum 2ND Harmonic (V (RMS))	ATM DC Power (W)	Vacuum DC Power (W)
163	-0.44	7.2	1.2	7.4	6.2	0.11	0.18	13.8	10.6
164	+0.25	2.8	30.0	9.7	9.5	0.04	0.08	13.7	10.5
165	-1.6	2.5	4.0	10.7	6.7	0.07	0.15	13.8	10.9
189	+3.3	7.8	4.6	8.9	8.5	0.26	0.54	13.5	10.7
196	+1.0	6.6	9.8	9.1	7.4	0.17	0.62	13.8	10.1
198	+1.5	11.6	14.0	9.8	7.8	0.18	0.72	13.8	11.3
163*	-0.82	—	—	6.7	5.6	0.11	0.48	—	—

*Spectral lamp changed.

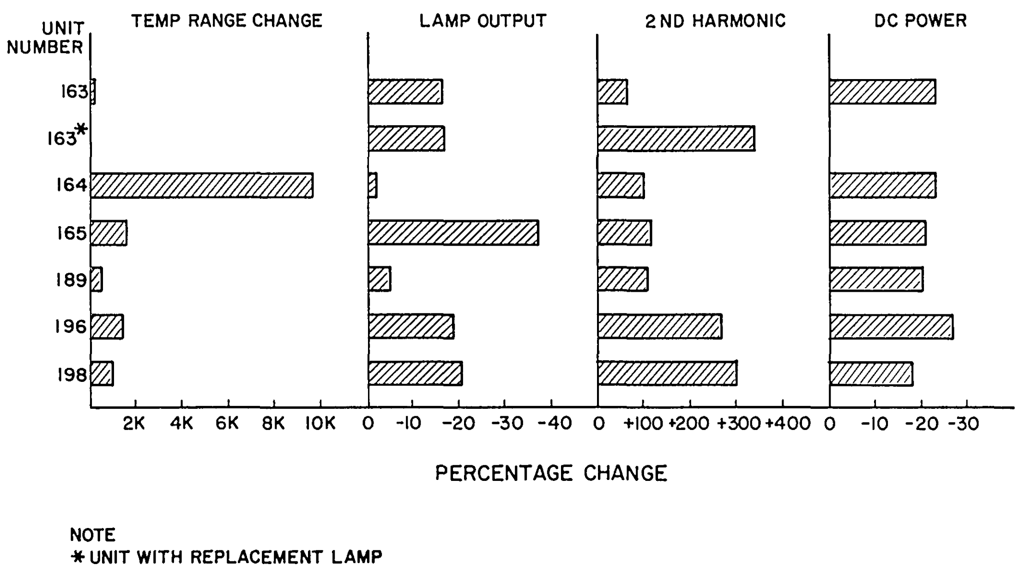


Fig. 41 — Rubidium vacuum data comparison, 6 units

The quartz oscillators were also tested in a vacuum chamber. Thermal changes caused by the removal of air resulted in a transient effect on the frequency during the first hour of pumping to create the vacuum. The final frequency in vacuum, however, is within 2 pp 10^9 of the ambient pressure frequency.

Irradiation

Radiation effects in frequency standards are an important consideration [16]. At an altitude of 7,500 n.mi., the predicted electron flux is 10^{11} to 10^{12} electrons (> 1

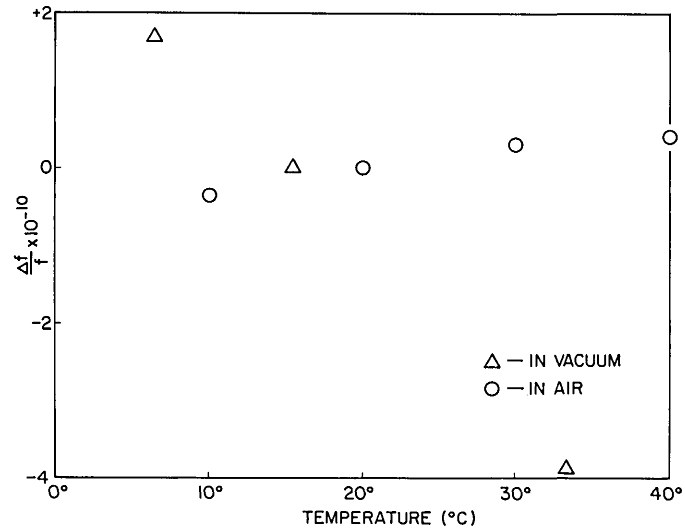


Fig. 42 — Temperature behavior of rubidium unit in vacuum and at ambient pressure

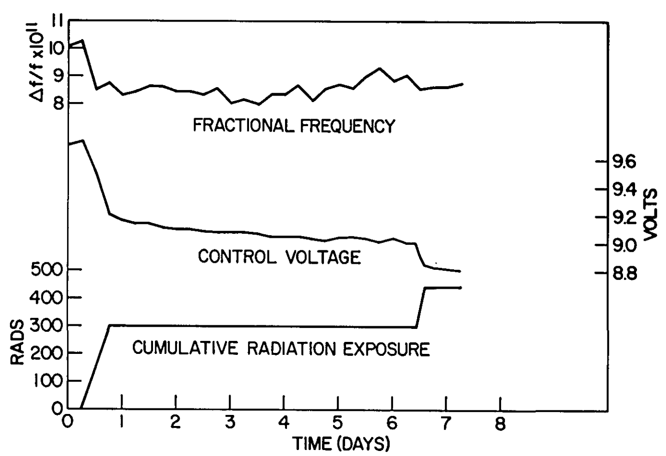


Fig. 43 — Rubidium irradiation test; △ in vacuum, 0 in air

MeV)/cm2 day. This flux will irradiate the frequency standard at a rate of approximately 0.5 rads per day. An irradiation test of the rubidium frequency standard showed a step jump of 1.5×10^{-11} at the beginning of the test, as shown by Fig. 43. There were no other changes in frequency during or after the test. The rubidium quartz oscillator did shift in frequency by approximately 7×10^{-11} rad, but this was compensated by the control voltage.

SYSTEM TEST RESULTS

The frequency standard system was monitored continuously during the satellite system test program. Final frequency, control, and monitor system checks were made at the launch site in April 1974. Table 7 shows the results of these tests. After these tests

TABLE 7
Frequency Standard Final Tests

Unit	Range		Aging Rate (per day)	(Δf/f)	Date	Control Voltage	Tuning Word			
	Low	High					1-3	4-6	7-9	10-12
FE Quartz 105	-9.3×10^{-8}	$+8.3 \times 10^{-8}$	-1.3×10^{-11}	-1.2×10^{-10}	4/26	—	101	001	000	000
165 Quartz	-4×10^{-6}	$+2 \times 10^{-6}$	—*	—	—	10.4	101	111	010	000
165 Rubidium	-3.7×10^{-9}	$+7.0 \times 10^{-9}$	-0.8×10^{-12}	$+2.2 \times 10^{-9}$	4/12	—	011	001	010	000
196 Quartz	-1.5×10^{-6}	$+1.2 \times 10^{-6}$	—	—	—	10.7	101	111	010	000
196 Rubidium	-3×10^{-9}	$+5.4 \times 10^{-9}$	-0.6×10^{-12}	-6.2×10^{-10}	4/12	—	101	010	101	100

*Dashes indicate data not taken.

TABLE 8
Frequency Standard System Parts Count

Component	Digital Control	FE Quartz	Rubidium (2 ea)	Total
ICs	64	2	15	96
Transistors	16	14	24	78
Diodes	21	6	23	73
Crystals	—	2	1	3
Misc (lamps htrs etc.)	3	6	2	11
Resistors	115	55	149	468
Capacitors	82	29	95	301
Inductors and Chokes	10	8	43	104
Subtotal	311	122	352	1137
Total	1137			

were completed, the rubidium units were not turned on again until after the launch. The FE quartz oscillator was kept running, although it was not checked again prior to launch. The satellite was integrated into the payload transfer system in May 1974 and launch was July 14, 1974.

System reliability was evaluated [17]. Table 8 shows the parts count for the entire system. The area of primary concern in the rubidium unit is the microwave assembly (rubidium lamps and resonance cavity assembly). Each unit was operated on the ground for at least 700 hr before launch. All adjustments were optimized after approximately 600 hr, and all flight units were subjected to vibration and thermal vacuum tests.

Outer Space Performance

As a result of the environmental tests described here, an estimate can be made of the expected performance in outer space. Table 9 shows the predicted effects of the outer space performance on a rubidium unit. The use of a rubidium vapor frequency standard in a satellite requires the consideration of the following factors: vacuum, thermal effects in a vacuum, magnetic effects, radiation effects, and zero gravity effects. Several profound changes occur when this frequency standard is placed in a hard vacuum ($< 5 \times 10^{-6}$ Torr). These include a large frequency shift which is typically 1 to 3×10^{-9}, a change in the thermal frequency characteristic, and a decrease in the DC power from 14 W to 11 W. The effect of frequency variation vs temperature is considerably different in vacuum than it is at normal atmospheric pressure. Over the temperature range of 10°C to 40°C the corresponding frequency range was typically 0.3 to 1×10^{-10} at atmospheric pressure. In vacuum ($< 5 \times 10^{-6}$ Torr) the same frequency standards had a frequency range of 1.2 to 14×10^{-10} over the temperature range of 6°C to 33°C.

Acceleration tests have shown that loading levels to 5 g will not cause the frequency standard to drop out of lock. It was also seen that there is a frequency shift of approximately -4×10^{-12}/g caused by acceleration. Since the rubidium units will not be on during launch, the only shift due to acceleration will be from the absence of earth's gravity.

The resonance frequency of the rubidium frequency standard varies as the magnetic field changes. The fine tuning of the standard is accomplished by varying the current in

TABLE 9
Estimated Rubidium Performance in Space

Parameter	Prior to Launch	At Launch	In Orbit
Frequency standard status	On	Off	On
DC power	14 W		11 W
Temperature stability	0.5×10^{-11}/°C		3×10^{-11}/°C
Launch vibration		13g for 2 min	
Frequency shift			
Vibration	Ref	—	1.0×10^{-10}
Vacuum	Ref	—	10.0×10^{-10}
"O" g	Ref	—	0.7×10^{-10}
Magnetic field	Ref	—	0.3×10^{-10}
Relativity	Ref	—	4×10^{-10}
Total estimated shift	Ref	—	1.2×10^{-9}

a coil (C-field) around the resonance cell. This C-field is protected from ambient fields by two magnetic shields. The horizontal component of the magnetic field in the Washington, D.C., area is about 0.3 gauss. At 7,500 n.mi. above the earth, a satellite with a 55° inclination would be in a magnetic field of 0.01 to 0.02 gauss. Tests [18] indicate that the expected shift due to this magnetic change will be about 3×10^{-11}. This effect, however, will be completely masked by the vacuum shift of frequency.

Orbital Results

The Frequency Electronics quartz oscillator was kept running continuously before, during, and after launch, whereas the Efratom rubidium standard was turned off prior to launch. After 2 weeks in orbit, the quartz oscillator was behaving well and was successfully tuned to within 3.5 pp 10^{10} of the correct frequency. The initial aging rate in space was less than -1 pp 10^{11} per day. A synthetic tuning circuit will correct the output frequency to the desired accuracy.

After one month in orbit, a rubidium frequency standard was successfully turned on. Control loop lock occurred within 5 min. A C-field adjustment was successfully made two days after turn-on, which brought the frequency to within the range of synthetic tuning. The second rubidium frequency standard has also been successfully turned on.

Orbital data analysis for the first five months of 1975 has been reported [19]. There is good correlation between ground tests and the orbital data analysis. Rb 1 (unit 165) shows an aging rate of 4.5×10^{-13}/day in orbit with a temperature coefficient of $-4.2 \times 10^{-11}/°C$ from 16°C to 36°C. The FE quartz oscillator had an initial aging rate of -5.7×10^{-12}/day which later changed to -2.5×10^{-11}/day.

CONCLUSION

Rubidium and quartz frequency standards were purchased, modified, tested, and incorporated into the frequency standard system for NTS-1. The quartz oscillator, purchased from Frequency Electronics, was the third in a series of satellite oscillators developed for NRL. It was modified to allow digital tuning. Short-term stability, aging, and environmental tests showed this oscillator to be a highly accurate, reliable component. A miniaturized rubidium vapor frequency standard was added to the satellite frequency standard system to obtain higher accuracy and stability. Although this frequency standard was intended for commercial use, NRL was able to modify it successfully for satellite use. Short-term stability, aging, and environmental tests showed its ability to perform to be better than the quartz oscillator. The frequency standard system was successfully integrated with the NTS-1 satellite which was launched on July 14, 1974.

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