PERFORMANCE OF ATOMIC CLOCKS FLOWN ON THE SPACE SHUTTLE EXPERIMENT NAVEX

J. Hammesfahr, H. Nau, S. Starker
Institute for Radio Frequency Technology
German Aerospace Research Establishment: DFVLR
D-8031 Wessling, F.R. Germany

ABSTRACT

At the first German Spacelab Mission D1 in autumn 1985 a navigation experiment was flown for seven days on board the NASA Space Shuttle Challenger. Two atomic clocks, one Cs- and one Rb-standard, were part of the spaceborne equipment and were carried back to earth. The Cs-clock was compared with a ground based Cs-clock by a two-way microwave link at 1.5 GHz in the periods of ground contact, while the comparison between the flying Cs- and Rb-clock occurred continuously. The influence of the space flight on clock rates was determined by comparison with many series of measurements on the ground before and after the D-1 Mission. Comparisons of the flight clocks at Cape Kennedy with the reference clock in Germany were performed via GPS. Results of the data evaluation will be presented with special attention to temperature effects. Unexpected rate oscillations between the two flying clocks correlated with the attitude of the space vehicle were discovered.

INTRODUCTION

NAVEX was an experiment to get first hand practical experience with new techniques and methods of future satellite applications for time and frequency transfer and navigation. One important task in this field will be the synchronization of atomic clocks in a space vehicle with one in a ground station. So we intended to do the best in this task by realizing a two-way clock comparison equipment. A detailed description of the main objectives "Clock synchronization" and "One-way range measurement" and their hardware realization was given already in the PTTI Planning Meeting in 1982 and a first report of the results achieved during the flight on board of the NASA Shuttle Challenger was given 1985. It was a very successful flight of the Spacelab Mission which was realized the first time by German payload control. We got a lot of measurement data from the clock comparisons between a cesium standard on board and on ground. A back up rubidium standard was controlled by phase measurements with the cesium standard during the 7 days of the spaceflight.

On board a pseudo-noise time code coherently derived from the cesium standard together with experimental data were modulated on a microwave carrier (1.5 GHz). This signal was received by a ground control station also equipped with a cesium clock. The time of arrival was measured with a time interval counter. The regenerated signal was sent back to the spacecraft where the round travel time was measured. By evaluating the time interval measurements of both stations, it was feasible to work out the differences between the readings of both clocks every second.

During the mission these data could be achieved only in times of contact when the Shuttle flew over Europe. This means intervals lasting 5 to 9 minutes, five to six times a day with time intervals in between of 1 1/2 to 16 hours respectively.

To compute the two-sample or Allan variance, which is usually used for the specification of clocks, it is necessary to have data in equidistant time intervals. This was true for short periods only in our data sets. Therefore it was not useful to determine the Allan variance on the on board clocks and was not in the ground measurements, too, because these data

had to be compared to the results of the mission.

There was one restriction in evaluating the difference in the performance caused by the spaceflight. The flight clocks had to be switched off a long time before the launch and were activated not earlier than 12 hours after the start of the D1 mission and switched off again before the landing. In general the rate of a clock differs from the previous rate after a disactivation period. That is why several ground measurements were performed in order to get data on the range of variation in the clock rates.

CLOCK MEASUREMENTS ON THE GROUND

Soon after delivery of the flight clocks they were compared versus a reference clock in several ground measurement periods as often as possible during the time of hardware integration and tests. By this means the long term rates of the frequency standard should be investigated as well as changes in the rates caused by varying environmental conditions, especially in the space trip on the D1 mission.

From 1983 to 1986 such clock comparisons were conducted at various locations. In Germany the access to the reference clock could be achieved easily. During two data collection periods in the U.S.A. the German reference clock and a second reference standard in the USAF Eastern Space and Missile Center at the Space Shuttle launch site were compared via frequency links to satellites of the Global Positioning System (GPS) using the common view technique.

The clocks had to be switched off several times during the integration and test phase. Thus the condition of undisturbed operation of the flight clocks could not been met and variations in the rates were expected.

On each measuring period the mean rate was computed by a least squares fit of a straight line using all differences in the time scale readings of flight clock versus reference clock. These differences are simply called readings from now on.

Because of the varying environments the results had to be transformed to uniform conditions in the temperature and in the geographic sites. The clock rates were transformed onto a temperature of 37 °C at the housing of the flight standards corresponding to an ambient temperature of 21 °C. In order to achieve that task the temperature coefficients were roughly determined in the first data collection period in 1983. Both standards were put in an air-conditioned box at controlled temperatures and the rates were measured. The cesium standard CFS showed a change in its rate of approximately

$$\alpha_{CGS} = 2.43 \times 10^{-14} \, \vartheta/°C,$$

and the rubidium standard RFS of

$$\alpha_{RFS} = 5.77 \times 10^{-12} \, \vartheta/°C.$$

It was assumed that the slope was linear.

In a second step the changes in the rates caused by the relativistic effect were computed because of the different places (DFVLR site in Munich/Germany and Kennedy Space Center in Florida/U.S.A.). The additional rate has an amount of $\Delta R_{rel} = 0.46 \times 10^{-12}$. This is derived in good approximation by the relation:

$$\Delta R_{rel} = \frac{\omega^2}{2C_o} \left[(r_o + h_2)^2 \cos^2 \phi_2 - (r_o + h_1)^2 \cos^2 \phi_1 \right] - \frac{\mu}{C_o^2} \times \left(\frac{1}{r_o + h_2} - \frac{1}{r_o + h_1} \right).$$

$$\omega = \text{the angular frequency of the earth's rotation,}$$
$$C_o = \text{the vacuum velocity of light,}$$
$$r_o = \text{the mean radius of the earth,}$$
$$\mu = \text{the gravitational constant,}$$
$$h_1, \ h_2 = \text{the altitudes,}$$
$$\phi_1, \ \phi_2 = \text{the latitudes of the sites.}$$

Table 1 shows the most important results of the ground measuring period from March 1984 through April 1986 for the cesium standard CFS.

There were two additional data collection series each before and after that time. But in the beginning the flight clocks were not mounted in the space configuration and at the end the cesium clock showed a drift; that standard failed to operate in November 1986. Therefore the rates of these intervals are omitted in Table 1.

Table 2 contains equivalent results in respect to the rubidium standard RFS. The rates are computed over a 12 hour interval per day. Given is the mean rate over all days of the period and the standard deviation in this rate, derived from all valid data in the indicated measurement period.

Despite the disadvantageous operation mode due to the transport and deactivation periods of the flight clocks the mean rates of the CFS are in a good accordance. Computation of the overall mean rate and the corresponding deviation in conjunction with the observed maxima and minima lead to

$$\overline{R}_C = 7.51^{+0.64}_{-0.37} \times 10^{-12} \text{ rate,}$$

$$\sigma_C = 1.88 \times 10^{-13} \text{ empiric standard deviation.}$$

Even more stringent results are obtained when only the periods around the space mission are considered, i.e. the year 1985, June to December:

$$\overline{R}_{C1985} = 7.47 \pm 0.34 \times 10^{-12} \tag{35}$$

This is a clear indication that the whole mission including launch and landing did not deteriorate the performance of the cesium standard in ground operation.

The performance of the rubidium standard RFS is different from the cesium's. There was a significant change in the rates between July and November in 1985 by an amount of approximately $1.5 \times 10^{-12}/°C$. Therefore the calculation of a mean rate is not that meaningful. The time of change must have been during the D1 mission in October/November or shortly before or after that interval. So there is no efficient way to deduce from the readings an interpolated rate which could be treated valid for the time of the space flight.

CLOCK MEASUREMENTS IN SPACE

During the mission time both the atomic standards in the Space Shuttle were compared in their timing signals. The difference in the readings was measured from the 5 MHz signals of either clocks giving the reading $T_{(RFS-CFS)}$. In the launch and landing phase of the Shuttle the clocks were switched off. They were active from 31 October 5:00 o'clock UTC until 5 November 19:20. Since the warm-up time, especially of the cesium standard, took 1 1/2 hours the readings were taken from 6:40 on for an interval of 5 1/2 days. The data were ambiguous in multiples of 200 nsec because of the 5 MHz signals and were adjusted. Moreover the ground measurements showed a temperature dependence of the clock's rates. That is why the readings have been corrected due to the varying in-flight temperature.

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The temperature was measured at a metal baseplate which both the clock housings were mounted on. The correction was done by transforming the ground based temperature coefficients for CFS and RFS onto the space environment.

The resulting corrected reading is shown in Figure 1. The day 304 corresponds to October 31 in 1985. To get a fine resolution in the graph a mean rate of 5.4×10^{-11} was subtracted. The line of the readings indicates that there has been a drift because its gradient is changing in the interval. Probably that drift is caused mainly by the rubidium standard in similarity to the ground measurements. Superimposed on this effect is a second phenomenon, namely six periods of slight oscillations in the readings.

To get a better idea the rate was computed and is depicted in Figure 3. The rate is derived from the readings by differentiating and therefore is in the same way corrected in temperature according to the ground based coefficients. The oscillations are clearly discernible in that line of rate. In Figure 3 (above) is additionally given the corresponding temperature curve and even if the temperature dependence should have been eliminated by the correction there remains a correlation between temperature and rate, obvious by the simultaneous rising and falling slopes in either curve. This indicates an over-correction. Thus by varying the temperature coefficient and introducing a time lag we tried to get a line of the rate that shows no significant correlation to the temperature. Such a curve achieved by best adaptation is shown in Figure 4 below. While the temperature factor in the ground measurements was

$$\alpha_{(RFS-CFS)} = 5.75 \times 10^{-12}/^{\circ}C \quad \text{(ground)},$$

the empirically found flight factor now is

$$\alpha_{(RFS-CFS)} = 3.4 \times 10^{-12}/^{\circ}C \quad \text{(flight)}.$$

An additional time lag of about 2 hours had to be used to get Figure 3, i.e. the temperature is taken at an instant which is two hours earlier than the instant when the appertaining reading is taken. The term of correction to the rate has been calculated by the product of $\alpha_{(RFS-CFS)}$ times the temperature. To get Figure 4 the coefficient α was adapted; the same result would have been achieved by changing the temperature instead of α by the same ratio.

Since the temperature was not measured inside the clock's housings but at the base plate a physical interpretation can be that in space a different temperature gradient from the plate to the oscillators took place than at ground. In space the heat inside the flight containers could be dissipated by radiation or solid transducing but not by thermal convection. This should have caused the deduced time lag, too. As a consequence to similar satellite missions it is recommended to be careful on such temperature corrections. The relations measured at ground cannot be transposed into space without a model of the thermal heat dissipation.

In Figure 4 six blocks of oscillations are recognizable in the rate RFS versus CFS which have no correlation to the measured temperature because temperature dependent changes in the rate have been eliminated. The upper part of the figure shows the attitudes of the Space Shuttle. Three main attitudes are to be discerned. In 'Earth alignment' the cargo bay bearing the NAVEX equipment looked towards the center of the earth. 'Space alignment' was an attitude perpendicular to the first one, the cargo bay looked in parallel to the earth's surface. In some periods the Shuttle was facing a telecommunication satellite ('Satellite alignment'). Comparing these attitudes with the clock's rates we see that oscillations with long periods occur during the earth alignment, in satellite alignment we have short periods and in space alignment no oscillations are recognized.

To look into the oscillations in more detail a section of the line of rate starting at day 308, ten o'clock, is shown in a different scale in Figure 2. The oscillation types are joining one

another directly. A coarse count of the cycles leads to periods of approximately 91.5 ± 1.5 minutes at earth and 46 ± 1 min at satellite alignment. Thus the frequency of the second oscillation section is twice that of the first one. The period of 91.5 minutes nearly equals the anomalistic period of the Shuttle around the earth which was 91.1 minutes. This is the time the satellite takes for one revolution. In that period a ground station on the earth's surface has moved because of the earth's rotation. The anomalistic period is not the period of a revolution of the satellite seen by a ground station; that one is greater (94.6 minutes).

Thus the oscillations appear not to be affected by an earth bound cause such as the magnetic field or a radiation from the earth but more likely may be caused by the Shuttle environment itself or an extraterrestial cause, perhaps the sun's electromagnetic field or the solar flux. Further details have not been investigated, and there is no stringent interpretation yet.

During the time of the mission D1 the Spacelab was circling around the earth in about 91 minutes per revolution. On that trip it could be 'seen' from the German ground control station near Munich six times per day in most of the cases. In the phases of radio contact the time differences between flight and ground clock have been computed by means of the two way signals. Following several corrections were applied in order to eliminate all known effects to get clock rates which are comparable to the rates in the ground measurements. As the most important the corrections for rate variations with temperature and for relativistic frequency changes should be mentioned.

The temperature coefficients used were those derived from the above discussed investigations in the relative rate of RFS versus CFS, i.e.

$$\alpha_{CFS, \, flight} = 2.43 \times 10^{-14}/^{\circ}C$$

$$\alpha_{RFS, \, flight} = 311 \times 10^{-14}/^{\circ}C$$

The empiric deduced time lag of two hours was incorporated. As reference temperature was taken $37^{\circ}C$, the mean clock temperature at ground.

By using the Shuttle trajectory data supplied by NASA the relativistic time dilatation was computed. The mean relativistic rate on the 5 days period was

$$\overline{R}_{rel} = 294.7 \times 10^{-12}/^{\circ}C$$

All corrections were done on a one-second-base. Thus every second a clock reading was yielded. Atmospheric corrections in troposphere and ionosphere have not been applied until now. The influence of the ionosphere was small because of a minimum in the sun spot activity in late 1985. The readings were taken on all those periods of contact when data were available and the elevation angle exceeded 10 deg. Twenty eight series of useful data have been achieved each one comprising up to 300 utilizable data points totaling approx. 6000 data sets.

The results gained after subtracting all mentioned effects including the relativistic effect are shown in Figure 5 for the CFS and the RFS.

Each "spot" in the graphs represents the data of one orbit. Because of the time scale of the x axis the individual points in an orbit are condensed to a dot or small vertical stroke when noise is recognizable.

As was expected the readings of the CFS give a straighter line than those of the RFS, corresponding to a more stable rate. The rates have been computed as

$$\overline{R}_C = 302.15 \times 10^{-12}, \quad \sigma_C = 0.2 \times 10^{-14}$$

$$\overline{R}_R = 248.3 \times 10^{-12}, \quad \sigma_C = 3.6 \times 10^{-14}$$

as seen from the ground station (relativistic effects inherent),

$$\overline{R}_C = 7.45 \times 10^{-12}$$

$$\overline{R}_R = -46.4 \times 10^{-12}$$

when relativistic effects are extracted.

The CFS flight rate is near to the ground rate, thus indicating that the cesium frequency standard didn't change its frequency appreciably in the mission time whereas the rate of the rubidium standard has slipped from the pre-mission measurements to the flight period and further again to the post mission time.

REFERENCES

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2. S. Starker, H. Nau, J. Hammesfahr: "The Shuttle Experiment NAVEX completed on Spacelab Mission D1", Proc. 17th PTTI Meeting 1985, pp 405-412

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ACKNOWLEDGMENT

Table 1
Mean Rates of CFS versus Reference Clock HO1, (HO1-CFS)
Temperature and Geographic Corrections Applied
$(37\ °C,$ Wessling, Germany$)$

Mean Rate 10^{-12}	Deviation 10^{-12}	Number of Measurement Days	Place	Measurement Period Days
7.75	0.86	11	Stuttgart	10.03.-01.04.84
7.85	1.14	12	Eberdingen(Stuttgart)	28.04.-17.05.84
7.35	0.31	1	C. Canaveral (U.S.A.)	26.06.85
7.50	0.23	4	C. Canaveral (U.S.A.)	28.06.-01.07.85
7.42	0.43	3	C. Canaveral (U.S.A.)	29.11.-01.12.85
7.38	0.61	6	C. Canaveral (U.S.A.)	03.12.-08.12.85
7.31	0.80	5	Wessling (Munich)	12.03.-16.03.86
7.60	1.17	7	Wessling (Munich)	10.04.-16.04.86
7.41	0.57	1	Wessling (Munich)	21.04.86

Table 2
Mean Rates of RFS versus Reference Clock HO1, (HO1-RFS)
Temperature and Geographic Corrections Applied

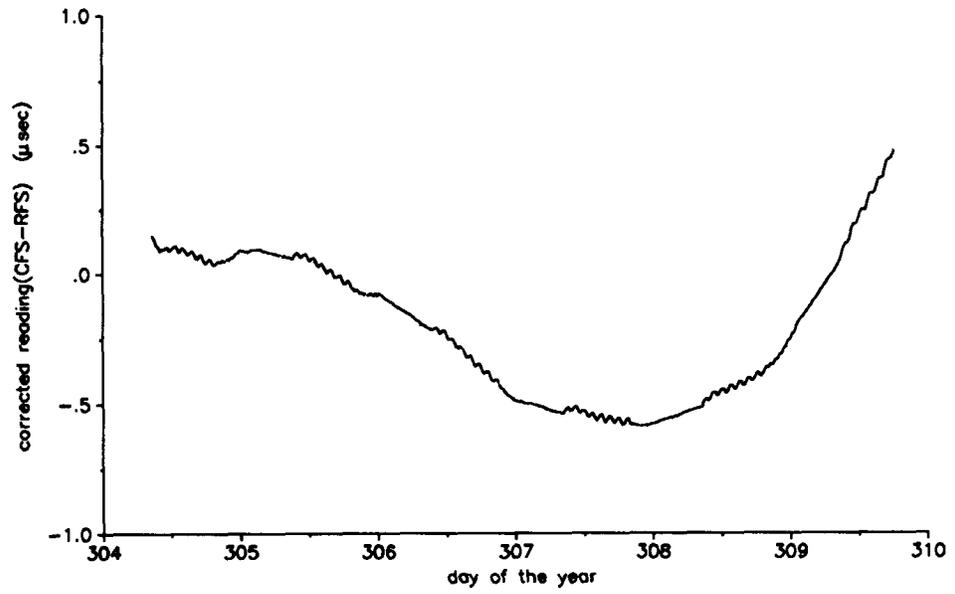| Mean Rate 10^{-12}	Deviation 10^{-12}	Number of Measurement Days	Place	Measurement Period Days
48.6	6.8	6	Stuttgart	11.05.-16.05.84
43.0	—	5	C. Canaveral	28.06.-02.07.85
-102.9	10.2	3	C. Canaveral	29.11.-01.12.85
-99.1	14.0	5	C. Canaveral	03.12.-08.12.85
-96.7	4.7	5	Wessling (Munich)	12.03.-16.03.86
-100.7	9.9	7	Wessling (Munich)	10.04.-16.04.86
-106.7	5.0	1	Wessling (Munich)	21.04.86

Figure 1
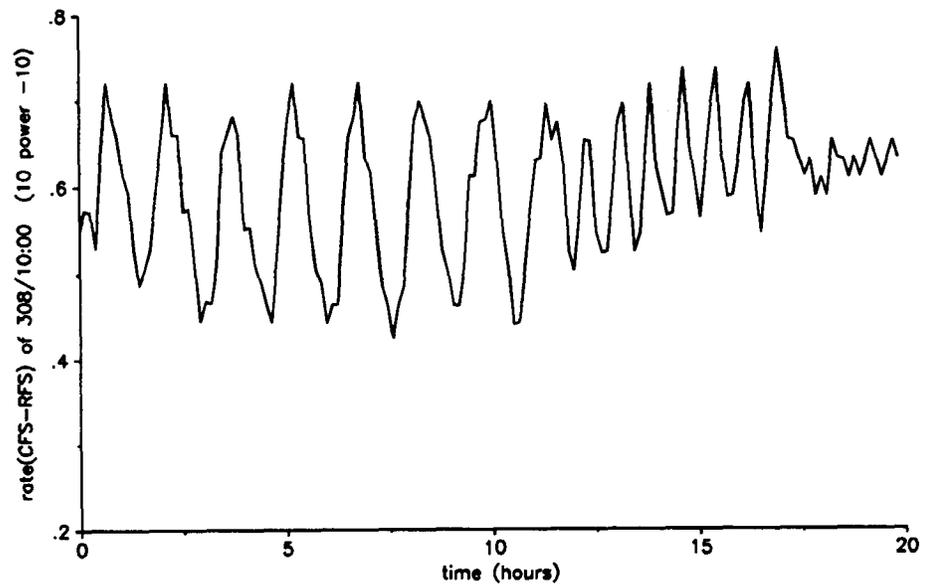**Reading(RFS-CFS), temperature corrected**

Figure 2
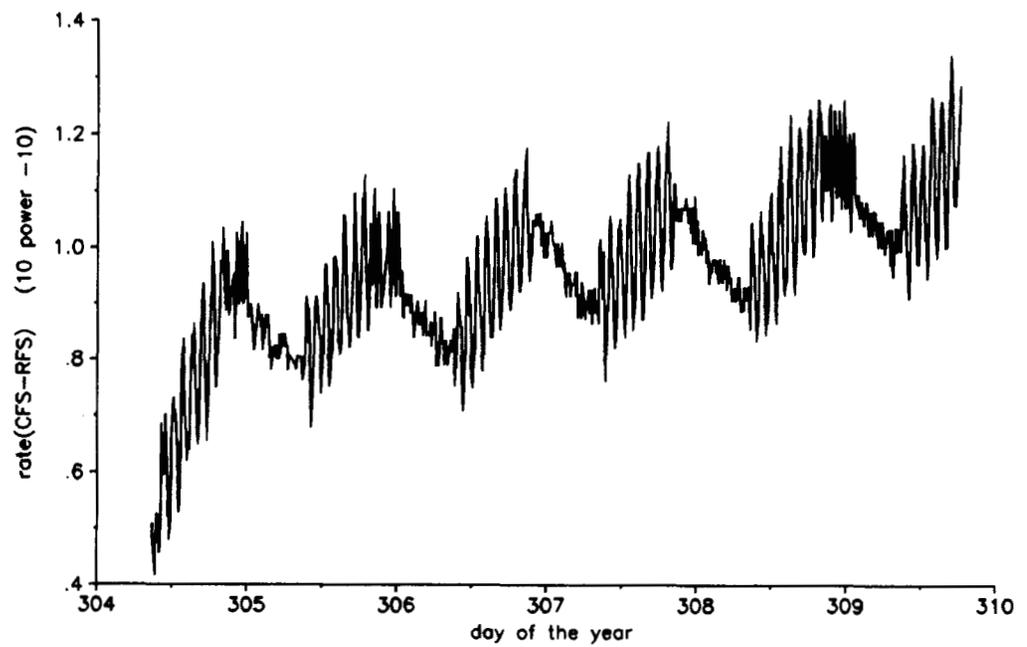**Rate(RFS-CFS), best temperature correction,**
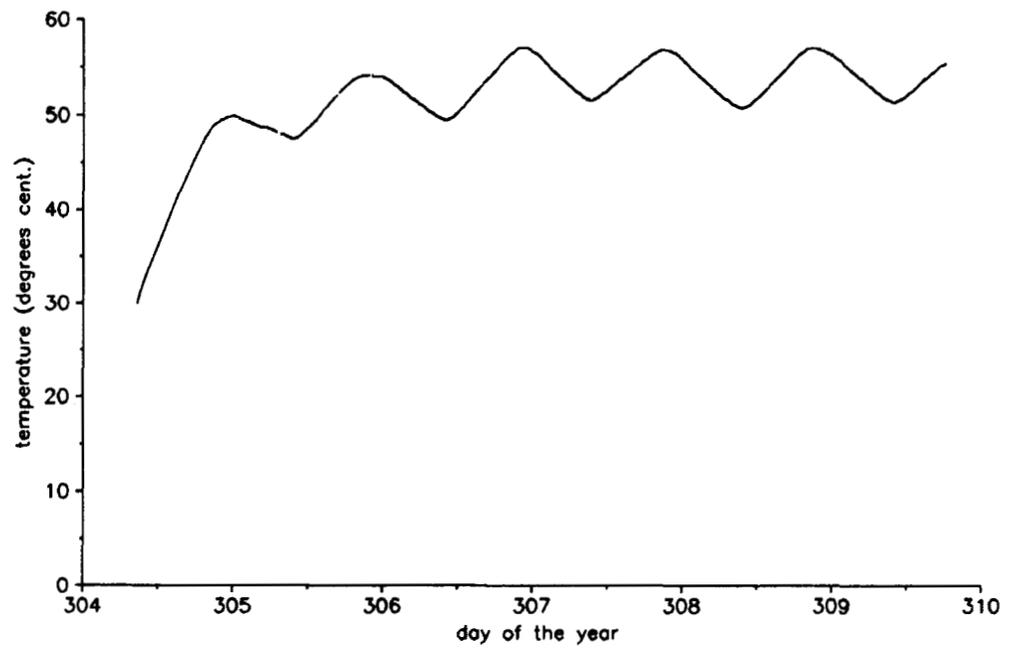 **time slice of 20 hours**

Figure 3
Rate(RFS-CFS), corrected by ground temperature coefficient
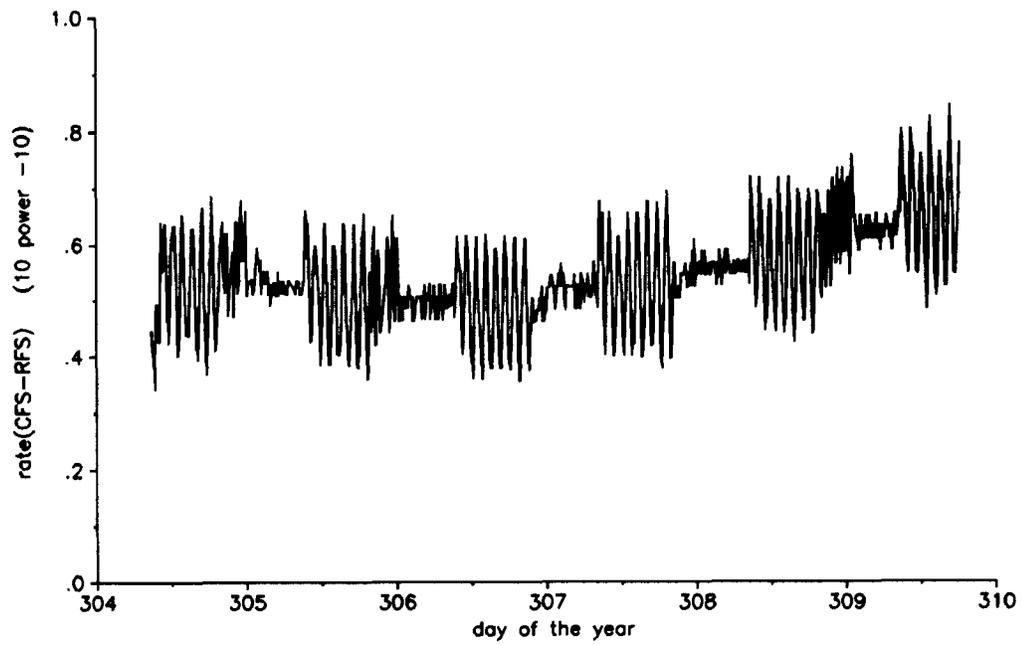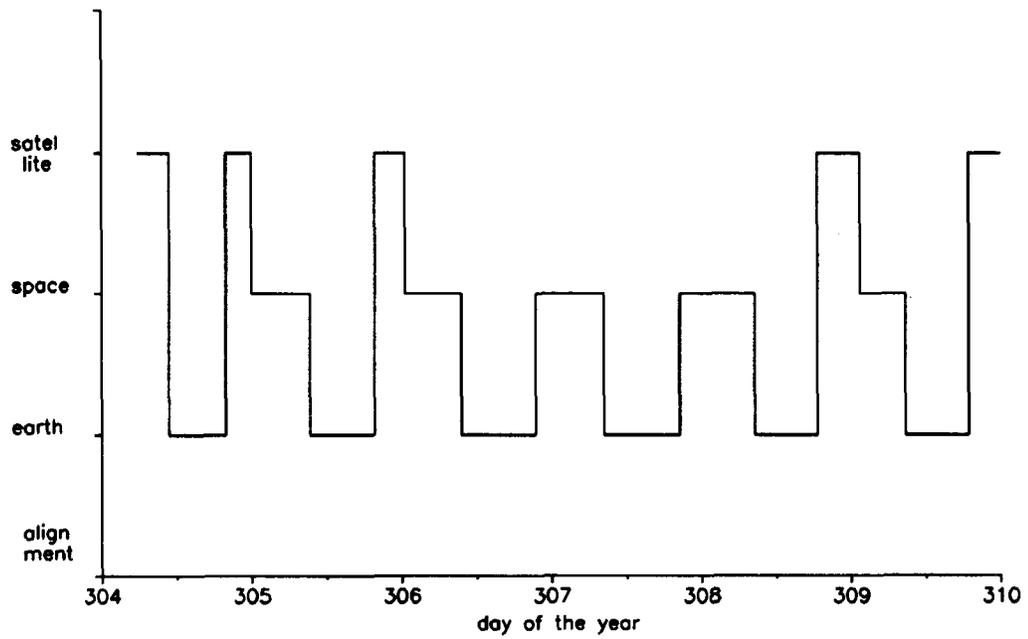Temperature curve (above)

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Figure 4
Rate(RFS-CFS), best temperature correction
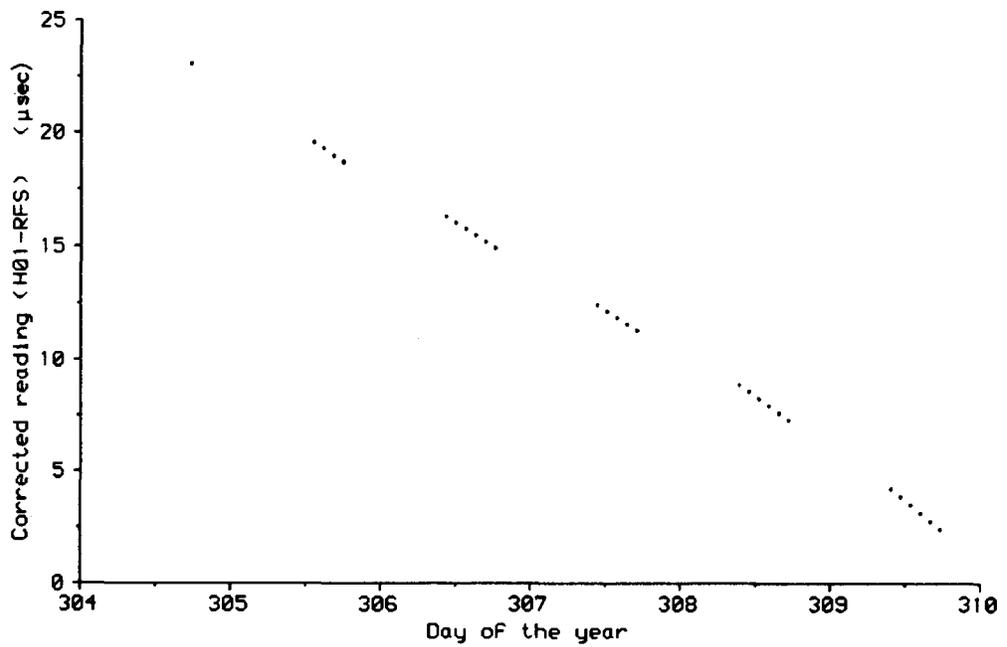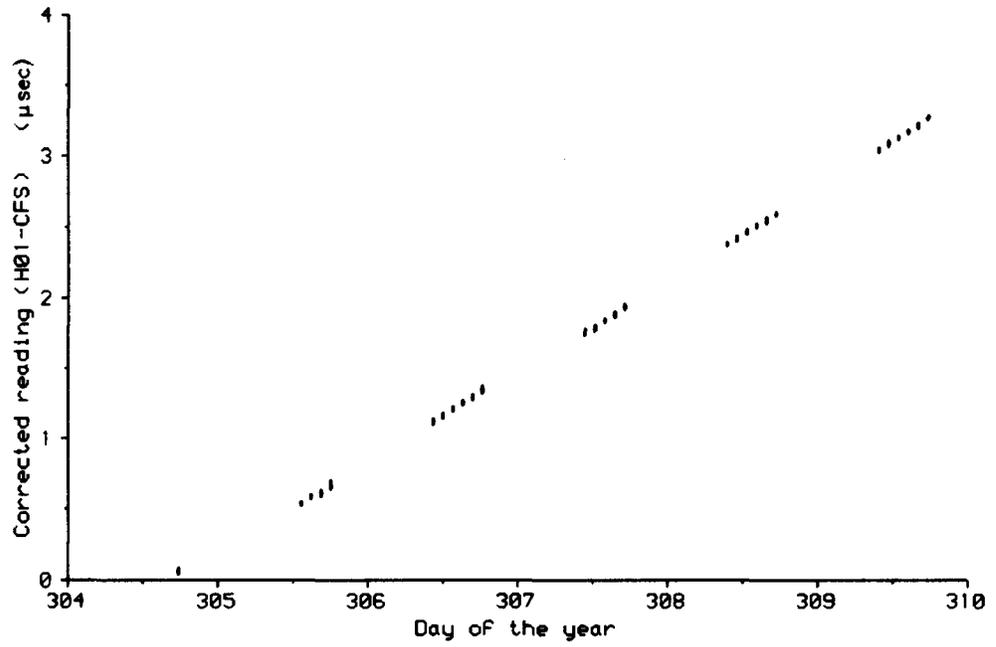Shuttle attitude (above)

Figure 5
Corrected reading for
(H01−CFS) above   and   (H01−RFS) below

QUESTIONS AND ANSWERS

Ed Mattison, Smithsonian Astrophysical Observatory: Did the cesium clock have associated with it an active thermal control?

Mr. Hammesfahr: No it hadn't. All the clocks were mounted on a metal plate. The cesium clock may have had an internal temperature control. The clock was one built by FTS and what internal temperature control they did, I don't know.

Mr. Levine, Frequency and Time Systems: This is a fascinating experiment. (The rest of the comment was not decipherable.)