Programmed Oscillator Tracking Accuracy Measurements

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The programmed oscillator has previously been shown to accurately track the low doppler rates encountered in cruise phase spacecraft and planetary radar situations. To determine whether the programmed oscillator (PO) would be able to track the high doppler rates encountered with orbiting spacecraft such as Mariner Mars 1971, further tests were conducted which demonstrated that the PO does have that capability. These tests further showed that the precision of the computations within the program used to drive the oscillator is of such a degree that no significant degradation in tracking ability is contributed by them.

I. Introduction

The programmed oscillator (PO) is an electronic frequency generation system that automatically produces a changing frequency as a precalculated function of time (Ref. 1). Tests of this device had shown its suitability for high-phase-stability tracking situations. Further tests were needed, and an experiment was designed which would determine the ability of the PO to reproduce the required frequency function of time for both low and high doppler rate conditions. Ephemerides for both Mariner Mars 1971 (MM'71) and Venus planetary radar were obtained and used to drive the PO. The output of the PO was measured, recorded, and compared to the ephemeris. These comparisons indicated that the error in tracking accuracy of the PO is less than the errors introduced by the high-quality measurement system; hence, the tracking error added is zero or negligible.

II. Measurement System

The measurement system block diagram is shown in Fig. 1. The PO receives the tracking information from the ephemeris paper tape. A 5-MHz reference signal provides a coherent reference for both the PO and the counter. A 1-s tick provides synchronization for the clock internal to the PO and for the arming of the counter for measurement. A modulo-N divider divides the 1-s tick to permit the repetitive sampling of the PO signal at known intervals. The printer records the results of the measurement for later processing.

The modulo-N divider was constructed specifically for these tests, but it has general utility. Referring to Fig. 2, this device consists of four functional units. The input buffer stage determines the trigger point and polarity of the input signal to be used by the divider circuit. It also provides proper drive for the divider circuit. The divider circuit produces one output pulse for every N input pulse as set by the manual entry switches. This output signal is buffered to provide two types of output: a 'trigger' signal, which is a replica of the buffered input signal, and a 'gate' signal, which is a square wave of frequency $1/2N$ times the input frequency. When grounded, the reset signal forces the divider to the value of N, the manual set point. An output is produced N pulses after the reset line is released from ground.

Two types of tests were performed with this system. In the first, the total output of the PO was measured once a minute and averaged for 10 s. In the second type, the expanded search oscillator (SO) output was measured and averaged for 1 min every other minute. While this latter test provides several orders of magnitude improvement in resolution, it does not measure the entire PO system.

III. Analysis of the Measurement System

The resolution of a counter measurement is determined by the duration of the measurement. The counter used in these tests was a Hewlett-Packard Computing Counter Model 5360A, which has a relative accuracy (Ref. 2)

$$\frac{\Delta f}{f} = \frac{\pm 1 \times 10^{-9}}{\text{measurement time}}$$

It was not possible to use arbitrarily long measurement times because the frequency being measured has an acceleration term. The error contributed by this acceleration term is derived below.

Assume that

$$f(t) = F_0 + \dot{F}t + \frac{\ddot{F}t^2}{2}$$

represents the frequency at time t. The average frequency over a period T is then

$$\bar{f}_T = \frac{1}{T}\int_t^{t+T} f(t)dt$$

$$= F_0 + \dot{F}\left(t + \frac{T}{2}\right) + \frac{\ddot{F}}{2}\left(t^2 + tT + \frac{T^2}{3}\right)$$

The frequency at the midpoint of the period is, however,

$$f(t_m) = F_0 + \dot{F}\left(t + \frac{T}{2}\right) + \frac{\ddot{F}}{2}\left(t^2 + tT + \frac{T^2}{4}\right)$$

and the error using this as an estimate of the average frequency is

$$\epsilon = \bar{f}_T - f(t_m) = \frac{1}{24}\ddot{F}T^2$$

If both Δf and ϵ can be made small enough, it is possible to use the instantaneous value of the ephemeris at the midpoint of the measurement interval for tracking accuracy comparisons. From the MM'71 ephemeris, it was determined that the maximum acceleration would not exceed 0.072 mHz/s^2 at the PO output, and that the PO output frequency for the MM'71 tracking situation is nominally 22 MHz. Table 1 shows counter (Δf) and acceleration (ϵ) error values in mHz for these parameters as a function of sample duration. The minimum of the sum of the two error terms was used to select the near-optimum sample duration of 10 s.

With the increase in resolution of 2×10^5 for the high-resolution test, an evaluation of the errors for this test yields a Δf of less than ± 0.1 mHz and an ϵ bounded by ± 11 mHz. The latter error term prohibits the use of the midpoint comparison described above. Therefore, the process of averaging was simulated with a computer program and this new ephemeris used to provide comparison values for this high-resolution test. By comparing results of these simulations with both 0.1- and 0.01-s integration steps, it was determined that the 0.1-s step produced values of sufficient accuracy for the comparisons.

IV. Results

The tests were conducted in April 1972 using both MM'71 and Venus radar ephemerides for the overall tests, and only the Venus ephemeris for the high-resolution test. Figures 3 and 4 plot the doppler rate and acceleration error (ϵ) for Venus planetary and MM'71 targets, respectively. Table 2 lists the extremes of doppler rate and ϵ for each target. Figures 5 and 6 are plots of the tracking error (measured–predicted) for the two targets. The maximum error encountered with Venus as the target was 0.006 Hz at the PO frequency. Translated to S-band, this represents a tracking error of 0.38 Hz at 2388 MHz. The same values for MM'71 are 0.003 Hz at the PO and 0.29 Hz at 2296 MHz. These figures serve to bound the tracking error but do not measure it well because they are of the same magnitude as the errors in measurement.

The bounds indicate, however, that the PO is able to track the ephemeris.

To determine how well the PO was tracking the input ephemeris, a high-resolution test was performed, and provided an increase in resolution of 2×10^5. The results of this measurement with Venus as the target were 150×10^{-9} Hz error at the PO output frequency, or 9.6×10^{-6} Hz at S-band (2388 MHz).

V. Conclusions

The two tests described above measure two different aspects of the PO. Each of these aspects indicates the tracking accuracy from a different point of view. The overall test of the PO demonstrates that it is capable of tracking both high and low doppler rates accurately. By measuring only the SO output, the high-resolution test ignores the effects of the fixed part of the synthesizer on the total output frequency. In effect, this test measures the software's ability to control the closed-loop portion of the PO.

Taken together, the two tests show that the PO is highly capable of tracking the high doppler rates of an orbiting spacecraft such as MM'71 and that the software does not significantly contribute to the tracking error.

References

1. Winkelstein, R., "Minicomputer-Controlled Program Oscillator," in *JPL Quarterly Technical Review*, Vol. 1, No. 3, pp. 79–87, Jet Propulsion Laboratory, Pasadena, Calif., Oct. 1971.
2. *Computing Counter 5360A Training Manual*, Hewlett-Packard, pp. 35–49.

Table 1. Counter (Δf) and acceleration (ϵ) errors for various sample durations

Sample duration	Δf $\times 10^{-3}$ Hz	ϵ $\times 10^{-3}$ Hz	$\Delta f + \epsilon$ $\times 10^{-3}$ Hz
100 ms	220	3×10^{-6}	220
1 s	22	3×10^{-3}	22
10 s	2.2	0.03	2.23
100 s	0.22	3	3.22

Table 2. Extrema of doppler rate and ϵ

Target	Doppler rate $\times 10^{-3}$ Hz/s	ϵ, Hz
Venus	-6.1	-1.2×10^{-6}
MM'71	-18	-0.3×10^{-3}

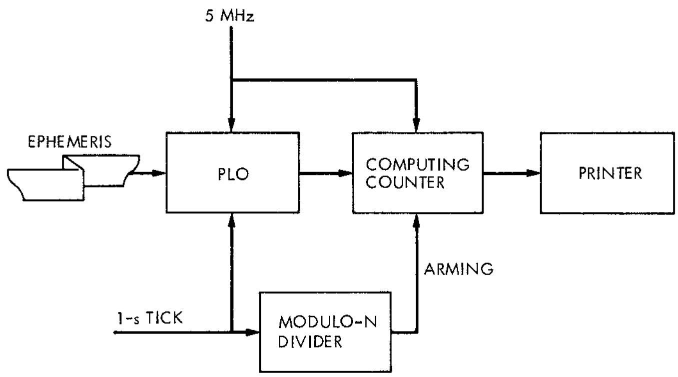

Fig. 1. Measurement setup

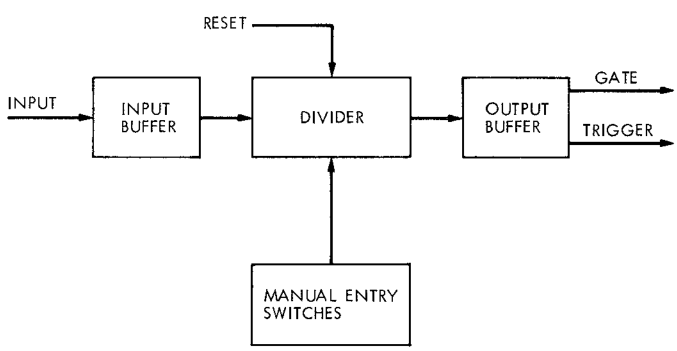

Fig. 2. Modulo-*N* divider block diagram

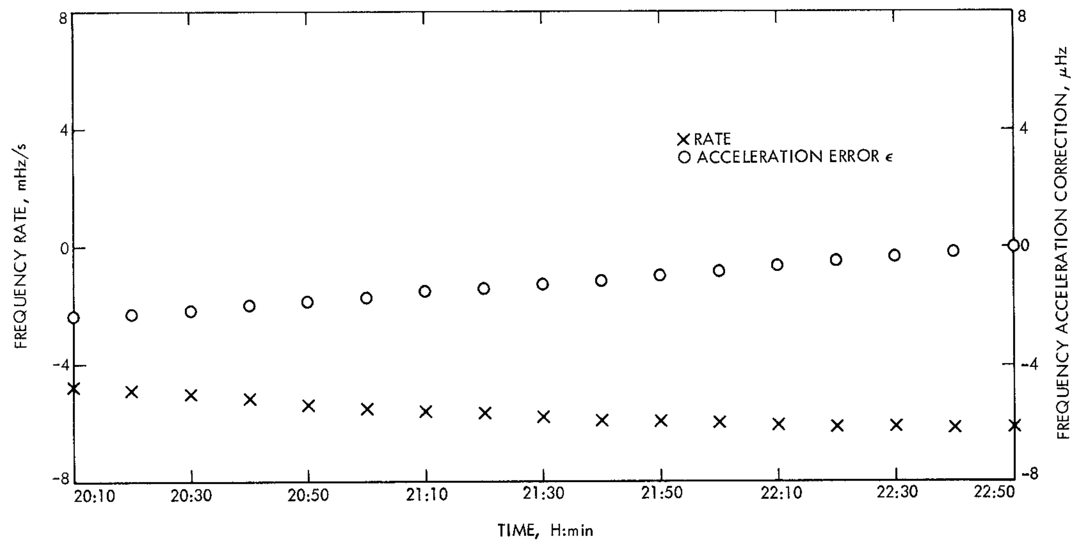

Fig. 3. Frequency functions—Venus

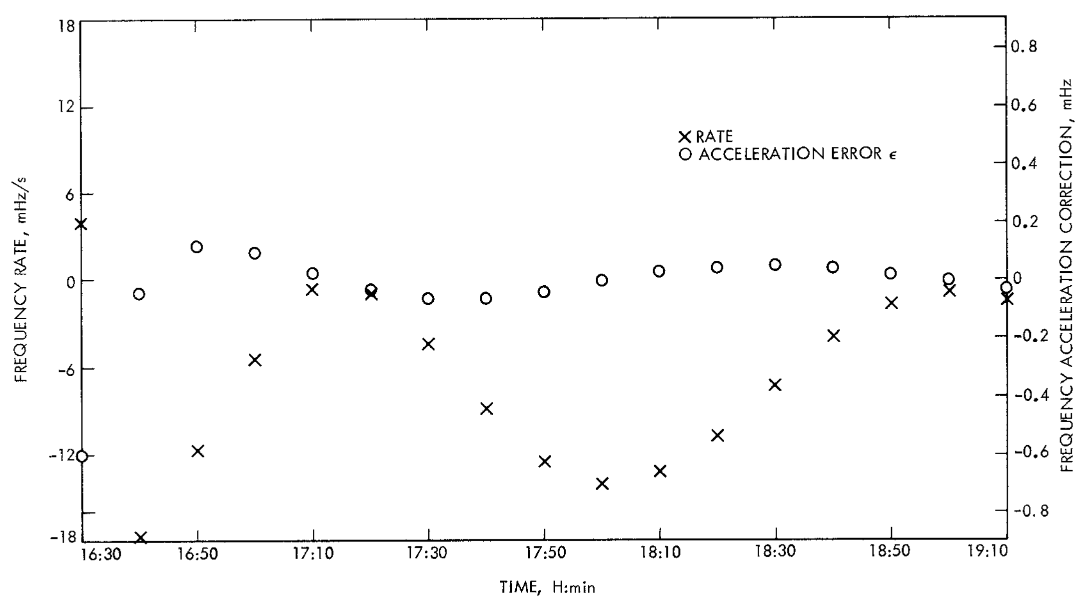

Fig. 4. Frequency functions—MM'71

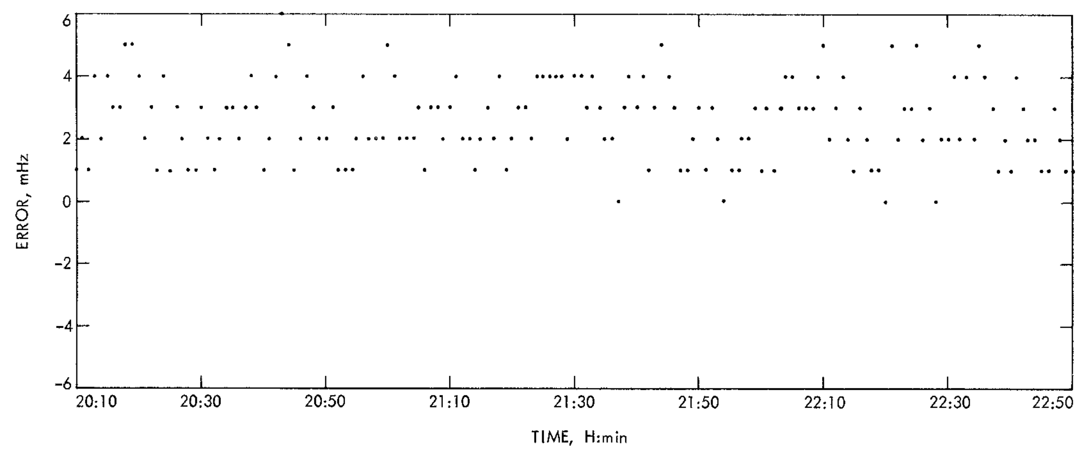

Fig. 5. PO tracking error—Venus

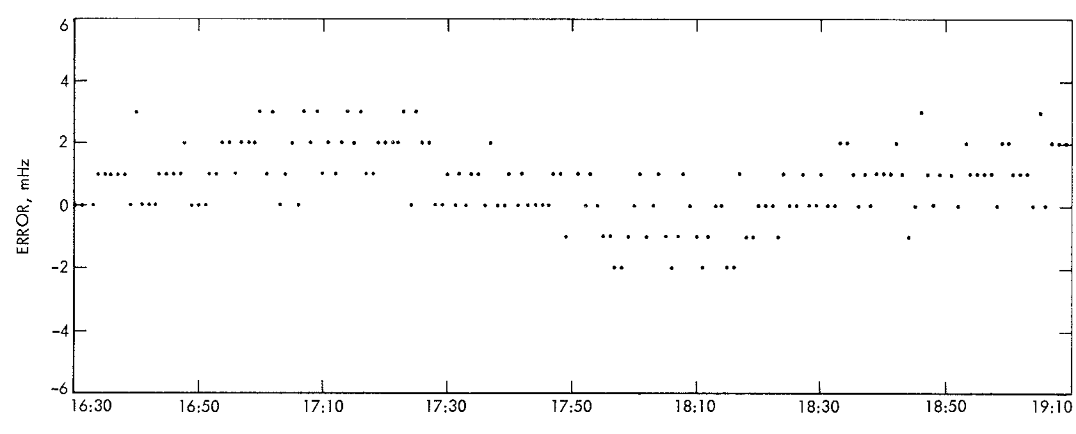

Fig. 6. PO tracking error—MM'71