

Minicomputer-Controlled Programmed Oscillator

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The programmed oscillator is a telecommunications receiver or transmitter subsystem which compensates for the known doppler frequency effect produced by the relative motion between a spacecraft and a tracking station. Two such programmed oscillators have been constructed, each using a low-cost minicomputer for the calculation and control functions, and each contained in a single rack of equipment. They are capable of operation in a phase-tracking mode as well as a frequency-tracking mode. When given an ephemeris suitable for the planet Venus, these units maintained phase coherence of better than 5 deg rms at 2388 MHz.

Introduction

A new design of the programmed oscillator has been developed and two units have been constructed and installed in the field. The programmed oscillator is an electronic frequency generation system that automatically produces a changing frequency as a precalculated function of time. This is accomplished currently by remote control of the search oscillator in a frequency synthesizer.

The programmed oscillator has been used as a receiver local oscillator subsystem for use in planetary radar (Reference 1) and to reduce the loop stress in phase-locked reception of spacecraft signals (Reference 2). As a transmitter exciter subsystem, the programmed oscillator has been used to reduce the stress in the spacecraft receiver loop (Reference 2) and to sweep the transmitter frequency in the Moon bounce time synchronization program (Reference 3).

Stimulus for this programmed oscillator development was the requirement for simultaneous coherent phase reception of signals at two Deep Space Network stations in an interferometer mode of operation. Phase stability needed for interferometric signal processing is less than 10 deg drift per minute and less than 5 deg rms phase noise at the S-band operating

frequency of 2388 MHz. Such accuracy is consistent with the development of the Hydrogen Maser Frequency Standard.

Additional objectives of the development were the utilization of a frequency synthesizer with a symmetrical search oscillator and the substitution of a minicomputer for the previously used medium-scale second-generation computer. The symmetrical search oscillator permits the midpoint of the search oscillator range to be set at any desired frequency resulting in fewer range crossovers with attendant loss of phase coherence than in the previous system which permitted ranges only at integral decade frequency points. Use of the minicomputer permits reduction of the equipment size from five racks of equipment to only one self-contained rack for the entire programmed oscillator system.

System Configuration

The programmed oscillator contains a modified commercial frequency synthesizer (Fluke 644A) controlled by a minicomputer (Lockheed MAC-16). A block diagram of the system is shown in Figure 1. At the beginning of a day's operation, station time and precalculated ephemeris polynomial constants are input to the computer. After the initial solution of the polynomial equations, the computer sets the range center frequency on the synthesizer through the decade control logic. The search oscillator range at the synthesizer output is 200 Hz. When multiplied by 64 in a receiver local oscillator chain, this range is equivalent to 12.8 kHz at an S-band frequency of 2388 MHz.¹ Frequencies within the selected 200-Hz range are obtained by controlling the search oscillator in a sampled data feedback control loop. The computer forms error numbers by differencing the desired phase calculated from the polynomial and the phase obtained from the counter. These error numbers are digitally filtered by the computer and output to the digital-to-analog (D/A) converter.

The D/A converter has 15 bits plus sign, thus accommodating a complete minicomputer word of 16 bits. An output of up to ± 10 V may be obtained from the converter with a resolution of $305 \mu\text{V}$. This voltage is fed to the integrator with a gain of 0.2155/second. The integrator has a linear output range of ± 10 V which matches the remote control specification of the synthesizer search oscillator.

The search oscillator is a voltage-controlled oscillator subassembly within the synthesizer used normally to obtain smooth but noncoherent frequency offsets from the coherent frequency selected by the synthesizer decades. For the two programmed oscillators constructed, the search oscillator subassemblies have been screened for low noise characteristics (Reference 4). In

¹ Spacecraft missions requiring larger frequency swings with phase coherence may require alternate techniques.

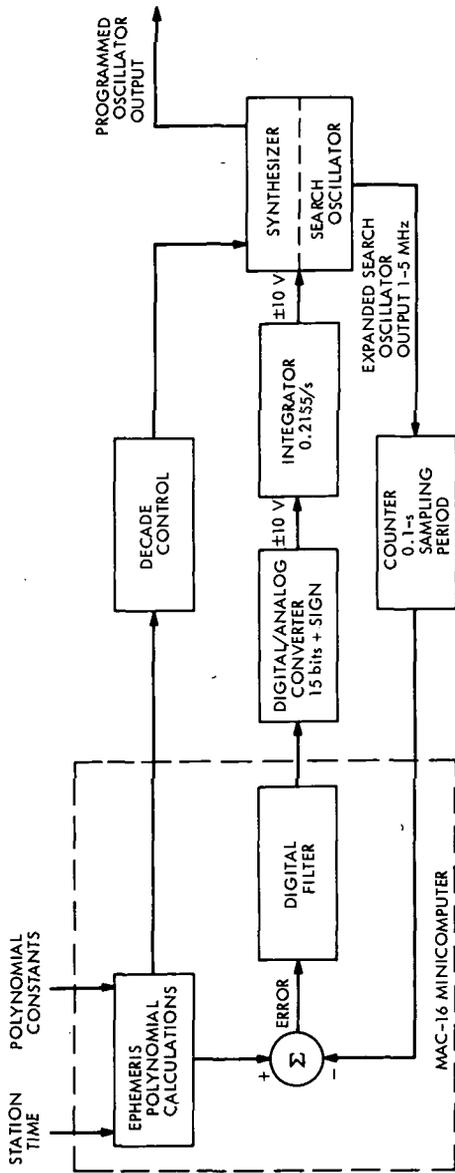


Figure 1. Programmed oscillator block diagram

addition to containing specially selected search oscillators, the synthesizers have been modified to provide a multiplied and frequency translated function of the search oscillator on a separate output connector. This expanded search oscillator output has a range from 1 to 5 MHz for the input control range of ± 10 V, and is required to obtain the resolution needed for loop operation.

A 32-bit counter counts the expanded output of the search oscillator. Counting is continuous with the counter automatically recycling to zero when a full count is reached. Every tenth second to the nearest microsecond the count is dumped into a buffer register and then input to the computer without disturbing the counting process. Two computer words are needed to hold the count information with the least significant bit of the least significant word equal to one count cycle. Each count cycle is equivalent to 1.15 deg of phase at S-band. A picture of the assembled programmed oscillator is shown in Figure 2.

Control Loop Design

Figure 3 is a mathematical representation of the search oscillator control loop. In the figure s is the Laplace complex frequency, z is equal to e^{sT} , e is the Naperian logarithmic base, and T is the sampling time of 0.1 second. Shown also are the noise sources which limit the obtainable system accuracy. N_s is the search oscillator internal phase noise, and N_c is the counter resolution noise distributed between ± 0.5 cycle at the counter output. Using the z -transform method of analysis, the open-loop transfer function G_0 is as shown in Figure 4. The digital filter equation has been chosen to cluster the poles of the closed-loop error transfer function G_c at z equal to 0.2, where (Reference 5)

$$G_c = \frac{1}{1 + G_0}$$

This cluster point represents a good compromise between the minimum transient response time which requires the poles to be clustered at z equal to 0 and the design of system response to internal noise sources which decreases as the cluster point is moved toward the unit circle.

As the gains of the loop components differ from their nominal values, the closed-loop poles will disperse from the design value of 0.2 as shown in the root locus diagram of Figure 4. Only the upper half plane is shown since the lower half plane is symmetric to the upper half plane about the real axis. K_n is an open-loop normalized gain constant which at unity places the closed-loop poles exactly at 0.2. Significant dispersion takes place for gain

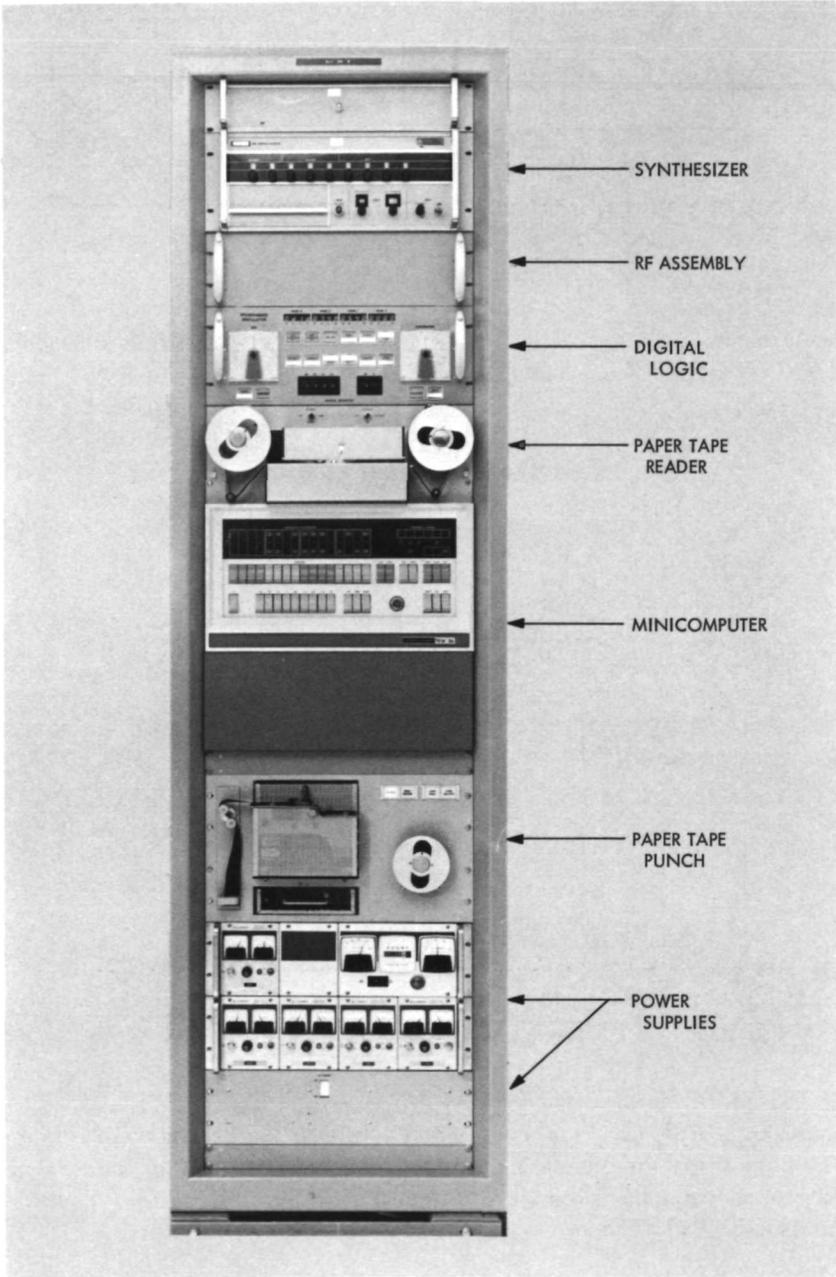
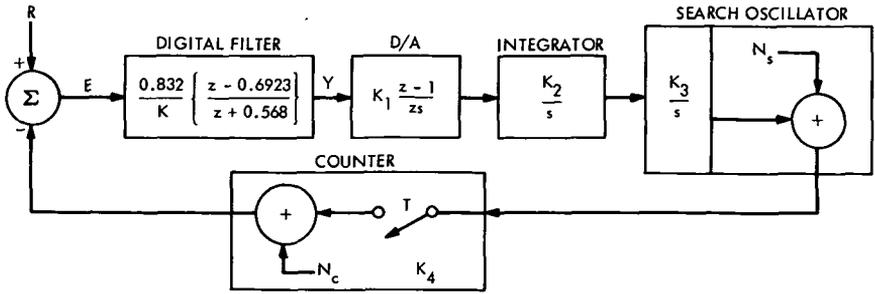


Figure 2. Programmed oscillator assembly



$$T = 0.1 \text{ second}$$

$$K_1 = 10 \div 2^{15} = 0.305 \cdot 10^{-3} \text{ volt/computer integer}$$

$$K_2 = 0.2155/\text{second}$$

$$K_3 = 4 \cdot 10^6 + 20 = 2 \cdot 10^5 \text{ cycles/volt-second}$$

$$K_4 = 1 \text{ computer integer/cycle}$$

$$K = \frac{T^2}{2} K_1 K_2 K_3 K_4 = 0.06577$$

Figure 3. Search oscillator control loop

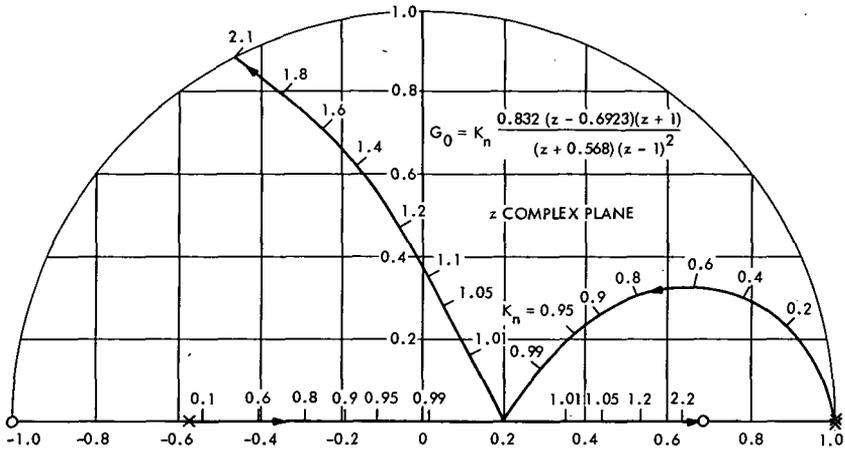


Figure 4. Closed-loop root locus

variations as little as 1% although the system is stable as long as the closed-loop poles remain within the unit circle. Tests on the operating system show that actual gains have remained within 5% of assumed values which still results in highly satisfactory operation.

Minicomputer

The MAC-16 minicomputer configuration used in the program oscillators includes a core memory of 8000 16-bit words, 7500 of which are used in the operational program. Other options included are hardware multiply/divide, direct memory access, power fail/auto restart, eight levels of priority interrupt, and a diode bootstrap loader. The peripherals used are an ASR-33

teletypewriter, a high-speed paper tape reader (300 characters per second), and a high-speed paper tape punch (60 characters per second). The reader is used to enter the program and the day's polynomial constants, and the punch is used to prepare the polynomial constant tape and for program development to meet revised requirements.

The primary function of the computer program is to compute the desired phase from the ephemeris polynomial equation versus time and using these values operate the search oscillator loop in a stable low-noise manner. The ephemeris polynomial is a 15th degree Chebyshev polynomial whose constants have been precalculated from orbit determination and curve fitting programs. Quadruple precision is used within the minicomputer to evaluate the polynomial every 32 seconds. The tenth-second phase numbers are obtained from a second-order interpolation of the frequency values obtained from the polynomial calculation. The calculation for the digital filter is determined directly from its mathematical expression in Figure 3 and is given by

$$Y_n = 12.65(E_n - 0.6923E_{n-1}) - 0.568Y_{n-1}$$

where, Y_n is the present output to the D/A converter, Y_{n-1} is the previous output, E_n is the present error number, and E_{n-1} is the previous error number.

In addition to the above functions, the program is responsible for certain initialization and auxiliary functions. At the beginning of a day's operation, the program inputs station time and date and then synchronizes the timing logic to the station second tick signal with an accuracy of $\pm 1 \mu\text{s}$. The program then reads in the correct day's ephemeris constants from a paper tape containing daily constants for the entire month. Power fail/auto restart and equipment configuration control are also program functions. During normal operation the program is responsible for operating the numeric display and for maintaining communication between the program and teletypewriter in a real-time mode. This real-time feature permits program alteration and control while the computer is actually controlling the synthesizer and is highly useful for program development and debugging.

Conclusion

Specifications of these newly constructed low phase noise programmed oscillators are outlined in Table 1. The controllability data is derived from the physical design constants, and the performance data is obtained from comparative measurements between the two units. Two columns of data are listed, one for values at the output of the synthesizer and the other for the

Table 1. Programmed oscillator specifications

Parameter	Synthesizer output	S-band \times 64
Controllability		
Output range	200 Hz	12.8 kHz
Least increment of phase control	0.018 deg	1.15 deg
Maximum rate of frequency change	21.55 Hz/s	1379 Hz/s
Performance		
Jitter	0.02 deg p-p	1.28 deg p-p
Drift	0.03 deg/min	1.92 deg/min

equivalent values at an S-band frequency of 2388 MHz when the programmed oscillator is used as a receiver local oscillator with a times 64 multiplier. The output range of 200 Hz has been selected to permit maximum resolution while avoiding a range crossover which would interrupt the coherency of phase operation. The least increment of phase control is equivalent to one count of the counter and the maximum rate of change occurs when a full 10 V is fed from the D/A converter to the integrator. The performance figures show that the phase jitter and drift are well within the design goals of 5 deg rms and 10 deg/min.

One programmed oscillator is located at DSS 14 Mars site and the other located at DSS 13 Venus site, where they are currently being successfully used in the Planetary Radar Mapping programs.

References

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