Tracking and Ground-Based Navigation: Hydrogen Maser Frequency Standard Automatic Cavity Tuning Servo

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This is the first of a series of reports describing the automatic cavity tuning servo to be incorporated in the DSN prototype hydrogen maser frequency standard. It is a first-order sample data control system, featuring stability monitoring circuits for the detection of malfunction in the maser and its receiver-frequency synthesizing system. The control system ignores error measurements exceeding an adjustable limit. The system's counter calibrates the Zeeman oscillator used to correct the maser output frequency for ambient magnetic field.

I. Introduction

The hydrogen maser output frequency is derived from an oscillation in a microwave cavity. The oscillation is sustained by energy from an atomic spin energy inversion. The microwave cavity must be tuned to the center frequency of the atomic resonance or an output frequency error will result. This error is caused by the pulling of the atomic gain profile (apparent line shape) by the cavity frequency response; therefore, the tuning error is a function of the atomic linewidth and the cavity bandwidth. The cavity tuning servo modulates the atomic linewidth and detects the resultant change in the maser output frequency to determine the cavity tuning direction for reduced pulling effect.

II. Description

Further details of the general cavity tuning technique were reported earlier (Ref. 1) and will not be included here. The block diagram, Fig. 1, illustrates the elements of the tuning control system and its relation to the maser-receiver systems. The primary function of the tuner system is to center the maser oscillator cavity frequency to within 1 part in 10^{10} of the atomic hydrogen spin resonance frequency. Other housekeeping functions included in the design are:

(1) A tracking mode in which a maser can be accurately controlled to a constant operator-set frequency offset of the tuning reference

(2) A frequency monitoring mode which outputs individual frequency error measurements (binary-coded decimal and sign)

(3) The system can be used to update the maser output frequency on a slow noninterfering basis. The minimum adjustable increment is 1 part in 10^{16} every 200 s.

(4) The tuner sequence counter can be switched to measure the output frequency of the Zeeman test oscillator.

The tuner sequence counter for the tune mode is shown in Fig. 2. An up-down counter 1 measures the difference in alternate periods of the 0.01-Hz beat between the hydrogen maser and its tuning reference oscillator at 100 MHz. These are intervals τ_1, τ_3, τ_5, τ_7 (Fig. 2). The differences are indicated in Fig. 3 by $\Delta\tau_1$, which is the difference between τ_1 and τ_3; and $\Delta\tau_2$, which is the difference between τ_5 and τ_7. Incremental frequency error is given by:

$$\frac{\Delta f}{f_0} = \frac{\Delta\tau}{\tau_0^2} \cdot \frac{1}{f_0}$$

where

$\Delta\tau << \tau_0$

$\Delta\tau$ = counter measured error increment

$\tau_0 = 100$ s

$f_0 = 100$ MHz

This results in a sensitivity of 1 part in 10^{12} for each second of measured error interval. For a counter time base of 0.001 s the minimum frequency resolution is, therefore, 1 part in 10^{-15}.

In the count sequence shown in Fig. 2, two traces during the down counts τ_3 and τ_7 represent the cases where the first count, τ_1 or τ_5, exceed the second, τ_3 or τ_7, (solid line) and the opposite error sense (dashed line). The time scales of these lines differ to simplify the drawing. This implementation allows the use of a simple comparator to sense the magnitude of the error, and makes the error available for digital display. The magnitude and sign of the last measurement error is displayed on the tuner module.

Dead times τ_2 and τ_6 are used to allow the physical system to reach equilibrium after a change in hydrogen flux level. During period "a" (Fig. 2), the error is compared to an operator-set limit. This limit reflects the stability of the reference oscillator or an error level present during initial cavity tuning. Errors below this level are entered into the summing counter 2 in the correct direction to decode the flux modulation sequence. Counter 2 is connected to a 16-bit digital-to-analog (D-A) converter which, in turn, drives the cavity tuning varactor. Errors greater than the set point provide an alarm signal and are not entered into the No. 2 counter.

The requirement for the error limiting design results from operation with long integrating times (several days) at the Goldstone DSCC. Occasional (one in five days) disturbances would cause large tuning offsets. The error comparator prevents the loss of integration time by ignoring abnormally large errors. Typical interference causes were power outages or operator changes in equipment auxiliary to the maser tuning system.

The tracking mode count sequence is shown in Fig. 3. This mode recycles the section of the tune mode sequence through the τ_2, τ_3 time intervals of Fig. 2. At the end of each error down count the counter is reset to a constant equal to the desired offset between the two frequency standards plus 100 s. The error is therefore zero when the offset between the two oscillators is 100 s minus the set point. The individual measurement errors are summed in counter 2 and control the cavity frequency as in the tuning mode. The error comparison and control is identical to the tuning mode.

The tuning mode with an adjustable initial count provides the slewing mode. The stability monitoring mode is the same as the tuning mode but without hydrogen beam modulation. No error is transferred to the tuning varactor.

Reference

1. Finnie, C., "Design of Hydrogen Maser Cavity Tuning Servo," in *The Deep Space Network Progress Report,* Technical Report 32-1526, Vol. II, pp. 86–88. Jet Propulsion Laboratory, Pasadena, Calif., April 15, 1971.
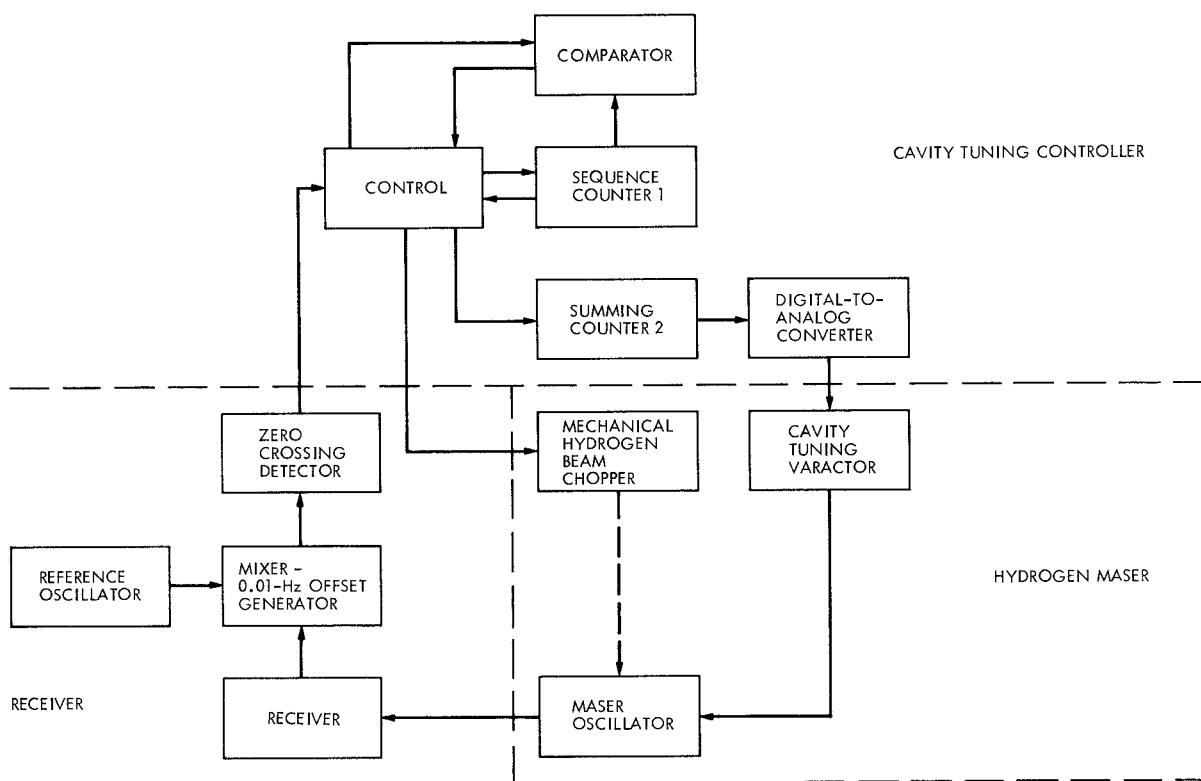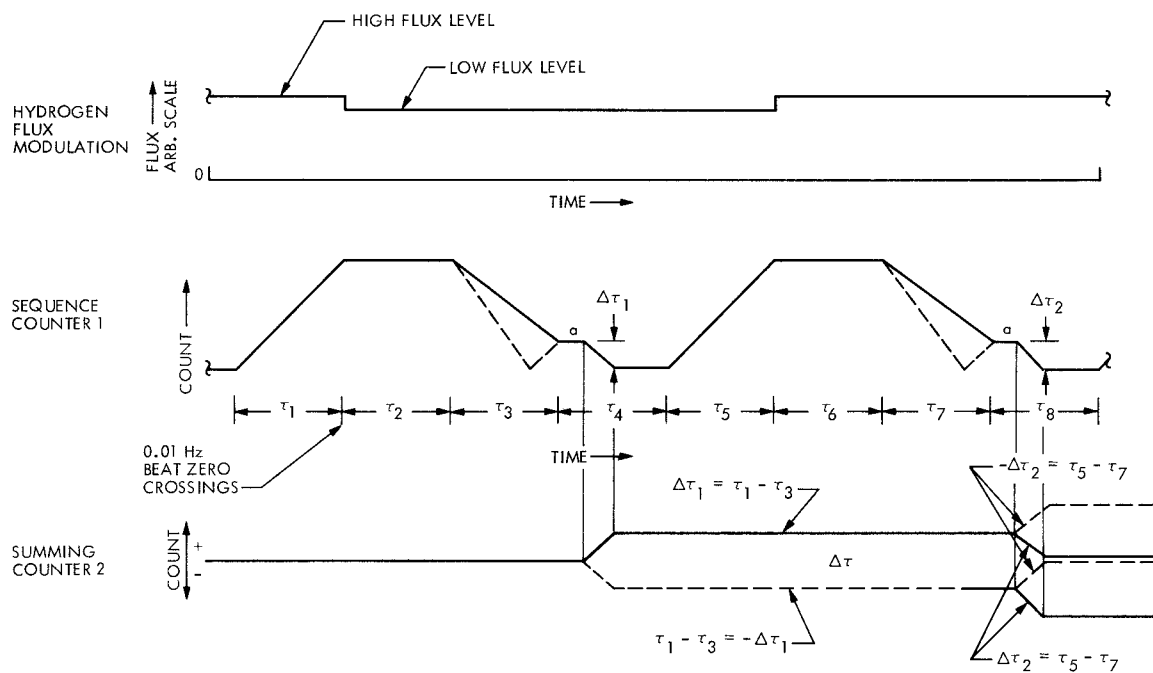
Fig. 1. Cavity tuning servo system block diagram

Within the diagram, the following labels appear:

COMPARATOR

CONTROL

SEQUENCE COUNTER 1

CAVITY TUNING CONTROLLER

SUMMING COUNTER 2

DIGITAL-TO-ANALOG CONVERTER

ZERO CROSSING DETECTOR

MECHANICAL HYDROGEN BEAM CHOPPER

CAVITY TUNING VARACTOR

HYDROGEN MASER

REFERENCE OSCILLATOR

MIXER – 0.01–Hz OFFSET GENERATOR

RECEIVER

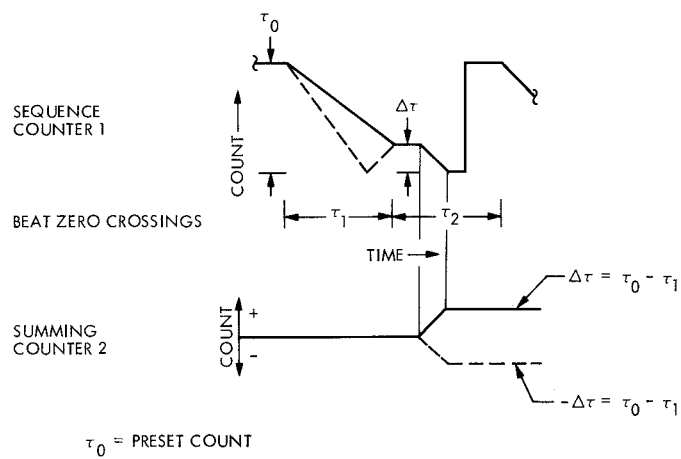RECEIVER

MASER OSCILLATOR

Fig. 2. Tuning mode count sequence diagram

Fig. 3. Tracking mode count sequence diagram