

# **Measuring Frequency Changes due to Microwave Power Variations as a Function of C-field Setting in a Rubidium Frequency Standard**

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## *Abstract*

*It has been shown in previous studies that in some cesium frequency standards there exist certain C-field settings that minimize frequency changes that are due to variations in microwave power. In order to determine whether similar results could be obtained with rubidium (Rb) frequency standards (clocks), we performed a similar study, using a completely automated measurement system, on a commercial Rb standard. From our measurements we found that changing the microwave power to the filter cell resulted in significant changes in frequency, and that the magnitude of these frequency changes at low C-field levels went to zero and decreased as the C-field was increased.*

## **Introduction**

Since the passive Rb87 gas-cell frequency standard (or clock) is the most commonly used type of atomic frequency standard, there is interest in quantifying and understanding all the factors that affect the stability of the standard's output frequency. Earlier work by Risley [1,2] identified the mechanisms whereby changes in microwave power cause changes in frequency. Risley concluded that the major cause of this frequency shift was the line inhomogeneity, which is a combination of the relatively immobile Rb87 atoms (immobilized by the use of the buffer gas in the absorption cell) and a frequency gradient across the absorption cell; this frequency gradient is in turn affected by the light-shift mechanism and the C-field. The Rb line inhomogeneity results in a frequency dependence upon changes in microwave power. The frequency changes that we measure will also include any small cavity-tuning effects that might be present as a result of any slight cavity mistuning.

## Measurements

The C-field experiment was performed in our laboratory on a commercial double-cell Rb frequency standard. This standard was modified to allow access to the C-field coil wires and the microwave power source. Figure 1 is a block diagram of the complete automated measurement system. Both of the parameters that are varied, namely the C-field current and the microwave power, are computer controlled; the current is set by a precision constant-current generator, while the microwave power is changed by using an electronic switch to change the resistance of a bias resistor on the step-recovery diode. The bias resistors were chosen to change the microwave power by +1.3, -1.1, -2.2, and -4.0 dB with reference to the nominal, factory-set power level  $P_0$ . The 6.834-GHz microwave power to the cell was sampled by coupling with a two-turn coil on the 6.834-GHz coaxial signal line. The bias resistors were chosen by using a Hewlett-Packard (H-P) model 8566 spectrum analyzer to observe the change in microwave power on this coupled signal.

The entire measurement system is controlled by an H-P series 300 computer, which also acquires and processes the data. Figure 2 is a block diagram of the frequency measurement system. The frequency reference for both the Fluke synthesizer and the H-P counter is an H-P model 5061A-004 cesium (Cs) frequency standard. A typical data-taking sequence consisted of the following steps:

1. Set the C-field current at some low value (typically 2 to 6 mA) and the microwave power at some value (e.g. at the nominal value  $P_0$ ).
2. Measure the beat frequency over some long averaging time T (typically 1000 sec).
3. Change the microwave power level [e.g. to  $(P_0 - 1.1 \text{ dB})$ ].
4. Measure the beat frequency over T again.
5. Increase the C-field current by some programmed amount (typically 0.5 mA).
6. Measure the beat frequency over T again.
7. Change the microwave power back to the initial value.
8. Repeat steps 2 through 7 until the final C-field current (typically 14 to 20 mA) is reached.

To determine the functional relationship between the C-field current and the Zeeman frequency, the microwave frequency is swept over approximately 1 MHz, centered about the main Rb resonance line. The output of the standard's dc-coupled current-to-voltage converter is then plotted as a function of frequency. Figure 3, for a C-field current of 4.5 mA, is a typical plot. This plot shows the main Rb transition state, as well as the four sigma transitions and the two pi transitions (the pi transitions are used to define the Zeeman frequency  $f_Z$ ). We should note that the 0-to-39.53-mV ordinate in Figure 3 rides on top of a  $\sim 5$  V bias, which we buck out with a precision low-noise floating voltage source. The Zeeman frequency is read from the plot in Figure 3. The measurement is then repeated for different C-field currents. For this particular standard, the Zeeman frequency is about 42.5 kHz per mA of C-field current.

Figure 4 is a plot of the signal at the absorption peak as a function of microwave power. The data, which are similar to those obtained by Risley [1], demonstrate that the manufacturer's drive-level power  $P_0$  results in a maximum signal.

## Measurement Results

Figure 5 shows the results of measurements made on the commercial Rb standard for changes in the microwave power level of +1.3, -1.1, -2.2, and -4.0 dB. Each data point, which represents the difference between two 1000-sec averages, is calculated as the difference in output frequency between the frequency at the higher power and that at the lower power, both powers being normalized to the nominal output. In other words,

$$\text{ordinate} = (\bar{f}_H - \bar{f}_L)/10 \text{ MHz}$$

where  $\bar{f}_H$  is the average output frequency for the higher microwave power and  $\bar{f}_L$  is the average output frequency for the lower microwave power. From Figure 5 we see that the maximum frequency change for the +1.3 and -1.1 dB data is about  $3 \times 10^{-11}$ , that for the -2.2 dB data is about  $6 \times 10^{-11}$ , and that for the -4.0 dB data is about  $1.4 \times 10^{-10}$ . As a function of the change in microwave power, the maximum frequency change is about  $2.6 \times 10^{-11}/\text{dB}$ .

The three curves have a similar shape, namely one that is fairly flat for Zeeman frequencies between 100 and 300 kHz, then decreasing monotonically for Zeeman frequencies between 300 and 850 kHz. In separate tests, data were obtained for the region of low Zeeman frequency. Figure 6 shows the results of those tests for the same microwave power changes as in Figure 5. From the curves in Figure 6 it is seen that there are zero crossings at about 20 and 80 kHz. The operation of the clock at one of these points would result in zero sensitivity of the clock frequency to microwave power changes and may result in improved long-term clock stability, as had been observed by De Marchi [3] in his investigations of Cs frequency standards. The manufacturer's C-field current setting for this clock was 4.5 mA, which gave a Zeeman frequency of about 191 kHz. Operating the clock at lower C-fields would also have the advantage of decreasing clock sensitivity to C-field current; i.e., a change in C-field current results in a smaller change in output frequency when the C-field current is small.

We suspect that the zero crossing at 80 kHz may be explained by the mechanisms discussed by Risley [2]. He states that this point may be interpreted in terms of (1) the opposing effect of the spacially inhomogeneous light shift and (2) the C-field gradient; the light shift produces a positive frequency shift, while the C-field gradient produces a negative frequency shift.

A comparison of the results in Figure 3 with similar results for Cs standards [3,4] shows that at the C-field setting that results in the maximum frequency change, the Rb standard is about ten times more sensitive to power changes than is the Cs standard. This result points out the need for a more stable microwave power source for Rb standards than for Cs standards. Most commercial Rb standards do not employ a microwave-power leveling circuit. This particular commercial Rb standard, however, did level the power into the final step-recovery-diode multiplier.

## Conclusions

We have presented experimental results regarding the interaction of the C-field and the microwave power on the output frequency of a commercial Rb standard. These results showed that in this particular Rb standard, the maximum frequency change due to microwave power variations was about  $2.6 \times 10^{-11}$  per dB of power change. At this C-field setting an standard deviation of 0.01 dB in the microwave power would result in an Allan standard deviation in the frequency of  $2.6 \times 10^{-13}$  from the power changes alone. This illustrates the need for a very stable microwave power source.

It was also observed that for a particular C-field setting, the frequency change goes to zero. The frequency sensitivity of this Rb standard to changes in microwave power was about ten times higher than that of a Cs standard.

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## References

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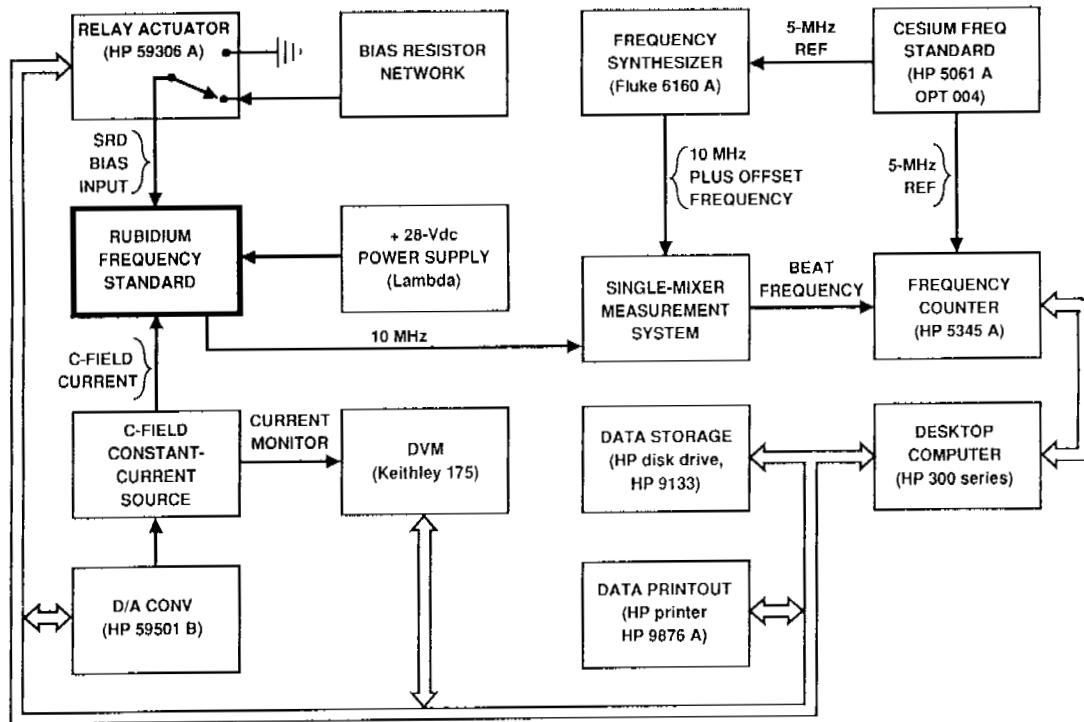


Figure 1. Block Diagram of the C-field Measurement System for a Rb Frequency Standard

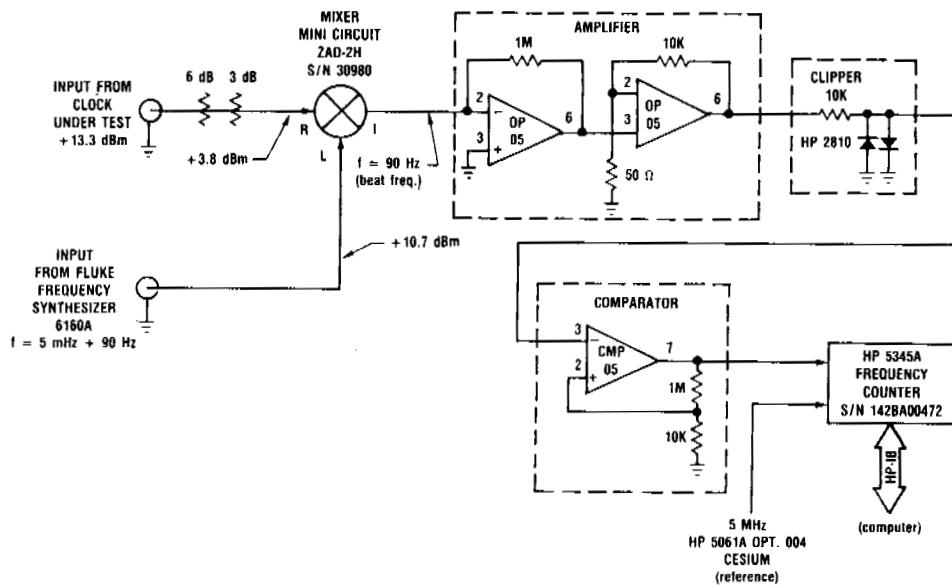


Figure 2. Circuit Diagram of the Single-Mixer Frequency-Measurement System Used to Determine the Fractional Frequency Changes at Different C-field Settings

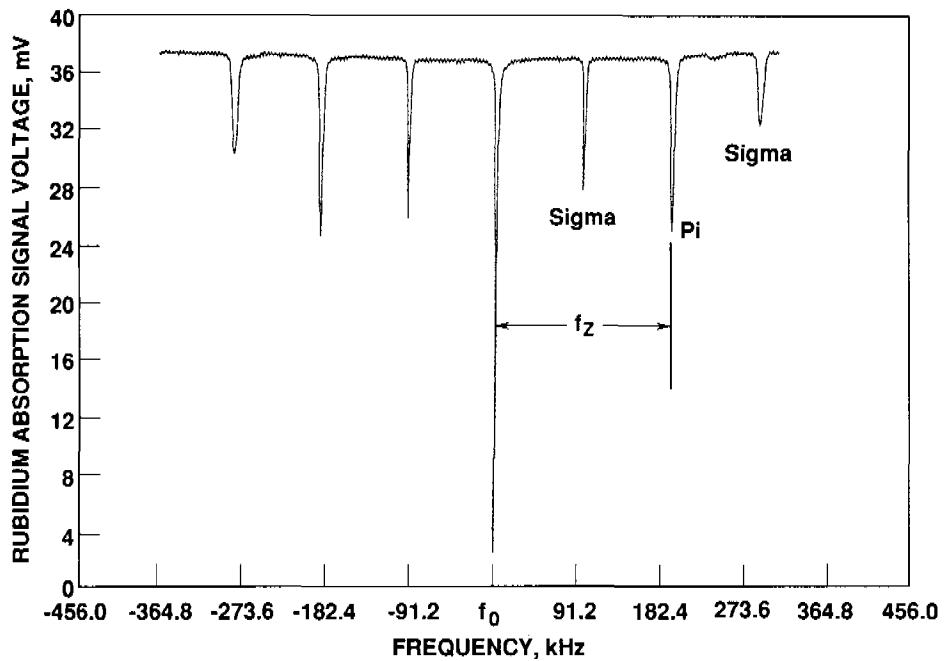


Figure 3. The CW Rb Resonance Patterns of the Seven Zeeman Transitions in a Rb Frequency Standard

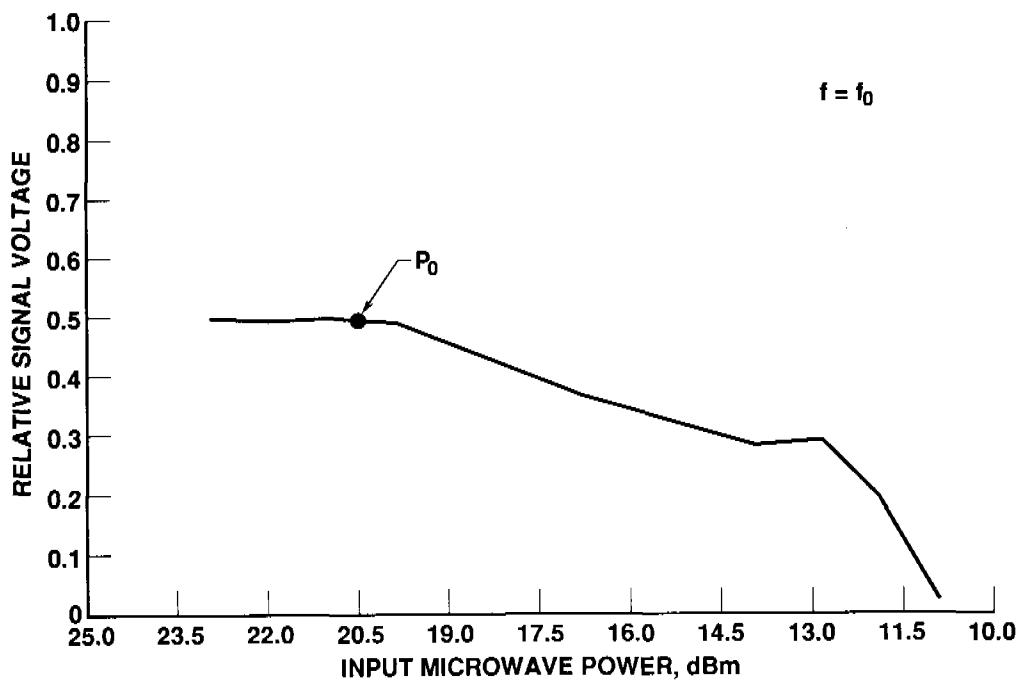


Figure 4. Plot of the Rb Resonance Signal Voltage vs. the Input Microwave Power of the Rb Frequency Standard with the Standard Tuned to  $f_0$

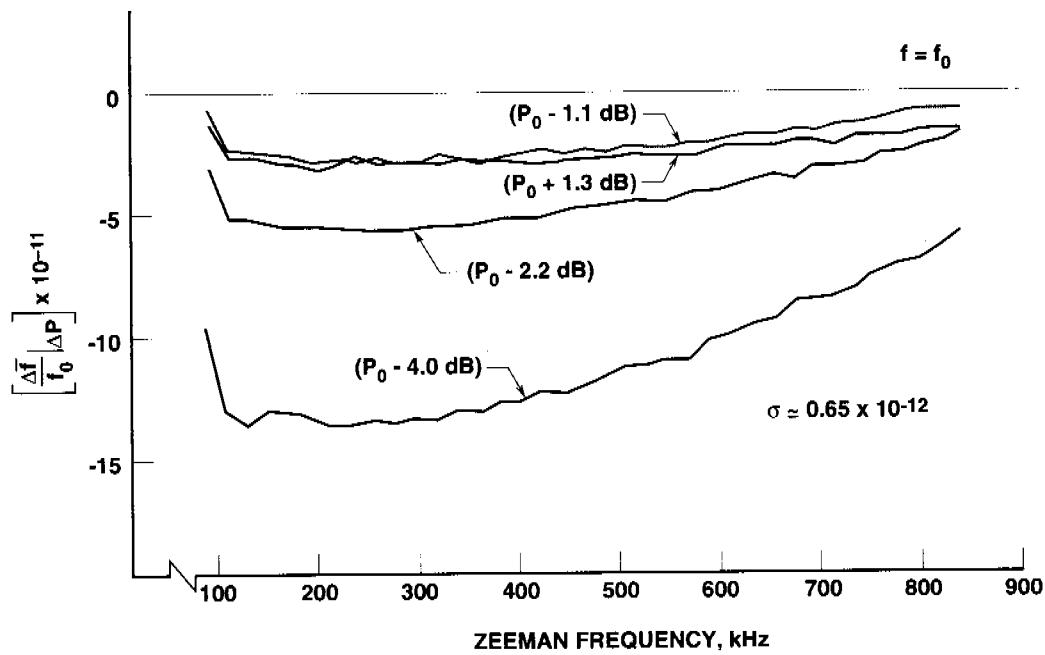


Figure 5. Average of the Final Data on the Rb Frequency Standard, Showing the Difference of the Average Frequencies as a Function of C-field for Microwave Power Changes of +1.3, -1.1, -2.2, and -4.0 dB with Respect to the Nominal Power Level  $P_0$

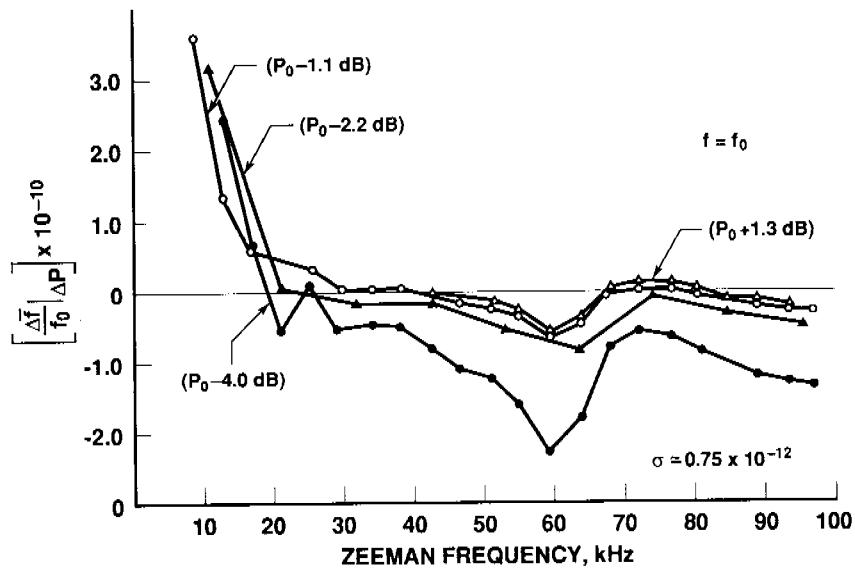


Figure 6. Plot of the Difference of the Average Frequencies of the Rb Standard as a Function of Low C-field for Microwave Power Changes of +1.3, -1.1, -2.2, and -4.0 dB with Respect to the Nominal Power Level  $P_0$