A Portable Cold ^{87}Rb Atomic Clock with Frequency Instability at One Day in the 10^{-15} Range

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Abstract—We present a small portable cold ^{87}Rubidium atomic clock with frequency uncertainty of less than 3×10^{-15} in one day of averaging time. The clock is under development at SpectraDynamics for the Defense Advanced Research Projects Agency (DARPA) Portable Microwave Cold Atomic Clock Small Business Innovation Research (SBIR) effort. The portable clock is about the size of a desktop computer (22x37x32 cm) and weighs 28kg.

Keywords—laser-cooled atomic clock, atomic clock, Rb clock

I. INTRODUCTION

We present a small, portable, laser-cooled ^{87}Rb atomic clock with frequency uncertainty of less than 3×10^{-15} in one day of averaging time. The clock is under development at SpectraDynamics for the Defense Advanced Research Projects Agency (DARPA) Portable Microwave Cold Atomic Clock Small Business Innovation Research (SBIR) effort. The portable clock is about the size of a desktop computer (22x37x32 cm) and weighs 28kg. If we compare to a commercial Cs beam clock with the high-performance option, we note that the volume of our clock is nearly identical, with the Cs clock being 29.74l and our Rb clock having a volume of 26l. The mass of both clocks is also very similar with the Cs clock being 30kg compared to the Rb clock at 28kg. The one-day instability of the Rb clock is about a factor of 10 smaller than a high-stability commercial Cs beam clock.

This clock is intended to be a product and is targeted for release into both defense and commercial markets. The prototype clock has outputs at 1 pulse-per-second, 5 MHz, 10 MHz and 100 MHz.

II. THE CLOCK

The clock uses ^{87}Rb atoms which are trapped and cooled using a compact 780nm laser system. Following state preparation, the light is extinguished and the atoms enter a microwave cavity where they undergo microwave interrogation. After the microwave interrogation sequence, the

Figure 1 – *Prototype of the portable cold Rb87 atomic clock. The clock is packaged in a 22 X 37 X 32 cm enclosure and weighs about 28 kg. The signal and power connections are on the rear panel of the instrument.*

fraction of atoms that made the clock transition is counted. This signal is then used to control the frequency output of the clock. The complete clock-cycle is shown in *Figure 2* and the clock block diagram is depicted in *Figure 3*.

The clock, which has been operational for about one year, typically operates continuously unless deliberately interfered
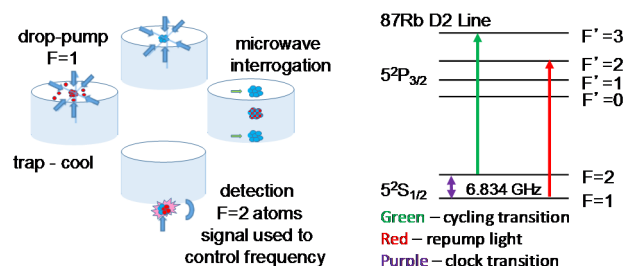

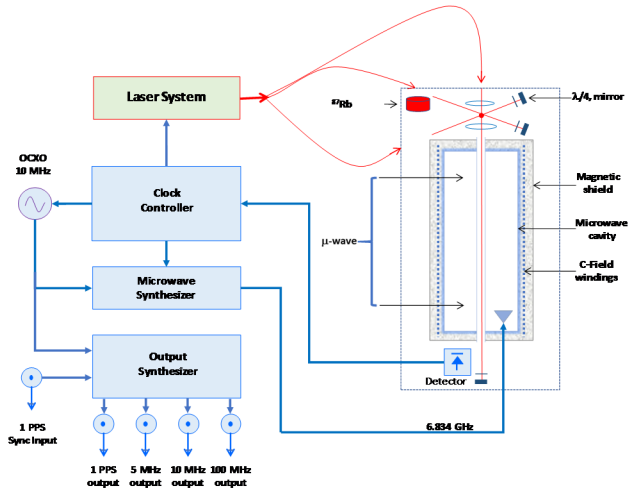Figure 2 – *The clock cycle and the 87Rb D2 line transitions used for the clock.*

Figure 3 – *Block diagram of the portable cold Rb87 atomic clock illustrating all major subsystems.*

Figure 5 – *Total Allan Deviation of the cold Rb clock as measured against UTC(NIST) [5]. No drift has been removed. The 1 s data is shown in Red, while the 60 s data is shown in Blue. The last two points in Blue come from the Theo1 statistic.*

with by an operator. The clock has operated in excess of 100 days with no interference. The 100 day-long run was stopped by the operators to investigate other aspects of clock operation.

III. MEASUREMENT SETUP

The prototype clock has been compared to the time-scale UTC(NIST) for extended periods, allowing characterization of both the short-term stability $(\sigma_y(\tau) < 8 \times 10^{-13}/\sqrt{\tau})$, and the long-term behavior of the clock [5]. The comparison is made between the clock's 5 MHz output and UTC(NIST) using the same measurement system which collects the clock data for the generation of UTC(NIST) [1,2,3]. During the same period of time, a second 5 MHz output of the clock is compared to a high-stability Hydrogen maser [4]. The measurement was configured to sample at 1 Hz allowing a characterization of the very short-term performance of the clock.
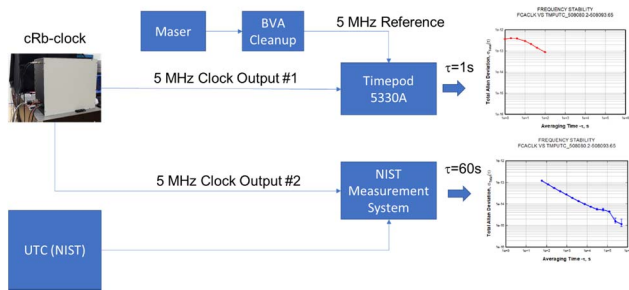

Figure 4 – *Clock measurement system configuration.*

IV. MEASUREMENT RESULTS

As shown below in *Figure 5*, the short-term performance of the clock, from $\tau = 1\ s$ out to $\tau \cong 10,000\ s$, is characterized by an Allan Deviation [5] of $\sigma_y(\tau) \cong 8 \times \frac{10^{-13}}{\sqrt{\tau}}$. The short-term performance can be improved further at the cost of a more
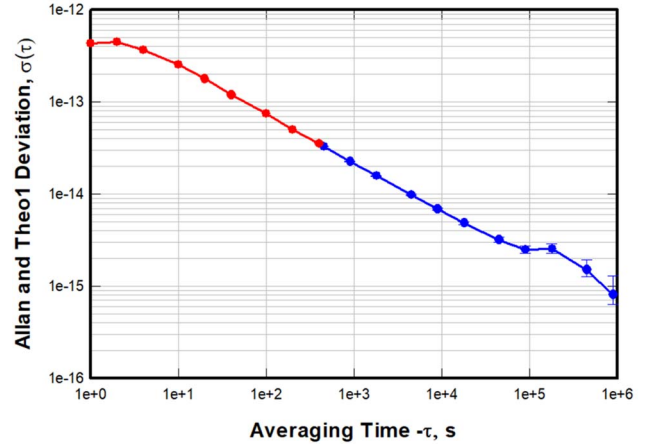
expensive local oscillator, but, even at this level, the clock should be able to reach a frequency uncertainty of less than 3×10^{-15} in one day of averaging. The long-term frequency instability is more complicated, in general, the Total Allan Deviation [6] plot shows a characteristic flattening of the previous $1/\sqrt{\tau}$ slope starting at around a day and persisting out to slightly longer than two days. The clock begins to improve with further averaging at that point. This behavior is illustrated in *Figure 5*.

Another way of comparing the cold-Rb clock is to look at other clocks in the UTC (NIST) timescale over the same measurement period. In *Figure 6* we show the frequency fluctuations of several clocks as measured by the NIST measurement system. Plotted in Figure 6, in Green is a very low drift maser, while a more typical maser is shown in Red. The cold-Rb clock is shown in Dark Blue, while a commercial high-performance Cs beam clock is shown in Light Blue (Cyan).
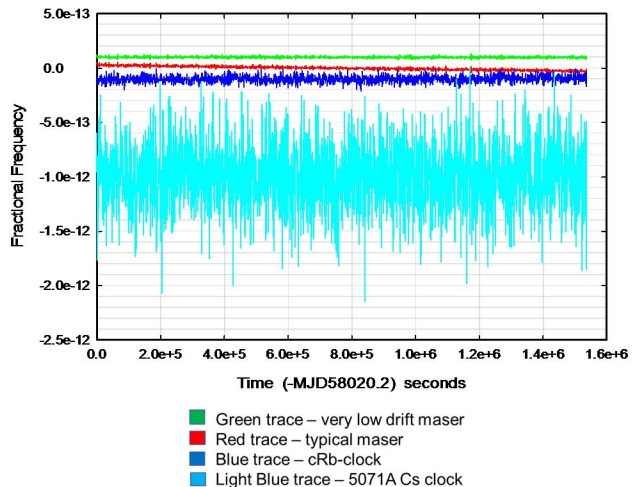

Green trace – very low drift maser
Red trace – typical maser
Blue trace – cRb-clock
Light Blue trace – 5071A Cs clock

Figure 6 – *Several clocks measured simultaneously by the NIST measurement system [5].*

Several things are readily apparent: first, the frequency fluctuations of the cold-Rb clock are much smaller than those of the commercial Cs clock albeit, not as small as the frequency fluctuations in a good hydrogen maser. Second, comparing the Blue curve to the Red curve, it is apparent that the drift in the cold-Rb clock is much smaller than the drift in a typical maser. In fact, the residual drift in the cold Rb clock is about 1×10^{-17}/day, consistent with no drift. All of the clocks shown in *Figure 6* have had arbitrary frequency offsets added to separate the curves for illustration purposes.

In *Figure 7* we show the Allan deviation of several active Hydrogen masers as measured by the NIST measurement system. The Allan deviation of the cold-Rb clock, shown in Blue, indicates better clock performance than all of the five masers for average times greater than 6 days.
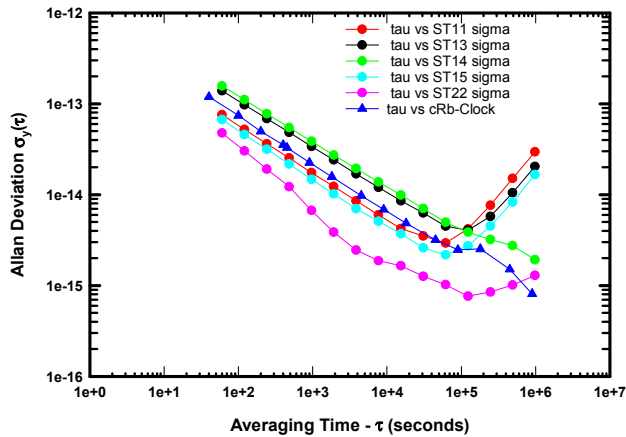

Figure 7 – *Several active Hydrogen masers measured by the NIST measurement system. In the long term the cold-Rb clock outperforms all of these masers.*

V. CONCLUSIONS

We present a new class of portable atomic clock with short-term frequency instability from 1 to 10,000 s, characterized by $\sigma_y(\tau) \cong 8 \times \frac{10^{-13}}{\sqrt{\tau}}$, and a long-term frequency instability of less than 9×10^{-16}. The frequency drift of the clock is less than 1×10^{-17}/day.

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