Long-term frequency instability of a portable cold 87Rb atomic clock

F. G. Ascarrunz, Y. O. Dudin, Maria. C. Delgado Aramburo, *SpectraDynamics, Inc*
J.Savory, S. R. Jefferts, *NIST Time and Frequency Division*

ABSTRACT

This paper presents measurements of the long-term frequency stability of a cold Rubidium 87 atomic clock that is under development at SpectraDynamics for the Defense Advanced Research Projects Agency (DARPA) Portable Microwave Cold Atomic Clock Small Business Innovative Research (SBIR) effort. The clock output at 5 MHz has been compared with the UTC (NIST) timescale over a period of several weeks. Analysis of the sources of frequency instability is presented. The portable clock is about the size of a desktop computer (22x37x32 cm) and weighs 28kg.

INTRODUCTION

SpectraDynamics, Inc has been developing a small portable cold atom clock for the DARPA Portable Microwave Cold Atomic Clock Project. This product is targeted for release into both defense and commercial markets. The prototype clock has outputs at 5 MHz, 10 MHz and 100 MHz. The clock uses ^{87}Rb atoms, which are trapped, cooled, and pumped into the F=1 hyperfine ground state 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.

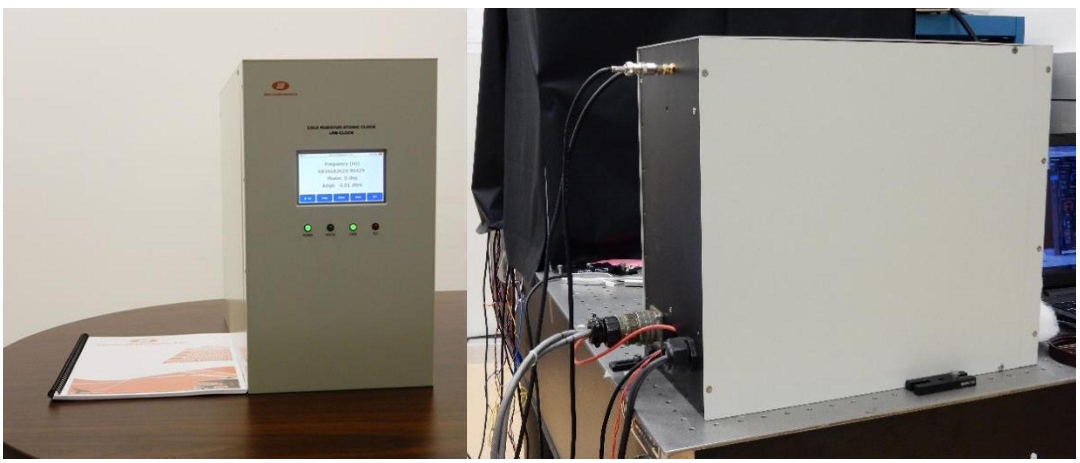

Figure 1 *– Prototype of the portable cold* ^{87}Rb *atomic clock. The clock is packaged in a 22 x 37 x 32 cm enclosure and weighs about 28 kg. The signal and power connections are on the rear panel of the instrument.*

After the microwave interrogation sequence, the fraction of atoms that made the clock transition to the upper F=2 ground state is counted. This signal is then used to control the frequency output of the clock. The complete clock is shown in ***Figure 1***. The clock, which has been operational for about one year, typically operates continuously unless deliberately interfered with by an operator. The clock has operated in excess of 100 days with no interference. This 100 day-long run was stopped by the operators to investigate other aspects of clock operation.

METHOD

The clock's 5 MHz output has been compared to UTC (NIST) [1] using the same measurement system [2,3] which collects the clock data for the generation of UTC (NIST). The phase of the clock is sampled once every 60s. Data was taken from MJD

Proceedings of the 2018 Precise Time and Time Interval Meeting,
ION PTTI 2018, Reston, Virginia, January 29-February 1, 2018

58080 to MJD 58093. During the same period of time, a second 5 MHz output of the clock was compared to a Microsemi maser [4] using a second measurement system. This measurement was configured to sample at 1 Hz, allowing a characterization of the short-term performance of the clock.

RESULTS

As shown below in ***Figure 2***, the short-term performance of the clock, from $\tau = 1s$ out to $\tau \cong 10{,}000s$, 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.

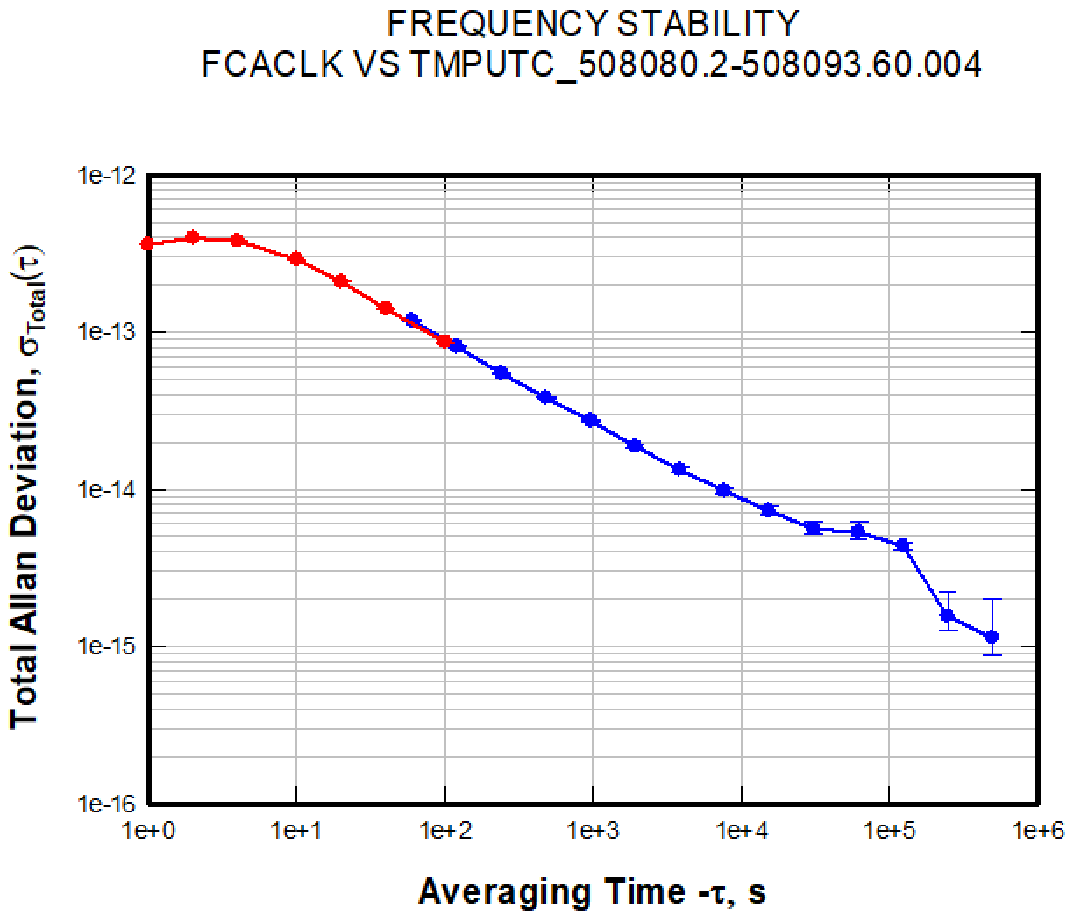

Figure 2 *– Total Allan Deviation of the cold Rb clock as measured against UTC(NIST). No drift has been removed. The 1 s data is shown in Red, while the 60 s data is shown in Blue. The noise between ½ and 2 days is under investigation.*

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 ½ day and persisting out to slightly longer than a day. The clock begins to improve with further averaging at that point. This behavior is illustrated in ***Figure 2***. 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 3***, we show the frequency of several clocks as measured in the NIST measurement system. 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). 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 3*** have had arbitrary frequency offsets added to separate the curves for illustration purposes.

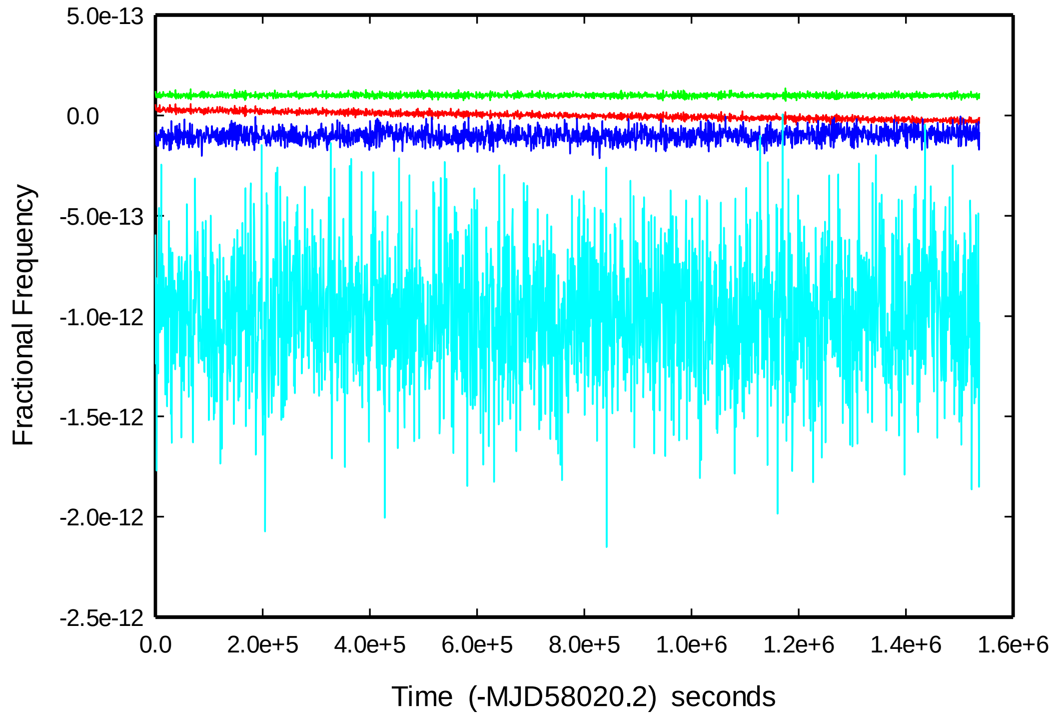

Figure 3 *– Several clocks measured simultaneously by the NIST measurement system. The cold-Rb clock performance is shown in Dark Blue, while a typical high-performance Cs beam clock is shown in Light Blue. The figure also shows two masers, one (in Green) with exceptionally small frequency drift, and one (in Red) with a more typical drift of about* $\frac{\delta f}{f} \approx 3 \times 10^{-15}/day$*. The measured drift in the cold-Rb clock over this period is about* $1 \times 10^{-17}/day$*.*

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 2×10^{-15}. The frequency drift of the clock is less than 1×10^{-17}/day.

ACKNOWLEDGMENTS

The authors thank Dr. Robert Lutwak for his support of the project and his invaluable advice. This work was funded in part by the Defense Advanced Research Projects Agency under contract HR0011-15-9-0007.

DISTRIBUTION STATEMENT

REFERENCES

1. Judah Levine, Invited review article: The statistical modeling of atomic clocks and the design of time scales. Review of Scientific Instruments, 83(2):021101, 2012.

2. S. Römisch, S. R Jefferts, and T. E. Parker, “A digital time scale at the National Institute for Standards and Technology,” in General Assembly and Scientific Symposium, 2011 XXXth URSI (IEEE, 2011), pp. 1–4.

3. S. Stein, D. Glaze, J. Gray, D. Hilliard, D. Howe, and L. A. Erb, 1983, “Automated high accuracy phase measurement system, ” IEEE Transactions on Instrumentation and Measurement 32, 227-231.

4. H. E. Peters and H. B. Owings, “Hydrogen maser improvements and future applications," in Proc. IEEE Int. Freq. Contr. Symp., 997, pp. 280-285.

5. D.W. Allan, "Statistics of Atomic Frequency Standards", Proc. IEEE, Vol. 54, pp. 221- 230, Feb. 1966.

6. D.A. Howe, "An Extension of the Allan Variance with Increased Confidence at Long Term," Proc. 1995 IEEE Int. Freq. Cont. Symp., pp. 321-329, June 1995.