A Laser-Cooled Frequency Standard for GPS

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BIOGRAPHY

Thomas P. Heavner is a physicist at NIST in the Atomic Standards Group and works on NIST-F1, the primary Cesium frequency standard for the U.S. government. He earned a B.S. in physics from the University of Virginia in 1989. Tom's Ph.D. work was performed at the University of Colorado/JILA in Boulder, CO and involved precision mass measurements of single Li ions using a Penning Trap apparatus. Upon completion of his Ph.D. in 1998, Tom was a NRC postdoctoral fellow in the Time and Frequency Division at NIST in Boulder, Colorado

Stephan Barlow received his PhD in Chemical Physics from the University of Colorado at Boulder in 1984. Since that time he has worked on the design and construction of various scientific instruments and devices, mostly at the Pacific Northwest National Laboratory in Richland, WA. Between 2007 and 2009 Dr. Barlow was at the Dugway Proving Ground where he conducted chemical and facilities tests and evaluations for the US Army. Dr. Barlow joined the NIST cold atom clock team in early January 2011.

Marc A. Weiss has worked at the National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards, NBS) in Boulder Colorado since 1978. He wrote the firmware for the NBS/GPS Time Transfer System for which he received the Applied Research Award of the NBS in 1983, along with the other principals. Dr. Weiss has been active in studying and developing time transfer systems especially using the Global Positioning System, for applications such as the generation of International Atomic Time. He also has led the NIST contract with the GPS program office for support of their clocks and timing systems. Marc Weiss received his B.S. degree from Valparaiso University, Valparaiso, Indiana in 1973. He received his M.S. degree in Mathematics in 1975, and his Ph.D. in Mathematical-Physics in 1981, both from the University of Colorado, Boulder, Colorado.

Neil Ashby received a B.A. degree from the University of Colorado in 1955 and a Ph. D. from Harvard University in 1961. He then spent a year in Europe as a Frederick Sheldon Postdoctoral Fellow at the Ecole Normale Superieure in Paris and at Birmingham University in the UK. He served on the Faculty in the Dept. of Physics, University of Colorado at Boulder from 1962 to 2003 and currently is an Affiliate of the National Institute of Standards and Technology in Boulder, CO where he works on relativistic effects and noise in clocks, time scales, and navigation. He has served on several international committees and working groups relating to relativistic effects on clocks with applications to timekeeping, geodesy, and navigation, and has contributed numerous studies of relativistic effects in the Global Navigation Satellite Systems such as the GPS. He has received several service awards from the University of Colorado including the University of Colorado Alumni Foundation Norlin Medal, May 2005. In January 2006 he received the F. K. Richtmyer Award of the American Association of Physics Teachers.

Steven R. Jefferts (M'01) received a B.S. degree in Physics from the University of Washington in Seattle in 1984 and a PhD in atomic physics/precision metrology from JILA/University of Colorado in Boulder in 1992. His thesis work involved ultra-high-precision mass spectroscopy of light ions. He then went "across the street" to NIST as an NRC postdoctoral fellow working with Dave Wineland on laser-cooled trapped ions. In 1994 he joined the Time and Frequency division of NIST as a permanent employee. Dr Jefferts leads the research group developing and operating cesium fountain primary frequency standards. Dr Jefferts received the Edward Uhler Condon award in 2001, a Department of Commerce Gold metal in 2004 and the Arthur S. Flemming award in 2005. He was also the IEEE-UFFC distinguished lecturer for 2003-2004.

ABSTRACT

Our group at the National Institute of Standards and Technology (NIST) is in the initial phase of developing a prototype laser-cooled atomic frequency standard (AFS) for potential use in a future global positioning system (GPS) system. The expected fractional frequency stability or Allan deviation, $\sigma_y(\tau)$, will be 2×10^{-13} at one

second, improving as the square-root of the averaging time to 7 × 10^{-16} at one day. This corresponds to an expected time dispersion of 0.060 ns at one day, or 0.02 m of user range error (URE). We discuss the design and development process underway at NIST, as well as capabilities enabled by this AFS in GPS.

INTRODUCTION

Laser-cooled atomic frequency standards are presently used by many national timing laboratories throughout the world including NIST in Boulder, CO. NIST-F1, a laser-cooled cesium fountain primary standard, is used to realize the SI (International System) second and has a fractional frequency inaccuracy of 4 × 10^{-16} [1]. A primary standard such as NIST-F1 has no frequency drift. Laser cooling is a technique in which atoms interact with the electromagnetic field from a laser beam in such a way that the atoms are essentially "frozen" in space [2]. Laser-cooled cesium atoms in NIST-F1 have a temperature of < 1 μK. Transitions in atoms at such low temperatures can have very narrow linewidths. In NIST-F1, the Ramsey Time (the period during which the atomic transition is probed) is on the order of 1 s, about 10^2 times longer than a long thermal beam standard, and yields an atomic line quality factor (Q) of $\approx 10^{10}$. The line Q is a basic figure of merit for atomic frequency standards. The 1997 Nobel prize in physics was shared by researchers from NIST, Stanford University, and École Normale Supérieure, Paris, France for their work in developing laser-cooling techniques and the underlying theory.

While this method has been used in laboratories throughout the world, it has not yet been built into a commercial atomic frequency standard. A decade ago the laser sources required to laser-cool atoms were custom made, expensive, large and power-hungry. In the last few years, a new generation of diode laser devices has arrived on the market. These show promise for building small, low-power, space-based laser-cooling platforms. NIST is researching the feasibility of this approach.

The NIST laser-cooled GPS frequency standard design is a beam tube, similar to previous GPS cesium beam-tube AFS (CAFS). However, the use of laser-cooling lowers the temperature of the atoms to ≈ 1 μK, instead of the previous 400 K temperatures of the CAFS. The beam-tube design has the potential to make the standard more consistent in performance than the cell-design in the current Rb AFS (RAFS). In particular, the beam-tube should have no systematic linear frequency drift. The line-width for detection will be about 3 Hz, compared to the 400 Hz line-width in the traditional CAFS. The narrow line-width allows the standard to be more stable and much less environmentally sensitive, thus eliminating the effect of the clock's "personality" from the GPS error budget.

This AFS would enable advanced signal integrity assurance, provide an improved signal-in-space (SIS), and potentially address problems of supply from the U.S. industrial base for space-qualified AFSs.

The industrial base for clocks capable of supporting GPS can be considered fragile. The problem is that while GPS requires an AFS on each satellite, many other systems can get time and frequency from GPS, hence do not require an AFS. Thus, GPS is one of the only users of space-based AFSs, and GPS buys only about 100 clocks every 10 years. Few businesses can keep the special expertise required to produce space AFS with that small of a volume. There is some possibility that a laser-cooled clock could be manufactured more simply and reliably than the current Rubidium AFS design. Also, the cold-atom technology might be used in other developing technologies. These factors might make the cold-atom clock easier to manufacture.

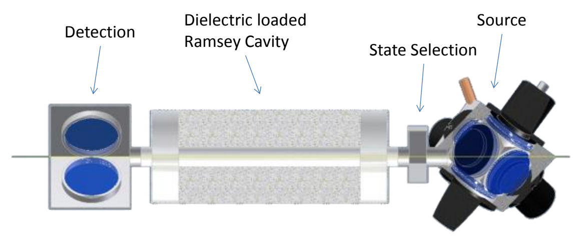

Figure 1. A sectional view of the proposed NIST GPS clock physics package.

This paper discusses our plans and progress towards incorporating the technology used in laser-cooled primary standards into a suitably sized package that can be commercially developed for use in GPS. Also, our work addresses issues of manufacturability, device lifetime, and shelf life.

The discussion of our GPS frequency standard will focus on the following subsystems: a laser and optics package, a physics package (including the laser-cooling chamber and microwave cavities), the microwave synthesizer, and the control system. Figure 1 is a diagram of the proposed physics package. Shown here is the laser cooling source chamber with fiber-optic cable output collimators, the microwave interrogation (Ramsey) region, and the atom detection region.

LASERS AND OPTICS

A main enabler behind this project is the recent availability of commercial diode laser systems that have the capability to support a laser-cooled GPS clock. Generally, a laser system with a sufficiently narrow linewidth and enough power for a laser-cooled frequency standard are too large and use too much power to be useful on space-based platforms. However, recently available DFB and DBR laser diodes have narrow linewidths (<1 MHz) and can generate ≈ 200 mW of power. The laser diodes we have obtained for this program are packaged in small cans containing the diode and a thermoelectric cooler (TEC). In later stages of this program, we will develop a complete package system for the diode laser including the necessary collimation and shaping optics, optical isolation, etc.

In addition to the raw laser sources, laser-cooling requires accurate and fast frequency shifting of various beams for the optical molasses, launching of the atoms, and detection. Typically, four to six acoustic-optic modulators (AOM) are needed in a system. However, each AOM requires several watts of RF power and the amplifiers are typically not very efficient. This approach is not suitable for a GPS frequency standard.

We have proposed and begun bench tests of a scheme to frequency-shift the laser beams by use of fiber-optic cable stretchers. A beam traveling through a fiber optic cable that is being stretched is Doppler- or frequency-shifted.

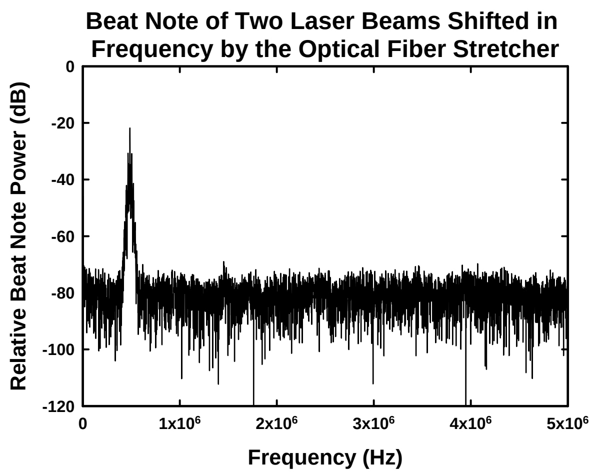

Figure 2. The measured beat note between two laser beams frequency-shifted by use of fiber-optic cable stretchers.

We are using commercially available stretcher systems to perform these preliminary tests. The units have a length of polarization-maintaining (PM) fiber wound on a bobbin fitted with a piezoelectric driven mechanical assembly that flexes the bobbin. By sending laser light through two stretcher assemblies and combining the two beams on a fast photodiode to generate a beat note, we are able to measure the frequency shifts imparted by the stretchers. Figure 2 shows preliminary results from these experiments. We are now experimenting with the time-varying voltages applied to the piezoelectric in order to optimize the frequency shift, and are exploring closed-loop control of the stretcher system.

PHYSICS PACKAGE

In NIST-F1 we use commercial ultra-high vacuum (UHV) components to construct the laser cooling chamber including optical windows and copper gasket sealed stainless steel flanges. These technologies are too bulky and dense for a GPS clock. We have designed and are presently fabricating several prototype laser cooling chambers from titanium. One prototype, shown in figure 3, uses custom optical windows for beam access. Cesium will be pumped by getters and background gasses by non-evaporative getters (NEGs). The optical molasses source is designed to operate in the (1,1,1) mode [3], which eliminates sending a cooling laser beam down through the beam tube and microwave cavities. Also, this beam geometry allows for cooling and launching the atoms with only two separate laser frequencies versus the three frequencies required in the (0,0,1) geometry. The chamber has holes to mount the fiber-optic cable output collimators. The collimators will be adjusted only once on the bench during the initial assembly and then locked into position. The goal of this approach is to address major concerns regarding the manufacturability of these clocks in a commercial environment.

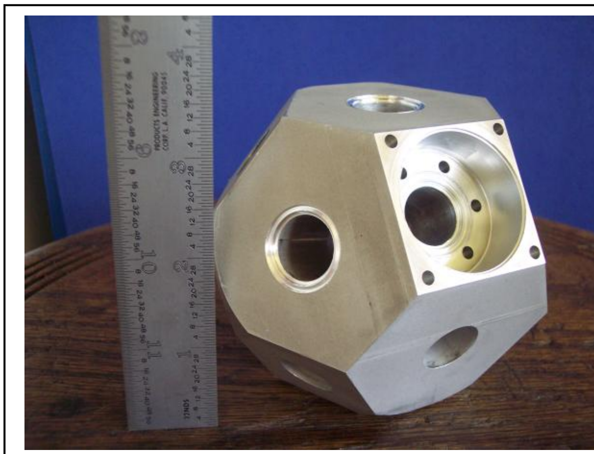

Figure 3. A photograph of the laser-cooling chamber under construction.

The second chamber design has no windows. Rather, the laser beam is delivered via fiber optic cables that pass through the vacuum walls by use of a novel sealing scheme we have designed. Inside the vacuum chamber, the beams from the fiber-optic cables are expanded and collimated by use of fixed optics.

The microwave cavity structure that we are modeling for the GPS clock, shown in figure 4, consists of two TE_{011} cavities resonant at 9.913 GHz and which are connected to one another by a below-cutoff waveguide. The structure is fed in the middle of the below cutoff waveguide. The result is that the two TE_{011} cavities are weakly driven but 180° out of phase. This geometry is suitable for a phase-modulation atomic line servo.

Figure 5 shows a CAD rendering of the complete physics package mounted on an assembly jig. Above the laser-cooling chamber is the microwave cavity structure, and above this is the atom detection zone.

MICROWAVE SYSTHESIZER

Due to the narrow linewidth offered by a laser-cooled clock and the low instability, the requirements for the microwave synthesis are much more extreme than for a beam clock. To achieve these requirements in a low-power package is challenging. We are studying a synthesizer architecture in which a high-quality quartz oscillator supplies the clock to a direct-digital synthesizer (DDS) with the anti-aliasing disabled. A high harmonic from the output is then fed into a microwave stripline bandpass filter and splitter to separate out the frequencies to be used for state preparation and for clock spectroscopy.

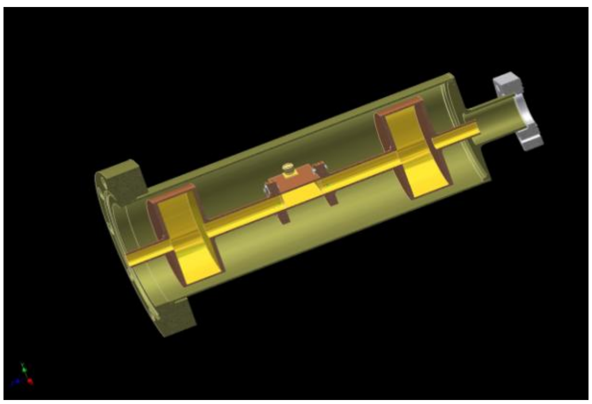

Figure 4. A CAD rendering of the Ramsey microwave cavity structure under consideration for the GPS clock.

CONTROL SYSTEM

In the first stages of our program, the frequency standard will be controlled by a standard laboratory computer and data acquisition hardware. We see no problems in the future development of embedded controllers to operate this device.

CONCLUSION

We are still in the early stages of this program, and much of our progress been in the areas of mechanical design and theoretical modeling of the microwave cavity structure. We expect soon to receive hardware prototypes of the cooling chamber so that we can begin assembly and testing of this part of the physics package. Also, the fiber-stretcher experiments are just beginning to give useful data that will allow us to decide whether this technique is feasible. Hopefully, by the ION GNSS 2012 meeting, we will be making cold atoms in our source and beginning to look at microwave signals.

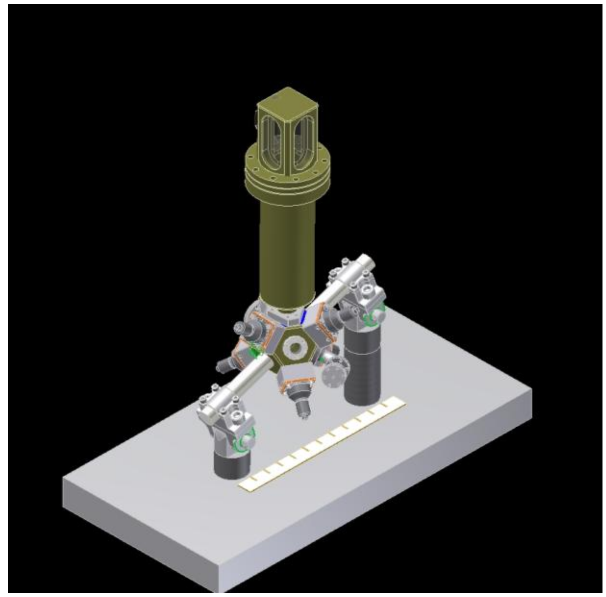

Figure 5. A CAD rendering of the complete laser-cooled GPS clock physics package shown on the assembly bench. The ruler is 30 cm (12 inches).

ACKNOWLEDGMENTS

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REFERENCES

[1] T.P. Heavner, S.R. Jefferts, E.A. Donley, J.H. Shirley, and T.E. Parker, “NIST F1: recent improvements and accuracy evaluations,” *Metrologia*, 42, 2005.

[2] Metcalf, H.J., *Laser Cooling and Trapping,* Springer, 1999.

[3] E.A. Donley, T.P. Heavner, J. W. O’Brien, S.R. Jefferts and F. Levi, “Laser cooling and launching performance in a (1,1,1)-geometry atomic fountain,” *Proceedings of the 2005 Joint Mtg. IEEE Intl.Freq. Cont. Symp. and PTTI,* pp. 292-296.