

ACCEPTED VERSION

Myoung-Sun Heo, Sang Eon Park, Won-Kyu Lee, Sang-Bum Lee, Hyun-Gue Hong, Taeg Yong Kwon, Chang Yong Park, Dai-Hyuk Yu, Giorgio Santarelli, Ashby Paul Hilton, Andre Nicholas Luiten, and John Gideon Hartnett

Drift-compensated low-noise frequency synthesis based on a cryoCSO for the KRISS-F1

IEEE Transactions on Instrumentation and Measurement, 2016; OnlinePubl:1-6

© 2016 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

Published version at: <http://dx.doi.org/10.1109/TIM.2016.2620187>

PERMISSIONS

http://www.ieee.org/publications_standards/publications/rights/rights_policies.html

Authors and/or their employers shall have the right to post the accepted version of IEEE-copyrighted articles on their own personal servers or the servers of their institutions or employers without permission from IEEE, provided that the posted version includes a prominently displayed IEEE copyright notice (as shown in 8.1.9.B, above) and, when published, a full citation to the original IEEE publication, including a Digital Object Identifier (DOI). Authors shall not post the final, published versions of their articles.

1 December 2016

<http://hdl.handle.net/2440/102920>

Drift-Compensated Low-Noise Frequency Synthesis Based on a cryoCSO for the KRISS-F1

Myoung-Sun Heo, Sang Eon Park, Won-Kyu Lee, Sang-Bum Lee, Hyun-Gue Hong, Taeg Yong Kwon, Chang Yong Park, Dai-Hyuk Yu, Giorgio Santarelli, Ashby Paul Hilton, Andre Nicholas Luiten, and John Gideon Hartnett

Abstract—In this paper, we report on the implementation and stability analysis of a drift-compensated frequency synthesizer from a cryogenic sapphire oscillator (CSO) designed for a Cs/Rb atomic fountain clock. The synthesizer has two microwave outputs of 7 and 9 GHz for Rb and Cs atom interrogation, respectively. The short-term stability of these microwave signals, measured using an optical frequency comb locked to an ultrastable laser, is better than 5×10^{-15} at an averaging time of 1 s. We demonstrate that the short-term stability of the synthesizer is lower than the quantum projection noise limit of the Cs fountain clock, KRISS-F1(Cs) by measuring the short-term stability of the fountain with varying trapped atom number. The stability of the atomic fountain at 1 s averaging time reaches 2.5×10^{-14} at the highest atom number in the experiment when the synthesizer is used as an interrogation oscillator of the fountain. In order to compensate the frequency drift of the CSO, the output frequency of a waveform generator, in the synthesis chain, is ramped linearly. By doing this, the frequency stability of the synthesizer at an average time of one hour reaches a level of 10^{-16} , which is measured with the fountain clock.

Index Terms—Cryogenic sapphire oscillator (CSO), frequency stability, frequency synthesizer, hydrogen maser, optical frequency comb, quantum projection noise (QPN), stable lasers.

I. INTRODUCTION

THE most accurate realization of the international system second has now been made by the atomic fountain frequency standards, some of which reached an uncertainty at a level of 10^{-16} [1]–[5]. To this end, an interrogation

Manuscript received July 11, 2016; revised September 8, 2016; accepted September 9, 2016. The work of M.-S. Heo, S. E. Park, W.-K. Lee, S.-B. Lee, H.-G. Hong, T. Y. Kwon, C. Y. Park, and D.-H. Yu was supported by the Korea Research Institute of Standards and Science under the project “Establishment of National Physical Measurement Standards and Improvements of Calibration/Measurement Capability” under Grant 16011007. The work of A. Hilton, A. N. Luiten, and J. G. Hartnett was supported by the Australian Research Council under Grant LP110200142 and Grant LE130100163. The Associate Editor coordinating the review process was Dr. Behnood Ghamsari.

M.-S. Heo, S.-B. Lee, H.-G. Hong, T. Y. Kwon, and D.-H. Yu are with the Division of Physical Metrology, Center for Time and frequency, Korea Research Institute of Standards and Science, Daejeon 341113, South Korea.

S. E. Park, W.-K. Lee, and C. Y. Park are with the Division of Physical Metrology, Center for Time and frequency, Korea Research Institute of Standards and Science, Daejeon 341113, South Korea, and also with the Science of Measurements, University of Science and Technology, Daejeon 34114, South Korea (e-mail: parkse@kriss.re.kr).

G. Santarelli is with the Laboratoire Laboratoire Photonique, Numérique et Nanosciences, CNRS-IOGS-Université de Bordeaux, 33400 Talence, France.

A. P. Hilton, A. N. Luiten, and J. G. Hartnett are with the School of Physical Sciences and the Institute of Photonics and Advanced Sensing, The University of Adelaide, Adelaide, SA 5005, Australia.

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/TIM.2016.2620187

oscillator, a microwave signal for the interrogation of the atomic resonance, needs to meet stability requirements at both short and long measurement time. Good short-term stability is essential to reduce the effect of the phase noise of the local oscillator on the pulsed operation of the clock [6], [7] and allows fountain clocks to operate in the quantum projection noise (QPN) limited regime [8], which is at a level of about 10^{-14} for 10^6 atoms. In addition, better short-term stability greatly facilitates the accuracy evaluation by dramatically shortening the time needed to reach the target stability. Long-term frequency stability at a level of a few parts in 10^{-16} or better is necessary to reach the target uncertainty of 10^{-16} .

As an interrogation oscillator for the Cs atomic fountain clock in the Korea Research Institute of Standards and Science, KRISS-F1(Cs), we used a hydrogen maser (H-maser) filtered by a low-noise BVA quartz oscillator. This approach meets the long-term stability requirements but limits the short-term stability of the fountain clock to about 1×10^{-13} at a 1 s averaging time, dominated by the phase noise of the interrogation oscillator. Recently, we introduced a cryogenic sapphire oscillator (CSO) using an ultralow vibration pulse-tube cryocooler (cryoCSO) developed by Hartnett’s group [9]. The stability of this cryoCSO was measured using another cryoCSO before shipment to the KRISS laboratory, as described in [10] (curve 4 in Fig. 6). The short-term stability of the cryoCSO was measured to be as low as 2×10^{-15} at 1 s averaging time with a long-term frequency drift of about 5×10^{-14} /day. The output frequency is at 11.200044 GHz, so we designed a stable frequency synthesizer for the fountain clock as briefly described in [11]. The short-term stability of its microwave output signals, which was measured by comparison with an ultrastable laser via an optical frequency comb, is better than 5×10^{-15} over an averaging time of 1 s. We confirmed that the short-term stability of the KRISS-F1(Cs) operating with this synthesizer is QPN limited for a wide range of atoms. The long-term frequency drift is usually compensated by a loose phase-lock to an H-maser with a large time constant (~ 1000 s) [3], [12]–[18]. In this paper, since this drift is almost linear, we canceled the linear frequency drift by applying a linear frequency ramp to the synthesizer. With this passive compensation, the long-term frequency stability reached 4×10^{-16} at a day.

II. DESIGN OF THE FREQUENCY SYNTHESIZER

We built a frequency synthesizer with the cryoCSO as shown in Fig. 1. The output frequency of the cryoCSO is about 11.200044 GHz. The frequency drift of the cryoCSO was

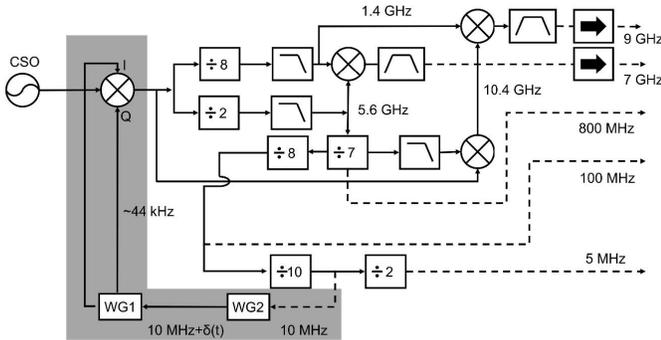


Fig. 1. Schematic of the frequency synthesizer. Not all the attenuators, filters, amplifiers, and isolators are shown. The first mixer in the gray region is an IQ mixer (IQ-0714, Marki microwave). It was used for both the small offset frequency cancellation and frequency drift compensation. WGs are WGs (AFG3022B, Tektronix). The important low-phase-noise components used are the Analog Devices dividers HMC-C005 ($\div 2$), HMC-C007 ($\div 8$), and the programmable divider HMC705LP4 ($\div 7$), the Analog Devices HMC-C050 amplifier, the Holzworth HX4210 divider ($\div 10$), and the Wenzel LNFD-2-10-13-1-13 divider ($\div 2$). The WG1 reference frequency 10 MHz from WG2 is remotely controlled, so that it is ramped linearly. Details are described in the text.

measured to be almost linear with the rate of 6.2 nHz/s. For the synthesis of exact integer frequencies, the small offset frequency 44 kHz was removed using an in-phase/quadrature (IQ) mixer [19] and two digital waveform generators (WGs) as shown in the shaded gray region in Fig. 1. Because the linear drift rate is too small to be compensated with a single WG (1 μ Hz frequency resolution), two WGs were used. We could compensate the linear drift by ramping 10-MHz output frequency from another WG (WG2) which is used as the reference frequency for the WG1. The ramping rate should be $1.4 \times 10^{-13}/s = 6.2 \text{ nHz/s}/44 \text{ kHz}$, so we changed the output frequency 10 MHz of the WG2 by 1 μ Hz every 710 ms. A fine adjustment of this 710-ms interval was made after a few days of observation of the frequency drift which is described in Section IV.

After the IQ mixer, microwave dividers and mixers were combined to obtain microwave signals at 9 GHz for Cs clocks and 7 GHz for Rb clocks. To minimize the excess phase noise, we selected ultralow-phase-noise microwave dividers and amplifiers made by analog devices, as described in Fig. 1. To reject any unwanted sidebands, narrow band-pass filters (200/150 MHz 3 dB bandwidth for 9/7 GHz, K and L microwave) were inserted just before the isolators at the output port of 9 and 7 GHz. The filter packages are thermoelectrically stabilized to minimize the temperature-induced phase variations. The auxiliary synthesized radio frequency outputs (5/10/100/800 MHz) are used for reference to various synthesizers or for comparison with other atomic clocks.

III. SHORT-TERM STABILITY

The short-term stability of our cryoCSO was previously measured using another cryoCSO by Hartnett's group as seen in Fig. 3 (dashed curve). That approach is not feasible in our laboratory. We instead used the ultrastable 578-nm clock laser developed for an Yb optical lattice clock and an optical frequency comb for stability analysis [13], [20]. In the later part of this section, using the 9-GHz signal from the synthesizer, we operated the KRISS-F1(Cs) and verified that

the short-term stability is not dominated by the noise of the interrogation oscillator, but instead by QPN.

A. Measurement With the Stable Optical Clock Laser

We have developed an ultrastable 578-nm clock laser for an Yb optical lattice clock [21]. It is locked to a high-finesse optical cavity, made of ultralow thermal expansion glass. Its frequency stability [Allan deviation (ADEV)] can be measured either by comparison with another independent clock laser or by direct measurement using Yb atoms in the optical lattice. Its short-term stability is about 2×10^{-15} for a 1 s averaging time.

Fig. 2 describes the measurement setup. To compare the optical laser frequency with a microwave signal, we used an erbium-doped fiber frequency comb (FC1500, Menlo systems) centered at 1550 nm with a repetition rate of 250 MHz. We transferred the stability of the clock laser into the microwave frequency region using high-bandwidth ($\sim 300 \text{ kHz}$) phase-locking of the frequency comb to the clock laser with a built-in electro-optic modulator, along with the carrier-envelope offset frequency (f_{ceo}) control using feedback to the pump laser current. The out-coupled comb is amplified and fed into a low-noise photodetector (DSC50S, Discovery). Its output signal is mixed with the output signals of the synthesizer or the cryoCSO. By doing this, the down-converted outputs of the synthesizer can be used for stability measurements using the phase detector (5125A phase-noise test set, Microsemi), which has an input frequency range from 1 to 400 MHz. The repetition rate f_{rep} is adjusted to 249.775 MHz, so the down-converted frequencies of 7, 9, and 11.2 GHz are 6.3, 8.1, and 210 MHz, respectively.

Before making stability measurements using the setup in Fig. 2, we first needed to verify that the 100-MHz reference to the 5125A test set has sufficiently low noise to measure the stability of the microwave signals at the level of 10^{-15} or below. Because the microwave signals are down-converted by three orders of magnitude, the stability of the 100-MHz reference needs only to be below 10^{-12} . This was verified by comparison with 250-MHz output from the comb. Fig. 3 (inset) shows that the instability of the 100-MHz signal is below 10^{-14} up to 100 s of averaging.

Fig. 3 shows the stability for the 7 and 9 GHz signals from the synthesizer and that of the 11.2-GHz signal from the cryoCSO. It is noted that these are the combined stability of microwave signals generated both from the frequency comb and the synthesizer. The stability of the 11.2-GHz output directly from the cryoCSO is 4×10^{-15} at 1 s, which is worse than that determined by Hartnett's group using another cryoCSO [see Fig. 3 (dashed line)]. This means that the short-term stability measurement is limited by the transferred stability of the frequency comb from the clock laser. Besides the electronic noise from the photodetection, we infer that our fiber frequency comb itself contributes to the instability from the fact that the measured stability at 1 s of f_{ceo} is at the level of 1 Hz, which corresponds to 4×10^{-15} against 259 THz (half the clock laser frequency).

From the results of the stability measurements, we conclude that the synthesized microwave signals have a short-term

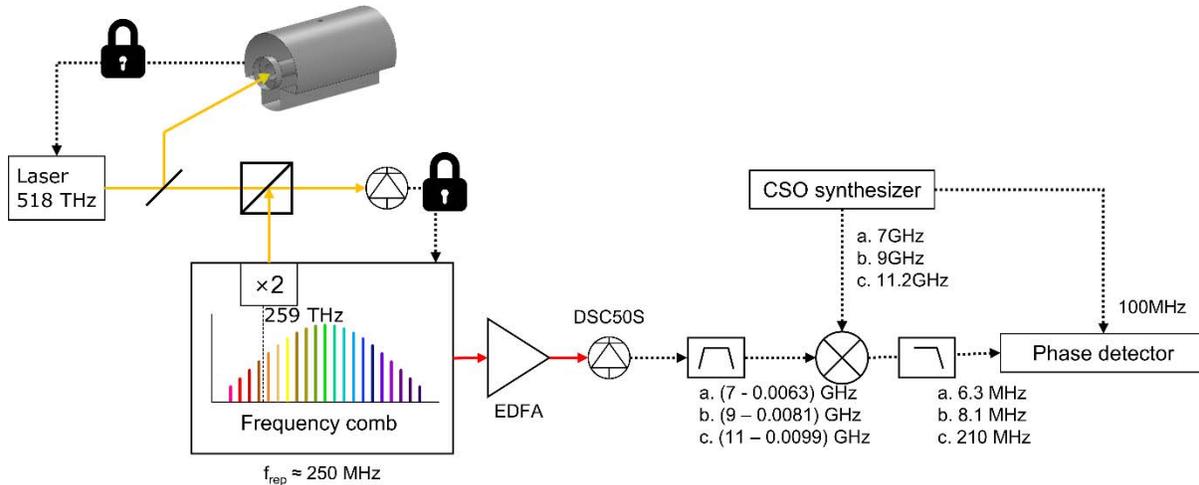


Fig. 2. Setup for the short-term stability measurements. Output signals from the synthesizer and the cryoCSO are down-converted by mixing with filtered beat signals from the frequency comb which is locked to the optical reference. The frequency stability of down-converted signals was measured using a phase detector, a Microsemi 5125A phase noise test set, which outputs phase difference data in units of cycles of the input signal. We used the 100-MHz signal from the synthesizer as a reference.

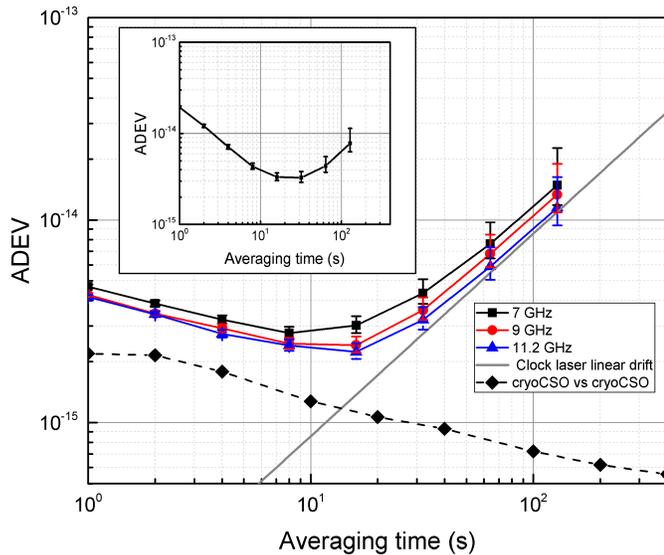


Fig. 3. Fractional frequency stability of the output signals from the synthesizer and the CSO. The noise equivalent bandwidth of the phase detector (5125A) is set to 0.5 Hz. ADEV is computed from the phase difference data. The frequency drift after 10 s comes from that of the clock laser whose drift is depicted in the gray solid line. The dashed line shows the stability measurement using another cryoCSO. Small error bars are not visible. The inset is the stability of 100 MHz from the synthesizer.

stability of $\sim 5 \times 10^{-15}$ at 1 s, which is sufficient to be used for an atomic fountain clock, and the stability of the output signals from the synthesizer is not degraded by more than a factor of three in comparison with that of the cryoCSO, assuming it still has the same frequency stability measured by Hartnett's group as shown by Fig. 3 (dashed line).

B. QPN-Limited Operation of the Atomic Fountain Clock

Since the short-term stability of the synthesized microwave signals is below 10^{-14} , we can expect that an atomic fountain clock will operate in the QPN limit when these microwave signals are used as an interrogation oscillator [22].

Fig. 4 shows the frequency synthesis chain of an interrogation oscillator for the KRISS-F1(Cs). The 9-GHz and

100-MHz output of the cryoCSO synthesizer are mixed with each other to make the 9.1-GHz microwave. The 9.1-GHz microwave signal is mixed again with a 92.63177-MHz output of a direct digital synthesizer (DDS), which is referenced to the 800-MHz signal from the cryoCSO synthesizer. To avoid aliasing in the DDS, the 800-MHz signal is used as the reference frequency of the DDS so that the Nyquist frequency of the DDS is much higher than the output frequency of about 92 MHz. Finally, the synthesized microwave of 9.19263177 GHz is sent to the atomic fountain. For pulsed microwave operation in the fountain, an interferometer switch [23] is used. The microwave signal delivered to the fountain is switched by switching the 100-MHz signal as shown in Fig. 4. The frequency of the microwave sent to the fountain for Ramsey interrogation is tuned by controlling the DDS output frequency.

To confirm that the stability of the microwave signal is better than the QPN limit in the fountain, the short-term stability of the fountain was measured with varying the trapped atom number as shown in Fig. 5. In the QPN limit, the stability at 1 s averaging time improves with increasing number of detected atoms [8] satisfying the following relation:

$$\sigma(\tau = 1\text{ s}) \propto N^{-1/2}, \quad (1)$$

where N is the number of detected atoms. Fig. 5 shows that the dependence of the stability on the number of detected atoms is in good agreement with (1). This result shows that the short-term stability of the fountain is not affected by the stability of the output signals from the synthesizer. Therefore, we confirm that the short-term stability of the synthesized microwave signal is better than the QPN limit of our atomic fountain. Fig. 5 shows that the frequency stability improves to 2.5×10^{-14} for the highest number of detected atoms.

IV. LONG-TERM STABILITY AND DRIFT COMPENSATION

The long-term stability of the synthesizer was measured by comparing the synthesized 9 GHz with the KRISS-F1(Cs)

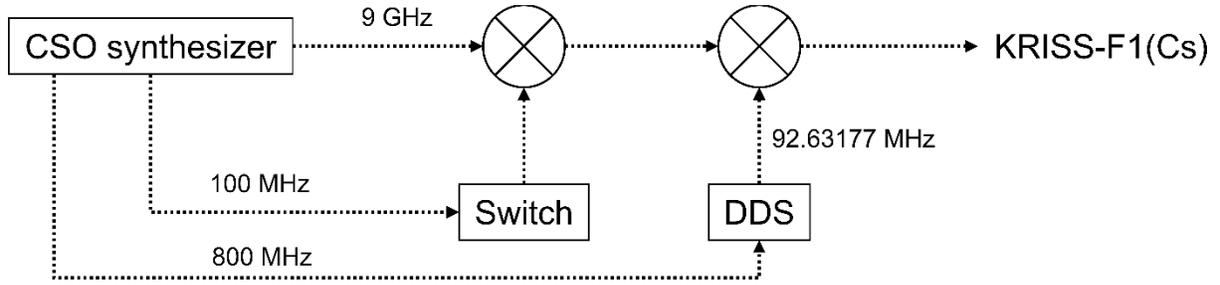


Fig. 4. Block diagram for the local oscillator for KRIS-F1(Cs) from the 9-GHz synthesizer output. Its pulsed operation is carried out by switching 100 MHz before the first mixer. Mixers are single-sideband mixers to suppress the unwanted carrier signals.

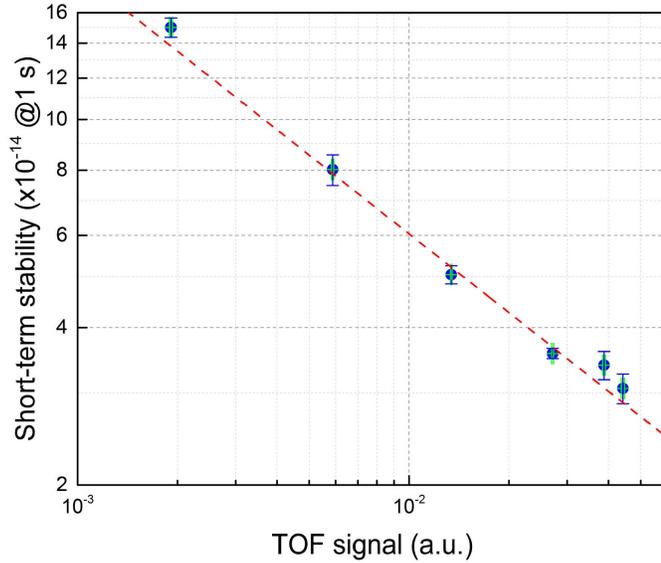


Fig. 5. Short-term stability measured by the KRIS-F1(Cs) with varying trapped atom number [11]. Dashed line is the fit according to (1). The horizontal axis represents the magnitude of the time-of-flight signal which is proportional to the number of atoms.

using the setup described in Fig. 4. The synthesizer has a linear frequency drift of $4.8 \times 10^{-14}/\text{day}$ coming from the cryCSO (curve 1 in Fig. 6). This drift can make it difficult to carry out some of the essential measurements for the accuracy evaluation of the fountain clock if they take longer than a few thousands of seconds to reach targeted uncertainty, because the drift takes effect after 1 h as seen in curve 1 in Fig. 6. One example of these measurements is the evaluation of the sensitivity of the distributed cavity phase shift, which demands interleaved measurements for various mechanical tilts of the fountain clock [24]. In the case of successive adjustments of two different tilts, total duration of measurements for a single tilt should be less than half an hour. This is challenging because we need to mechanically change the tilt every half an hour or less. Because the frequency drift has been quite linear, we decided to compensate passively the linear part of the drift within the frequency synthesizer setup as shown in Fig. 1, instead of active phase-locking to an H-maser.

Fig. 6 shows the frequency stability of the synthesized 9-GHz signal measured by comparing it with the KRIS-F1(Cs), and that of the cryCSO itself measured with another cryCSO by Hartnett's group before being

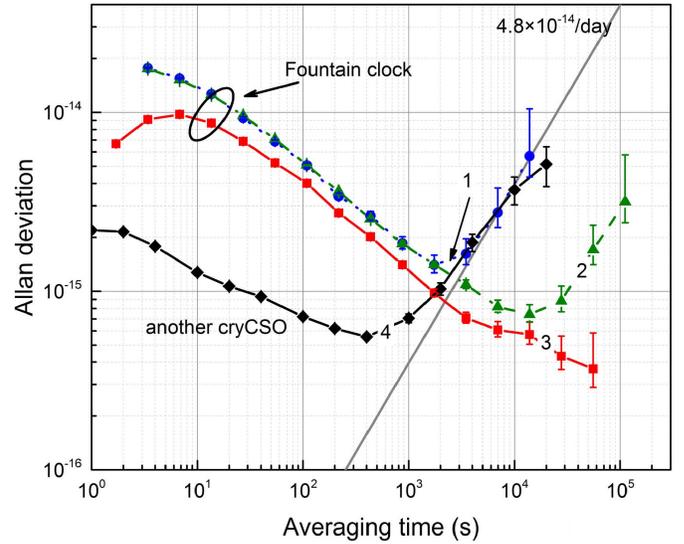


Fig. 6. Long-term stability of 9 GHz (curves 1–3 with no drift compensation, the first compensation and the second compensation, respectively) measured with the KRIS-F1(Cs) and the cryCSO itself (curve 4) measured with another cryCSO by Hartnett's group before the shipment to our laboratory. The gray line corresponds to the linear frequency drift of $4.8 \times 10^{-14}/\text{day}$. Overall, curve 3 shows better stability than curves 1 and 2, because curve 3 was measured with the higher number of atoms.

shipped to our laboratory. As seen in curves 1–3 in Fig. 6, the stability up to 1000 s is governed by the stability of the KRIS-F1(Cs). After 1000 s, the frequency drift from the cryCSO becomes dominant. This drift measurement agrees well with the measurement made using another cryCSO (curve 4 in Fig. 6). We first tried compensation by ramping the frequency of the WG2 in Fig. 1 by $1 \mu\text{Hz}$ frequency steps every 710 ms estimated from curve 1. From curve 2, it was found that there still existed the linear frequency drift due to an error in the estimation of the time interval from curve 1. So, we adjusted the interval by about 50 ms. After the second compensation, the long-term-stability of the fountain clock reached a level of 7×10^{-16} within an hour.

V. CONCLUSION

We designed and implemented a frequency synthesizer using a cryCSO for use as an ultrastable interrogation oscillator of a Cs/Rb atomic fountain clock. The short-term stability of the microwave signals from the synthesizer was about 5×10^{-15} at 1 s of averaging. With this ultralow-noise microwave local oscillator, we have demonstrated the QPN-limited operation of our Cs fountain

clock, KRISS-F1(Cs). From this result, we are assured that the short-term stability of the microwave synthesizer is below the QPN limit of our fountain. For the accuracy evaluation of the fountain with 10^{-16} uncertainty level, the long-term frequency drift of the cryoCSO was compensated by adjusting an offset frequency from a WG deployed in the synthesizer. The resultant long-term stability of the synthesized microwave signals, as measured by the fountain clock, approach a level of a few parts in 10^{-16} .

REFERENCES

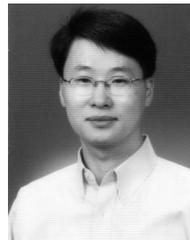
- [1] T. P. Heavner *et al.*, "First accuracy evaluation of NIST-F2," *Metrologia*, vol. 51, no. 3, pp. 174–182, May 2014.
- [2] F. Levi, D. Calonico, C. E. Calosso, A. Godone, S. Micalizio, and G. A. Costanzo, "Accuracy evaluation of ITCsF2: A nitrogen cooled caesium fountain," *Metrologia*, vol. 51, no. 3, pp. 270–284, May 2014.
- [3] J. Guena *et al.*, "Progress in atomic fountains at LNE-SYRTE," *IEEE Trans. Ultrason., Ferroelect., Freq. Control*, vol. 59, no. 3, pp. 391–409, Mar. 2012.
- [4] S. Weyers, V. Gerginov, N. Nemitz, R. Li, and K. Gibble, "Distributed cavity phase frequency shifts of the caesium fountain PTB-CSF2," *Metrologia*, vol. 49, no. 1, pp. 82–87, Nov. 2012.
- [5] R. Li, K. Gibble, and K. Szymaniec, "Improved accuracy of the NPL-CsF2 primary frequency standard: Evaluation of distributed cavity phase and microwave lensing frequency shifts," *Metrologia*, vol. 48, no. 5, pp. 283–289, Aug. 2011.
- [6] G. J. Dick, "Local oscillator induced instabilities in trapped ion frequency standards," in *proceedings of the Precise Time And Time Interval systems and applications meeting*, Redondo Beach, CA, USA, 1987, pp. 133–147.
- [7] G. Santarelli, C. Audoin, A. Makdissi, P. Laurent, G. J. Dick, and C. Clairon, "Frequency stability degradation of an oscillator slaved to a periodically interrogated atomic resonator," *IEEE Trans. Ultrason., Ferroelect., Freq. Control*, vol. 45, no. 4, pp. 887–894, Jul. 1998.
- [8] G. Santarelli *et al.*, "Quantum projection noise in an atomic fountain: A high stability cesium frequency standard," *Phys. Rev. Lett.*, vol. 82, no. 23, pp. 4619–4622, Jun. 1999.
- [9] J. G. Hartnett and N. R. Nand, "Ultra-Low vibration pulse-tube cryocooler stabilized cryogenic sapphire oscillator with 10^{-16} fractional frequency stability," *IEEE Trans. Microw. Theory Techn.*, vol. 58, no. 12, pp. 3580–3586, Dec. 2010.
- [10] J. G. Hartnett, N. R. Nand, and C. Lu, "Ultra-low-phase-noise cryocooled microwave dielectric-sapphire-resonator oscillators," *Appl. Phys. Lett.*, vol. 100, no. 18, p. 183501, Apr. 2012.
- [11] M.-S. Heo *et al.*, "Drift-compensated low-noise frequency synthesis based on a cryoCSO for the KRISS-F1(Cs)," in *Proc. Conf. Precis. Electromagn. Meas.*, Ottawa, ON, Canada, 2016, pp. 1–2.
- [12] J. Guena *et al.*, "Demonstration of a dual alkali Rb/Cs fountain clock," *IEEE Trans. Ultrason., Ferroelect., Freq. Control*, vol. 57, no. 3, pp. 647–653, Mar. 2010.
- [13] M. Kumagai *et al.*, "Synthesis chains based on ultra-stable cryogenic sapphire oscillator at NICT," in *Proc. IEEE Int. Freq. Control Symp., Eur. Freq. Time Forum*, Besançon, France, 2009, pp. 496–500.
- [14] A. Takamizawa *et al.*, "Atomic fountain clock with very high frequency stability employing a pulse-tube-cryocooled sapphire oscillator," *IEEE Trans. Ultrason., Ferroelect., Freq. Control*, vol. 61, no. 9, pp. 1463–1469, Sep. 2014.
- [15] A. Takamizawa *et al.*, "Preliminary evaluation of the cesium fountain primary frequency standard NMJ-F2," *IEEE Trans. Instrum. Meas.*, vol. 64, no. 9, pp. 2504–2512, Sep. 2015.
- [16] K.-I. Watabe *et al.*, "Cryogenic-sapphire-oscillator-based reference signal at 1 GHz with 10^{-15} level instability," *Jpn. J. Appl. Phys.*, vol. 47, no. 9R, pp. 7390–7392, Sep. 2008.
- [17] D. Chambon *et al.*, "Design and realization of a flywheel oscillator for advanced time and frequency metrology," *Rev. Sci. Instrum.*, vol. 76, no. 9, p. 094704, Sep. 2005.
- [18] M. Abgrall *et al.*, "High-stability comparison of atomic fountains using two different cryogenic oscillators," *IEEE Trans. Ultrason., Ferroelect., Freq. Control*, vol. 63, no. 8, pp. 1198–1203, Aug. 2016.
- [19] N. R. Nand, J. G. Hartnett, E. N. Ivanov, and G. Santarelli, "Ultra-stable very-low phase-noise signal source for very long baseline interferometry using a cryocooled sapphire oscillator," *IEEE Trans. Microw. Theory Techn.*, vol. 59, no. 11, pp. 2978–2986, Nov. 2011.
- [20] J. Millo *et al.*, "Ultralow noise microwave generation with fiber-based optical frequency comb and application to atomic fountain clock," *Appl. Phys. Lett.*, vol. 94, no. 14, p. 141105, Apr. 2009.
- [21] D.-H. Yu *et al.*, "An Yb optical lattice clock: Current status at KRISS," *J. Korean Phys. Soc.*, vol. 63, no. 4, pp. 883–889, Apr. 2013.
- [22] S. Weyers, B. Lipphardt, and H. Schnatz, "Reaching the quantum limit in a fountain clock using a microwave oscillator phase locked to an ultrastable laser," *Phys. Rev. A*, vol. 79, p. 031803(R), Mar. 2009.
- [23] G. Santarelli *et al.*, "Switching atomic fountain clock microwave interrogation signal and high-resolution phase measurements," *IEEE Trans. Ultrason., Ferroelect., Freq. Control*, vol. 56, no. 7, pp. 1319–1326, Jul. 2009.
- [24] J. Guéna, R. Li, K. Gibble, S. Bize, and A. Clairon, "Evaluation of Doppler shifts to improve the accuracy of primary atomic fountain clocks," *Phys. Rev. Lett.*, vol. 106, no. 13, p. 130801, Apr. 2011.



Myoung-Sun Heo was born in South Korea in 1977. He received the B.Sc. and Ph.D. degrees in physics from Seoul National University, Seoul, South Korea, in 2000 and 2007, respectively.

He was a Post-Doctoral Associate with the Massachusetts Institute of Technology, Cambridge, MA, USA, from 2010 to 2012, where he was involved in ultracold atoms and molecules. Since 2013, he has been with the Korea Research Institute of Standards and Science, Daejeon, South Korea. His current research interests include microwave and optical frequency standards, and long-distance fiber optical frequency dissemination.

Dr. Heo is a member of the Korean Physics Society.



Sang Eon Park was born in Seoul, South Korea. He received the M.S. and Ph.D. degrees in physics from Chungnam National University, Daejeon, South Korea, in 1994 and 2001, respectively.

Since 1992, he has been with the Center for Time and Frequency, Research Institute of Standards and Science, Daejeon, where he was involved in the development of slow atomic beam frequency standards. In 2009, he was a Visiting Scientist with the National Physical Laboratory, Teddington, U.K. His current research interests include atomic fountain clocks, optical frequency combs, laser frequency stabilization, and optical phase-locking of diode laser.

Dr. Park is a member of the Korean Physical Society and the Optical Society of Korea.



Won-Kyu Lee was born in South Korea in 1971. He received the Ph.D. degree in physics from Seoul National University, Seoul, South Korea, in 2002.

Since 2002, he has been with the Korea Research Institute of Standards and Science, Daejeon, South Korea. His current research interests include optical frequency standards, laser frequency stabilization, laser spectroscopy, and high-precision measurements using laser technology.

Dr. Lee is a member of the Korean Physical Society and the Optical Society of Korea.



Sang-Bum Lee received the Ph.D. degree in physics from Seoul National University, Seoul, South Korea, in 2004.

He is currently with the Korea Research Institute of Standards and Science, Daejeon, South Korea. His current research interests include atomic frequency standards and atomic interferometers for application as inertial sensors.

Dr. Lee is a member of the Korean Physical Society and the Optical Society of Korea.



Hyun-Gue Hong was born in Seoul, South Korea, in 1980. He received the B.S. and Ph.D. degrees in physics from Seoul National University, Seoul, in 2004 and 2011, respectively. His Ph.D. dissertation was on a study on the novel characteristics of the laser based on the cavity quantum electrodynamics.

He was with the Samsung Advanced Institute of Technology, Giheung, South Korea from 2012 to 2013, where he was involved in the micro-optics design and fabrication for image sensors. Since 2014, he has been with the Korea Research Institute of Standards and Science, Daejeon, South Korea, where he has been involved in research on atomic frequency standards.

Dr. Hong is a member of the Optical Society of Korea, and the Korean Physical Society.



Taeg Yong Kwon was born in Busan, South Korea, in 1966. He received the M.S. and Ph.D. degrees in physics from Pusan National University, Busan, South Korea, in 1991 and 1996, respectively.

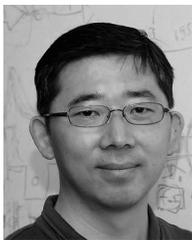
In 1996, he joined the Korea Research Institute of Standards and Science, Daejeon, South Korea. Since 1996, he has been engaged in research on atomic clocks.



Chang Yong Park was born in South Korea in 1970. He received the Ph.D. degree in physics from Korea University, Seoul, South Korea, in 2002.

Since 2003, he has been with the Korea Research Institute of Standards and Science, Daejeon, South Korea. His current research interests include optical frequency standards, laser frequency stabilization, laser spectroscopy, and high-precision measurements using laser technology.

Dr. Park is a member of the Korean Physical Society and the Optical Society of Korea.



Dai-Hyuk Yu was born in Daegu, South Korea, in 1969. He received the Ph.D. degree in physics from Seoul National University, Seoul, South Korea, in 2000.

In 2002, he joined the Time and Frequency Group, Korea Research Institute of Standards and Science, Daejeon, South Korea, as a Senior Researcher. He has been the Head of the Center for Time and Frequency since 2013. His current research interests include fountain frequency standard, optical frequency standards, and high-precision measurements

using laser technology.

Dr. Yu is a member of the Korean Physical Society and the Optical Society of Korea.



Giorgio Santarelli was born in Geneva, Switzerland. He received the degree "Master on Engineering", from Marche Polytechnic University, Ancona, Italy, and the Ph.D. degree from Université Pierre et Marie Curie, Paris, France, in 1990 and 1996, respectively.

Since 1991, he has been a Research Staff Member with the Laboratoire national de métrologie et de rétrologie, Observatoire de Paris, Paris. In 2012, he joined LP2N, Talence, France, to establish new activities

on low-noise laser sources. He has authored or co-authored over 100 peer-reviewed technical articles. His current research interests include very low-phase-noise frequency synthesis, cold atoms frequency standards, long-distance fiber optical frequency dissemination, ultrastable lasers, and femtosecond laser combs.

Dr. Santarelli received the 2015 European Time and Frequency Forum Award for his outstanding contributions to the development of ultralow-phase noise methods and systems for microwave and optical atomic clocks, of fiber-based optical frequency combs, and of optical fiber link. He is an Associate Editor of the IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL.



Ashby Paul Hilton received the B.Sc. degree in physics and the M.Phys. degree (Hons.) from The University of Western Australia, Perth, WA, Australia, in 2013 and 2015, respectively. He is currently pursuing the Ph.D. degree with The University of Adelaide, Adelaide, SA, Australia.

He is currently with the Precision Measurement Research Group, Institute of Photonics and Advanced Sensing, The University of Adelaide, and holds the position of President of The University of Adelaide Joint OSA-SPIE Student Chapter.



Andre Nicholas Luiten received the Ph.D. degree in physics from The University of Western Australia, Perth, WA, Australia, in 1997.

He is currently the Director of the Institute for Photonics and Advanced Sensing and a Chair of Experimental Physics with The University of Adelaide, Adelaide, SA, Australia. He has authored or co-authored six book chapters and authored 94 journal papers (with 3000 citations) and over 100 conference papers. His work has aimed at the development of state-of-the-art instruments across

many diverse fields of physics. He is particularly excited by the possibility of applying these instruments to solve problems, or to make measurements that were not previously possible. In recent times his groups focus has broadened to include more practical measurements for assisting industry.

Dr. Luiten is a fellow of the Australian Institute of Physics. He has subsequently held three prestigious fellowships from the Australian Research Council. He received a South Australian Research Fellowship from the Premiers Research and Innovation Fund. For his efforts, he was the joint inaugural winner of the WA Premiers Prize for Early Career Achievement in Science. He received the Bragg Gold Medal for his Ph.D. degree. In 2013, he was the Chair of Experimental Physics with The University of Adelaide.



John Gideon Hartnett received the B.Sc. (Hons.) and Ph.D. degrees in physics from The University of Western Australia (UWA), Perth, WA, Australia.

He has served as a Research Professor with the Frequency Standards and Metrology Research Group, UWA, and an Associate Professor with the School of Physical Sciences, Institute of Photonics and Advanced Sensing, The University of Adelaide, Adelaide, SA, Australia. His current research interests include the development of ultrastable microwave oscillators based on sapphire resonators

and low-phase-noise frequency synthesis.

Dr. Hartnett was a recipient of the 2010 IEEE UFFC Society W.G. Cady Award. He was a co-recipient of the 1999 Best Paper Award from the Institute of Physics Measurement Science and Technology. He received an Australian Research Council Discovery Outstanding Researcher Award Fellowship in 2013.