Report of the NRC to the 21st Meeting of the CCTF

National Research Council of Canada, Ottawa, Canada

June 8th and 9th, 2017

1. Introduction

This report describes the activities of the National Research Council of Canada in time and frequency metrology since the CCTF meeting in 2015. The report is divided into three sections on Time and Frequency Generation, Time and Frequency Standards in Development, and Time Comparison and Dissemination.

2. Time and Frequency Generation

An Agilent 5071A is the source of TA(NRC). UTC(NRC) is generated by the same clock using a frequency offset generator to track UTC within 100 nanoseconds. Three 5071A clocks and one hydrogen maser are reported to the BIPM for contribution to TAI and for the Rapid UTC calculations.

Caesium Clocks: A total of twelve commercial clocks (Agilent 5071A) are available. Three high-performance clocks and one standard-performance clock are operated simultaneously at our main laboratory. Two standard-performance Agilent 5071A clocks are in operation at our short wave radio station (CHU), which is located approximately 20 km from the main laboratory.

Hydrogen Masers: Two hydrogen masers are in use: Symmetricom MHM-2010 (provides a local oscillator reference for the GPS receivers) and Vremya-CH CVCH-1003M.

Frequency Measurements of Molecular Transitions: Since September 2015, one series of comb-based absolute frequency measurements has been performed of one of the two NRC-built 193-THz (1.54 μm) reference laser systems stabilized on component P(16) of the $\nu_1 + \nu_3$ band of $^{13}C_2H_2$.

Two series of comb-based absolute frequency measurements were conducted since September 2015 of the three NRC iodine-stabilized 474-THz (633-nm) HeNe lasers for the reference “d”, “e”, “f”, and “g” (a_{18}, a_{17}, a_{16}, and a_{15}) lines of the R(127) 11-5 transition in $^{127}I_2$. One system (INMS2) has recently ceased to operate due to a failure of the gain tube and is currently under repair. The two other systems continue to operate within the specified accuracy, and long-term reproducibility at the kilohertz level is achieved for these standards.

Phase Comparators: We currently use 3 multi-channel phase comparators: 5 MHz NRC-built, 80-MHz from Timetech, and 100 MHz from Timetech.

Time Interval Counters: We operate two CNT 91 counters that are part of our K001.UTC system.

Frequency combs: Two frequency combs are in use in our laboratory. A Ti:sapphire comb is used in calibrations of optical frequency/wavelength for standard lasers in our group (I_2/HeNe lasers at 633 nm and acetylene-stabilized lasers in the region of 1540 nm), and for polarization-stabilized HeNe lasers belonging to the NRC Dimensional Metrology Laboratory (544 nm, 594 nm, 612 nm, and 1153 nm).

A fibre comb is used for the measurement of the clock transition frequency at 445 THz (674 nm) of the single strontium ion optical-frequency standard against a hydrogen maser. A second, 100-MHz frequency comb is under construction to be used as a source of rf signals for direct comparison with microwave standards.

3. Time and Frequency Standards in Development

Cesium Fountain: The new NRC cesium fountain frequency standard, FCs2, is currently under evaluation. FCs2 contains a new physics package as well as upgraded optical systems, microwave and RF electronics, and control systems. The physics package was constructed at NPL and is similar to NPL-CsF2. It was tested in NPL and shipped to NRC in January 2017. It replaces the physics package in FCs1 which used a transverse (horizontal) C-field. A new SpectraDynamics synthesizer, referenced to an ultrastable oscillator (Cs-1C), serves as the microwave source. The injection-locked diode lasers that were used in FCs1 have been replaced by tapered amplifiers resulting in improvements to the stability of the laser system. A fast current feedback loop has also been implemented in the master cooling laser to improve the frequency stability. The FCs2 physics package has been set up in NRC laboratory and experiments and evaluations are underway. The MOT atom cloud has been launched and Ramsey fringes have been detected. Experiments to map the C-field and evaluate the black-body shift are in progress. The stability of the fountain clock is limited by the local oscillator.

Strontium Ion Standard: The $^{88}Sr^{+}$ ion optical frequency standard system has been evaluated. Its fractional frequency uncertainty is 1.2 x 10^{-17}, currently limited by the evaluation of the blackbody radiation field at the ion [1, 2]. The system includes an endcap ion trap designed to control micro-motion shifts down to fractional frequency levels of 10^{-17}. Further reduction of the micro-motion shifts to the 10^{-19} level is achieved by selecting the trap drive frequency such that the second-order Doppler shift and the scalar Stark shift cancel each other [2]. The blackbody shift uncertainty has also been reduced, compared to the first evaluation given in [1, 3], through a high-accuracy determination of the differential scalar polarizability of the clock transition [2]. Significant improvements to the stability of the single-ion frequency standard were also made by implementing a clear-out laser and a state-preparation step using optical pumping, yielding a stability of about 3×10^{-15} at 1 s averaging [4]. A new software locking algorithm has been implemented for improved tracking of variations in the drift rate of the ultra-stable clock laser and a series of measurements of the frequency of the single-ion standard through a GNSS link to the SI have been completed [5].

Ultra-stable Lasers: The 674 nm ULE laser linewidth has been demonstrated to be below 4.0 Hz and its thermal noise is estimated to be $\approx 3 \times 10^{-16}$. The ULE cavity is stabilized at the temperature where its thermal expansion coefficient vanishes. The isothermal creep rate is typically 10 mHz/s.

4. Time Comparison and Dissemination

GPS: GPS all-in-view is used to compare UTC(NRC) with other clocks around the world. We currently use 9 GPS receivers and 4 antennas located at our main building and at the CHU radio station. Starting in February 2017, a Septentrio PolaRx4TR became the main receiver of our K001.UTC system. This receiver was calibrated in the summer of 2016 through a travelling receiver from NIST (NIST-G1). Other receivers include a Topcon NET-G3A, Novatel OEMV and OEM4 receivers, and a Javad TRE_G3T DELTA. NRC participates in the TAIPPP and Rapid-UTC projects at BIPM and in the SIM time and frequency comparison.

CMC: No changes to CMC occurred since CCTF-2015.

Time Dissemination: Time is disseminated through a telephone talking clock (+1 613-745-1576 (English), +1 613-745-9426 (French)), computer time code via telephone, a web clock, network time protocol (time.nrc.ca and time.chu.nrc.ca), shortwave radio broadcasts from CHU (3330, 7850, and 14 670 kHz), and on public radio through the national broadcaster, CBC/Radio-Canada. For a listing of our services, see http://www.nrc-cnrc.gc.ca/eng/services/time/index.html and http://www.nrc-cnrc.gc.ca/fra/services/heure/ index.html. Low-level calibrations are routinely performed for stopwatches and quartz crystals. High-level calibrations for Cs and Rb frequency standards as well as H masers are performed as routine services. Calibrations of laser frequency/wavelength are offered for wavelengths from 530 to 1200 nm and from 1510 to 1560 nm.

Two new traceable time dissemination services have been developed by NRC since CCTF-2015: A Monitored NTP service and the NRC Remote Clock. The former is targeted at clients who wish to comply with regulatory requirements for time synchronization at the level of milliseconds, limited by public internet traffic delays. The latter service provides traceable time dissemination at the client's location with uncertainties at the sub-microsecond level.

For redundancy purposes, the NRC time dissemination laboratory has a secondary remote site at the CHU facility. Two standard-performance Agilent 5071A clocks and two commercial rubidium standards (HP 5065 and Symmetricom 8040C), along with two GPS receivers (Novatel OEMV and OEM4), are in operation at the CHU facility and provide a backup for the time dissemination services and the NRC time scale.

5. References

[1] P. Dubé, A. A. Madej, Z. Zhou, and J. E. Bernard, "Evaluation of systematic shifts of the $^{88}Sr^{+}$ single-ion optical frequency standard at the 10^{-17} level," Phys. Rev. A, vol. 87, 023806 (2013).

[2] P. Dubé, A. A. Madej, M. Tibbo, and J. E. Bernard, “High-accuracy measurement of the differential scalar polarizability of a $^{88}Sr^{+}$ clock using the time-dilation effect,” Phys. Rev. Lett., vol. 112, 173002 (2014).
[3] A. A. Madej, P. Dubé, Z. Zhou, J. E. Bernard, and M. Gertsvolf, “$^{88}Sr^{+}$ 445-THz single-ion reference at the 10^{-17} level via control and cancellation of systematic uncertainties and its measurement against the SI second,” Phys. Rev. Lett., vol. 109, 203002 (2012).
[4] P. Dubé, A. A. Madej, A. Shiner, and B. Jian, “$^{88}Sr^{+}$ single-ion optical clock with a stability approaching the quantum projection noise limit,” Phys. Rev. A, vol. 92, 042119, (2015).
[5] P. Dubé, J.E. Bernard, and M. Gertsvolf, “Absolute frequency measurement of the $^{88}Sr^{+}$ clock transition using a GPS link to the SI second,” Metrologia, vol. 54, 290 (2017).