National Research Council, Canada
Report on Activities to the 17th Session of the Consultative Committee for Time and Frequency
September 2006

This report describes the work done at National Research Council of Canada in the field of time and frequency metrology and some connected activities since the last CCTF meeting. Also, a lot of effort has been devoted to the quality system and the ISO 17025 implementation.

Time and Frequency Generation and Dissemination

Caesium Clocks: CsVIA, one of the three caesium clocks (CsV, CsVIA and CsVIC) built by NRC thirty years ago, has been the source of TA(NRC) up to the end of 2005. Since then, a commercial clock (Agilent 5071A) has been used for that purpose. UTC(NRC) is generated by the same clock using a frequency offset generator to track UTC within 100 nanoseconds.

Hydrogen Masers: Our two hydrogen masers H3 and H4, built fifteen years ago, are operating normally as well as the Quartzlock hydrogen maser CH1-75A, named R1. The latest provides the signal for our GPS multi-channel receivers. Their excellent short term stability allows a good link through the frequency comb generator from the caesium frequency to optical frequencies of the Strontium Single Ion trap or the Optical Lattice Clock under development.

H3 and H4 are still in the process of refurbishing, but this is done as minute improvements generally not affecting the performance of the ensemble. The masers are providing Allan deviations of $(1.5 \ldots 5)\times10^{-13}/\tau$, H3 and R1 being the less noisy.

Caesium Fountain: A caesium primary standard fountain clock NRC-FCs1 was designed based on the results obtained from an earlier prototype which demonstrated a short term stability of $1.5\times10^{-12}\ \tau^{-1/2}$ up to 4000 seconds, better than our current caesium beam tubes. NRC-FCs1 uses a 110 configuration, an optimized launch height between 30 cm and 50 cm, rotating disk light shutters for high duty time operation (juggling) and phase modulation interrogation. A transversal C-field is used with a rectangular TM_{210} microwave cavity located 58cm above the MOT. The drift region is surrounded by three magnetic shields and an active magnetic field compensation system.

All parts of the fountain are built except for the microwave cavity. The detection section of the vacuum chamber is assembled and under vacuum.

Phase Comparators: We are currently testing different systems operating at 80 MHz or 100 MHz. We have a few channels that can measure noise at the level of

3.5×10^{-14}. The full development of the 80 or 100 MHz system is still to be completed.

GPS: We developed a traveling GPS station based on the Novatel OEM3 receiver. The traveling station is used to calibrate clients' clocks in their laboratories. The station was successfully tested with a client and we may add this calibration service to our CMC in near future.

We still have an old NBS type GPS receiver, which is our official link with TAI. Our Ashtech Z-12T GPS receiver has been working well since its installation three years ago and is ready to take over the old NBS receiver. We also tested the Novatel OEM3 receivers which can be used as backup for the GPS link.

We also participate to the SIM (Systema Interamericano de Metrologia) Time and Frequency Comparisons via Common-View GPS[1]. We are in the process of replacing the original antennas by the Novatel pinwheel. Preliminary results show improvement in the noise and multi-path rejection.

We also plan to participate in the development of the PPP method for time transfer.

CHU: this radio station is still transmitting at three short wave frequencies but the cost of operation is still increasing while the need is probably decreasing. A survey will soon be launched to try to measure the usage of CHU. A message will be added to the signal during the period from the tenth to the thirtieth second. According to the results, we will decide if we can justify the expense.

NTP: internet popularity ever increasing, our Network Time Protocol service is still in high demand, with over 5 millions hits per day. Any disruption or appearance of disruption of service is immediately signaled by our clients. Our authenticated service clientele is still expanding.

Frequency transfer through GPS: Some clients in Canada are using their GPS data to compare with the last four days of data from our old single channel GPS, published every day on our web site. In order to provide calibration to clients, we ask them to provide their GPS data on our ftp site. The system is still under evaluation; most clients do not have a CGGTTS or similar format output from their GPS discipline oscillators.

Optical Frequency Standards:

Research work has continued on the front of optical frequency standards, taking advantage of the use of a frequency comb generator to improve the link with the caesium reference and the new probe laser stabilized on an ULE cavity for

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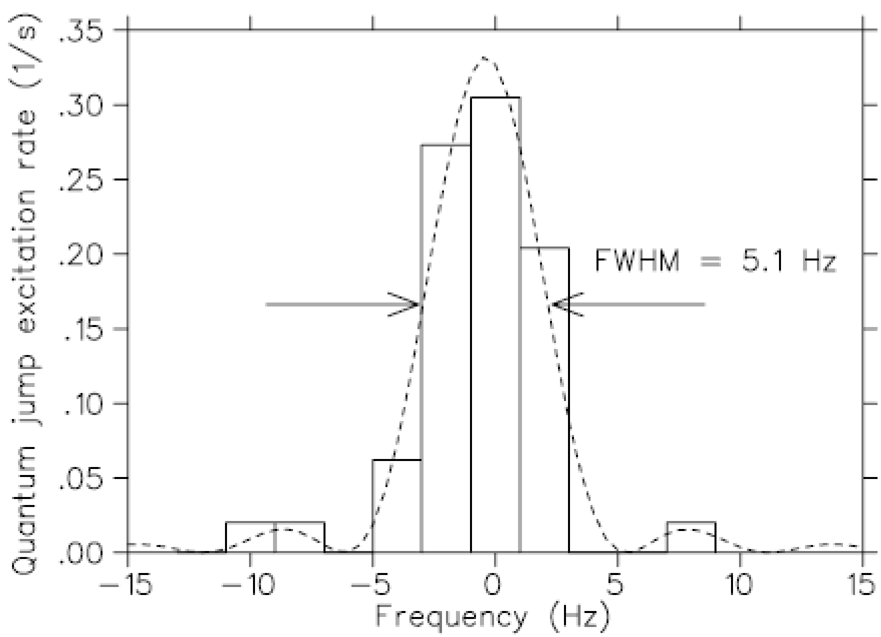
[1] M. A. Lombardi, A. N. Novick, J. M. Lopez, J. S. Boulanger, and R. Pelletier, "The Interamerican Metrology System (SIM) Common-View GPS Comparison Network," *Proceedings of the 2005 IEEE Frequency Control Symposium*, August 2005, pp. 691-698.

probing the reference transition in a single trapped and laser cooled Strontium ion. Some highlights of the key activities are outlined below:

Frequency comb generator: The frequency link built around a Titanium: Sapphire femtosecond laser has simplified the comparison of frequencies at virtually any wavelength from microwave to visible. The 10-s comb measurements of a 445 THz ultra stable laser's frequency produces measurements with a standard deviation of the 10-s measurements of 5×10^{-14}. This instability is thought to be a result of the comb's acoustically noisy environment. Work is being directed to further stabilize the comb to the limit of the reference maser. The comb reference has been used for the absolute measurement of 1540 nm (194 THz), 1552 nm (260 THz), 674 nm (445 THz), 633 (474 THz), 612 nm (490 THz), and 543 nm (552 THz) laser frequency standards. In the case of the 445 THz frequency measurements, the comb was used to determine the centre reference frequency of the S-D single strontium ion transition. The results showed that the ion frequency reproducibility was limited to the level of the knowledge of the calibrated reference maser frequency of 1×10^{-14} as determined via comparisons to NRC thermal Cs clocks and GPS comparison. Future improvement using comb based frequency measurements of the single ion standard will be obtained when the NRC Cs fountain becomes operational.

Ultra stable laser: improvements to the ultra-stable laser has resulted in a drift better than 10 mHz per second, allowing a much better tracking of the reference transition of the strontium ion frequency. Recent work has employed increased vibrational isolation of the probe laser table via air bearing suspension together with active noise cancellation on the fiber optic cable linking the probe laser table



and the table holding the ion trap. The line width of the observed ion transition is 5 Hz (see figure) which is approaching the linewidth limit of the single ion transition of 0.4 Hz and places an upper limit on the current stability of the probe laser of better than 1×10^{-14} at 1 s.

Single ion trap: A study of the systematic shifts[2] has been completed and resulted in better understanding and characterization of the ion systematic uncertainties and the current limitations on the single ion absolute frequency. A series of measurements has been done, reducing the current uncertainty budget to a few parts in 10^{-14}. In addition, a new method has been developed for the measurement and reduction of the quadrupole moment shift in single ion standards. The technique was applied to the last series of absolute frequency measurements and shows excellent applicability. Recent measurements now set the NRC determinations of the $^{88}Sr^+$ 445-THz S-D centre frequency to an uncertainty of 15 Hz (1□)[3]. Recent work has been performed with a relative spectral resolution of better than 1×10^{-14} (5 Hz) and has employed a 422-nm saturation dip stabilized diode laser source for precision control of the ion laser cooling and excitation. A new second ion trap system is currently being constructed using an end-cap style design. The goal of this work is to further reduce any systematic uncertainties in the ion standard to the 10^{-17} level. It is our intention to use this trap concurrently with the existing ion trap for systematic shift evaluations.

I_2/HeNe laser: The NRC facility can now monitor and calibrate the 474 THz standards on a regular basis providing traceable measurement to the SI second for metrological needs.

1.5 µm laser standards: Two independent saturation stabilized laser systems were developed based on an external cavity diode laser system which is frequency stabilized on an acetylene gas filled resonant cavity. Short term linewidths of 50 kHz width were observed and instabilities of 3×10^{-12} at 1 s decreasing to 1×10^{-13} at 200 s averaging were obtained. Reproducibility of these standards is at the few kHz level. Absolute frequency measurements of selected reference lines in $^{13}C_2H_2$ were obtained by frequency doubling the radiation and using the NRC frequency comb system to measure the doubled 770 nm frequency[4]. The work has been recently been extended using an infrared Cr:YAG laser frequency comb to measure frequency interval between a known

[2] A.A. Madej, J.E. Bernard, P. Dubé, and L. Marmet, "Absolute Frequency of the $^{88}Sr^+$, 5s $^2S_{1/2}$ - 4d $^2D_{5/2}$ Reference Transition at 445 THz and Evaluation of Systematic Shift Parameters for the Single Ion Standard," Phys. Rev A **70**, 012507 (2004).

[3] P. Dubé, A.A. Madej, J.E. Bernard, L. Marmet, J.S. Boulanger, and S. Cundy, "Electric Quadrupole Shift Cancellation in Single-Ion Optical Frequency Standards" Phys. Rev. Lett. **95**, 033001 (2005).

[4] A. Czajkowski, J.E. Bernard, A.A. Madej, and R.S. Windeler, "Absolute frequency measurement of Acetylene Transitions in the region of 1540 nm", Applied. Phys. B 79, 45-50 (2004).

laser stabilized to the P(16) reference line in $^{13}C_2H_2$ and another laser system stabilized to the line to be measured. In this way, 60 lines in $^{13}C_2H_2$ and 63 lines in $^{12}C_2H_2$ have been measured to the limiting reproducibility of these devices (few kHz)[5,6]. This work together with that of other groups creates an atlas of known reference frequencies from 1511 nm to 1550 nm (193 to 198 THz) that span a significant portion of the spectrum used for telecommunication.

Infrared frequency comb: Development of a new, robust fiber-based frequency comb with improved long-term stability has started in collaboration with University of British Columbia (UBC).

Optical Lattice Clock: The development of an optical lattice clock was approved and several pieces of equipment were purchased. The clock will be based on ^{88}Sr atoms in a system similar to the one used by Katori at the University of Tokyo. A Ti:Sapphire laser is available for the lattice trap but all other laser sources have to be built. The probe laser at 698 nm will be locked to a new reference F-P cavity of finesse 400000, providing an improvement over our currently operating 674 nm system (linewidth <5 Hz, low drift of 10 mHz/s).

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[5] A.A. Madej, J.E. Bernard, A.J. Alcock, A. Czajkowski, and S. Chepurov, "Accurate Absolute Frequencies of the $\nu1+\nu3$ Band of $^{13}C_2H_2$ Determined using an Infrared Mode-locked Cr:YAG Laser Frequency Comb", Journ. Opt. Soc. Am. B 23 , 741-749 (2006).

[6] A.A. Madej, A.J. Alcock, A. Czajkowski, J.E. Bernard, and S. Chepurov, "Accurate Absolute Reference Frequencies from 1511 nm to 1545 nm of the $\nu_1+\nu_3$ Band of $^{12}C_2H_2$ Determined using Laser Frequency Comb Interval Measurements", Journ. Opt. Soc. Am. B **23** (no.10) (October 2006).