Questionnaire previous to the 2005 meeting of the CCL/CCTF joint working group

The CIPM on its meeting in autumn 2004 has decided that the unperturbed ground-state hyperfine quantum transition of ^{87}Rb may be used as a secondary representation of the second with a frequency of :

f_{Rb}= 6 834 682 610.904 324 Hz

and an estimated relative standard uncertainty (1σ) of 3 x 10^{-15}

1. Frequency sources in the microwave domain

1.1.Have you made or are you aware of new absolute frequency measurements of the Rb hyperfine transition?

No

If yes, please list the values and uncertainties obtained and refer to the publication in which they may be found. Please be sure to include measurements made in other laboratories.

1.2. Are you aware of absolute frequency measurements of other microwave standards that should be proposed as secondary representations of the second?

No

If yes, please list the values and uncertainties obtained and the method used and refer to the publication in which they may be found. Please be sure to include measurements made in other laboratories in your country.

1.3. Are you currently developing new frequency sources in the microwave domain?

Yes

If yes, please give a brief description of your experiment.

The NRC Frequency and Time group is currently developing a Cs fountain microwave clock to support the Canadian Time scale and scientific research. The fountain is similar to other Cs fountain clocks currently in existence with the exception of certain key features. The chosen configuration of cooling/trapping beams is in a 110 configuration. A pair of electro-static driven shutters have been developed to block stray light from reaching the microwave drift region when the cold atom samples are being prepared and interrogated. This arrangement allows the system to operate with minimal dead time between samples of cooled Cs, and thus improve on the stability of the device. Phase modulation on the microwave cavity will reduce amplitude modulation and cavity pulling. The chosen microwave waveguide configuration is rectangular (TM_{210}) with the bias C-field in the direction transverse to the direction of propagation of the atoms. To date, an initial operation of the system has obtained Ramsey fringes of the Cs atoms with 1.0 Hz linewidth and 50 S/N. The current system has been rebuilt using non-magnetic materials and optimization of the ballistic drift height for an accuracy goal of 1×10^{-15}. Assembly and tests of the system are underway.

2. Frequency sources in the optical domain

2.1. Have you made or are you aware of new absolute optical frequency measurements suitable to serve as secondary representations of the second?

Yes

If yes, please list the values and uncertainties obtained and refer to the publication in which they may be found.

Radiation Involved	Frequency /Hz	Type A Uncertainty	Type B Uncertainty	Combined Uncertainty	Method	Reference
$^{88}Sr^+$	444 779 044 095 484	4 Hz	13 Hz	15 Hz	Comb	1,2

<u>Strontium Single Ion Absolute Frequency</u>:

A Cs atomic clock-H maser based, Ti: Sapphire femtosecond laser frequency comb has been operated at NRC since 2002. This system has been used to measure the 445 THz (674 nm) $^{88}Sr^+$, 5s $^2S_{1/2}$- 4d $^2D_{5/2}$ absolute transition frequency. A paper outlining the preliminary results of the measurements was published in 2004. In this work, a thorough examination of the systematic shifts of the system was undertaken [1] including the calculation of a number of the relevant shift parameters. The estimated systematic uncertainties when corrections were applied were shown to be well below the ascribed total uncertainty of ±50 Hz (1σ). More recently, a careful series of measurements were made of the ion centre frequency showing the observation of systematic shifts in the ion frequency with upper state m_J level. Using the results, the shifts were found to arise from micromotion induced time dilation and Stark effects together with the electric quadrupole shift of the D state. A method was demonstrated for the effective cancellation of the electric quadrupole shift and tensor contributions of the Stark effect. The results were based on a series of independent measurement periods spanning Feb. 2004 to May. 2004. Measurements were performed on a single trapped and laser cooled $^{88}Sr^+$ atom and correspond to the centre frequency of the Zeeman multiplet. The measurement results yielded a value of [2]:

$$\nu = 444\ 779\ 044\ 095\ 484 \pm 15\ \text{Hz}\ (1\sigma)$$

References:

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

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

2.2 Are you currently developing new frequency sources in the optical domain?

YES

If yes, please give a brief description of your experiment.

Research has continued in the development of an optical frequency/time standard based on a single, trapped and laser-cooled strontium ion at 445 THz (674 nm). Resolutions using the newly developed probe laser system have yielded ion transition linewidths of 50 Hz (1.1×10^{-13}). A new series of absolute frequency measurements were undertaken to determine the centre frequency via the NRC Ti: Sapphire frequency comb measurement system linked to the NRC Rf time standards. An extended series of measurements have been completed which has improved the knowledge of the reference frequency to an uncertainty of ± 15 Hz (1σ). The obtained value is in excellent agreement with that obtained by the group of the National Physical Laboratory (U.K.) whose quoted uncertainty is 1.5 Hz (3×10^{-15}).

The improved resolution and stability of the probe laser to interrogate the single Sr^{+} ion system has allowed the absolute determinations of the reference transition to be limited in type A uncertainties by Canada's realization of the SI second via its present rf time standards ($(1\text{-}2) \times 10^{-14}$). Further improvement is expected with the implementation of the NRC Cs fountain standard, which is currently under development. The observation of residual systematic shifts as outlined in Ref. [2] has prompted efforts into the assembly of a second new ion trap system, which will provide better control of the ion micromotion in all three degrees of motion and allow intercomparison between independent trapping systems. This will enable a closer examination of parameter shifts for the single ion standard. The anticipated ultimate systematic uncertainties for the Sr^{+} S-D transition are estimated to be at or below the 10^{-17} level [1].

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