Recommendation CCTF 1 (2001): Secondary representations of the second

Joint WG CCL/CCTF

The CCTF,

considering that

- the present definition of the second, based on the Cs 133 atom, remains unchanged,
- there are a number of new atoms and ions being studied as potential bases for atomic frequency standards,
- new optical-frequency measurement concepts may allow the use of optical transitions as practical frequency standards, since they provide for a direct microwave output from such standards,
- new frequency standards based on other microwave transitions are being studied,
- one of these new standards could eventually be considered as the basis for a new definition of the second;

intends to examine and approve accurate frequency measurements of atom and ion transition frequencies made relative to the caesium frequency standard as secondary representations of the second,

recommends that

- a list of such secondary representations of the second be established,
- the requirements for documentation of uncertainty that apply to secondary representations of the second be the same as those for primary caesium standards for use in International Atomic Time.

Report of the Joint Working Group on secondary representations of the second to the 16. CCTF

Joint WG CCL/CCTF

- Brief sketch of history - Current situation
- On the criteria for identification of possible candidates for secondary representations of the second
- Frequencies considered and recommended by the JWG for secondary representations of the second
- On the future tasks of the working group(s)

Prepared by F. Riehle (PTB)

for the meeting on 1th April 2004

Activities I (2001)

June 2001, CCTF

- CCTF has established a working group whose task was to propose a list of quantum transitions at the next CCTF to be used as secondary representations of the second
- Members: IEN, BNM-SYRTE, NMIJ, NIST, NPL, NRC, PTB, VNIIFTRI
- PTB was asked to chair this working group
- BIPM was asked to establish proper links to the CCL working group MeP

September 2001, CCL

- Dr. Quinn, BIPM proposed the subject to CCL
- CCL presented an updated MeP to the CIPM including frequencies to be used as secondary representations of the second

October 2001, CIPM

CIPM recommended that discussions between CCTF and CCL should continue possibly leading to a Joint Working Group of CCL and CCTF (JWG) to set up a single list of frequencies that includes reference frequencies for the definition of the metre and frequencies used as secondary representations of the second.

Consequences of the CIPM decision

- **With a single list there will be no ambiguity in the recommended frequencies**

- **It strengthens the definition of the metre that links length and time measurements**

- **It is left to the JWG to take into account that some of the needs of the length and time community are orthogonal**

  e.g. 1. I_2-stabilised HeNe or acetylene stabilized lasers are very useful for length metrology but they are not at all suited to serve the needs of time keeping

  2. Microwave clocks and fs-laser based optical standards at present are not very practical for length metrology

Activities II (2002 - 2003)

February 2002, CCTF-WG

- Questionaire sent by PTB to the members of the WG

  (document CCL-CCTF/03-04)

April 2003, CCTF-WG

- Summary of the Questionaire sent to the members of the WG

  (document CCL-CCTF/03-05)

May 2003, CCTF-WG with guests from the CCL (Ad hoc JWG)

- Informal meeting during the joint meeting of the 17th EFTF and the 2003 IEEE IFCS in Tampa

  (Minutes of the Tampa meeting : document CCL-CCTF/03-06)

September 2003, Formation of the Joint Working Group CCL/CCTF (JWG) under the joint leadership of

Dr. Myung Sai Chung, President of the CCL and
Prof. Sigfrido Leschiutta, President of the CCTF
together with the Director of the BIPM, Dr. Quinn

Members: IEN, BNM-SYRTE, NMIJ, NIST, NPL, NRC, PTB, VNIIFTRI

Chairmen: Dr. P. Gill (NPL), Dr. F. Riehle (PTB)

Current situation

Joint WG CCL/CCTF

2001

CCL

WG: MeP

CCTF

WG: Secondary repres. of the second

2004

CCL

WG: MeP

CCTF

JWG CCL/CCTF

Secondary repres. of the second

Criteria developed by the JWG

Joint WG CCL/CCTF

As a consequence of the decision of the CIPM:

- There must be a single list prepared and periodically updated by the JWG
- An entry in this list could carry a label stating:
  - **transition is approved as a ref. transition for the realisation of the metre**
  - **transition is approved as a secondary representation of the second (As long as the tasks of the CCs remain unchanged, the CCL should confirm the first, CCTF the second type of attribution.)**

As a consequence of the mandate of the CCTF

(to examine and approve **accurate** frequency measurements;

one of these new standards could eventually be considered

as the basis for a new definition of the second):

- A frequency qualifying for a secondary representation of the second should have an uncertainty should be substantially lower than that of a high-quality GPS-disciplined oscillator, preferably not more than a factor 10 above the current uncertainty of primary frequency standards.

Criterion (according to the WG-CCTF questionaire)

Joint WG CCL/CCTF

It does not seem appropriate to recommend any transition that has a relative uncertainty much above 10^{-14} ?

- IEN agreed,
- NMIJ recommended ”smaller than 10^{-13}”
- NRC: Some colleagues find 10^{-14} reasonable but others want to include the whole MeP
- NPL was in favour of a fixed hard limit **(at the moment between 10^{-14} to 10^{-13}),**
- PTB agreed
- VNIIFTRI liked to discuss these matters on a meeting
- NIST asked for a floating limit **“that must have an uncertainty that is no larger than a factor of 10 of the best primary standards of that date”. NIST furthermore asked that the joint working group of CCTF and CCL should review and discuss the proposed standard’s error budget and evaluate its validity. NIST furthermore insisted that the proposed standard must be evaluated and used in more than one laboratory.**

Requirements for consideration as secondary representations of the second

Joint WG CCL/CCTF

1) The SI value of the unperturbed frequency of a quantum transition suitable as a secondary representation of the second must have an uncertainty that is evaluated and documented so as to meet the requirements adopted for the primary frequency standard for use in International Atomic Time.

2) This uncertainty should be no larger than about a factor of 10 of the primary standards *of that date* that serve as the best realisations of the second.

Working procedure

The joint CCTF and CCL working group should review and discuss the proposed standard's uncertainty budget and evaluate its validity before making their recommendation to the CCTF for the standard being added to the list of frequencies appropriate for secondary representations of the second.

The joint working group would keep the CCL informed about its activity.

Activities III (2003 - 2004)

The JWG CCL/CCTF in its sessions
on 9th and 10th September 2003
and 30th March 2004
reviewed
3 microwave standards

and

7 optical standards (most of them included in the MeP)

- **based on documented reports sent to JWG and CCTF**
- **verbal reports**

as potential candidates to be recommended as secondary representations of the second

Frequencies in the μ-wave regime

Joint WG CCL/CCTF

- ^{87}Rb hyperfine transition measured in an atomic fountain:

  f_{Rb}= 6 834 682 610.904 324(4)(7) Hz

  (1.2×10^{-15})

  Report to the JWG CCL/CCTF (CCL-CCTF-04-06 by BNM-SYRTE)
  and Verbal Report concerning the responses from USNO and Prof. K. Gibble (PennState)

- $^{199}Hg^{+}$ hyperfine transition

  $f_{Hg,mw}$ = 40 507 347 996.841 59(14)(41) Hz

  (1.1×10^{-14})

  D. J. Berkeland et al: Laser-Cooled Mercury Ion Frequency Standard,
  Phys. Rev. Lett. **80**, 2089-2092 (1998)

- $^{171}Yb^{+}$ hyperfine transition

  $f_{Yb,mw}$ =12 642 812 118.468 5(7)(6) Hz

  (7×10^{-14})

  Report to the CCTF (CCTF-04-06 by CSIRO)

Frequencies in the optical regime (I)

Joint WG CCL/CCTF

- $^{171}Yb^{+}$ optical transition (435.5 nm) $6s\,^{2}S_{1/2}(F = 0, m_F = 0)$ - $5d\,^{2}D_{3/2}(F = 2, m_F = 0)$ of a single trapped ion:
  $\nu_{Yb} = 688\,358\,979\,309\,311(6)$ Hz
  (9×10^{-15})
  Report to the JWG CCL/CCTF (CCL-CCTF-04-07 by PTB)
  (2.9×10^{-14} from Quinn, Metrologia **40** (2003) 103-133)

- $^{171}Yb^{+}$ optical transition (466.9 nm) $^{2}S_{1/2}(F = 0, m_F = 0)$ - $^{2}F_{7/2}(F = 3, m_F = 0)$ of a single trapped ion:
  $\nu_{Yb} = 642\,121\,496\,772.3\,(6)$ kHz
  (9×10^{-13})
  Verbal Report to the JWG CCL/CCTF by Dr. P. Gill, NPL
  (4×10^{-12} from Quinn, Metrologia **40** (2003) 103-133)

- $^{199}Hg^{+}$ optical transition (281.6 nm) $5d^{10}\,6s\,^{2}S_{1/2}(F = 0)$ - $5d^{9}\,6s^{2}\,^{2}D_{5/2}(F = 2)\ \Delta m_F = 0$ of a single trapped ion:
  $\nu_{Hg} = 1\,064\,721\,609\,899\,143$ Hz
  (1.9×10^{-14})
  (from Quinn, Metrologia **40** (2003) 103-133),
  Verbal Report to the JWG CCL/CCTF by Dr. J. Bergquist, NIST

Frequencies in the optical regime (II)

Joint WG CCL/CCTF

- $^{88}Sr^{+}$ optical transition (674 nm) $5\ ^2S_{1/2}$ - $4\ ^2D_{5/2}$ of a single trapped ion:

  ν_{Sr} = 444 779 044 095 510(50) Hz

  (1.1×10^{-13}) Report to the JWG CCL/CCTF (CCL-CCTF-04-10 by NRC), + Verbal Report to the JWG CCL-CCTF by Dr. P. Gill, NPL (7.9×10^{-13} from Quinn, Metrologia **40** (2003) 103-133)

- ^{40}Ca optical transition (657 nm) $^1S_0$ - $^3P_1$ $\Delta m_J = 0$ of a cloud of 10^7 atoms

  ν_{Ca} = 455 986 240 494 143(5.4) Hz

  (1.2×10^{-14}) Report to the JWG CCL/CCTF (CCL-CCTF-04-07 by PTB) (1.1×10^{-13} from Quinn, Metrologia **40** (2003) 103-133)

- ^1H optical two-photon transition 1S - 2S in a beam of atoms

  ν_H = 1 233 030 706 593.55 Hz

  (2×10^{-13}) (from Quinn, Metrologia **40** (2003) 103-133)

Frequencies in the optical regime (III)

Joint WG CCL/CCTF

- ^{87}Sr optical transition (689 nm) $^1S_0$ - $^3P_0$ in an optical lattice operated at the „magic wavelength“ i.e. no perturbation by the light shift (frequency and uncertainty budget not available)

  Report to the JWG CCL/CCTF (CCL-CCTF/04-08 by NMIJ/AIST)
  and Verbal Report by Dr. Onae, NMIJ

Recommendation of the JWG (Part 1)

Joint WG CCL/CCTF

The CCL/CCTF Joint Working Group (JWG) for the secondary representations of the second was originally formed as a working group of the CCTF at its 15th session in 2001 (Recommendation CCTF1(2001)). It was first given the task of establishing a list of secondary representations of the second. At the suggestion of the CIPM (CIPM 2001) its terms of reference were re-formulated to include the interests of the CCL.

The JWG subsequently considered the results of its questionaire and the ongoing discussions between IEN, BNM-SYRTE, NMIJ, NIST, NPL, NRC, PTB, and VNIIFTRI.

And as a result of its sessions on 9th and 10th September 2003 and 30th March 2004 it

Recommendation of the JWG (Part 2)

recommends

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 3×10^{-15}

and recognizes

that several optical frequency standards have been reviewed by the JWG. Although none has been proposed at this stage, the JWG believes that the rapid progress with these optical frequency standards requires that they should again be reviewed at its next meeting for their possible use as secondary representations of the second.

Conclusions

With the current status of the joint working group and a single list of frequencies it is ensured that no numerical ambiguity can occur with frequencies that can be used for the realization of the meter or those recommended as secondary representations of the second.

Such a single list has furthermore the capability to include also frequency standards that have been recommended neither for the realization of the meter nor as secondary representations of the second, but rather have applications in basic research or applied technology.

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  on Secondary Representations of the Second
- the members of the CCL WG MeP
- the members of the Joint WG CCL/CCTF
  on Secondary Representations of the Second

are gratefully acknowledged