Report of the CCL-CCTF Joint Working Group on Frequency Standards to the CCTF

CCL-CCTF FSWG

- Activities of the FSWG
  - 2006 at CCTF
  - 2007 at CCL
  - Report to CCU on 26 May 2009 in Paris

- Recommendations to the CCTF
  - Terms of Reference for the FSWG
  - Entries in the List of Recommended Frequencies

- Other actions / subgroups

Prepared by F. Riehle (PTB) and Patrick Gill (NPL) for the CCTF on 04 June 2009

Activities I (2006)

- **Establishment of FSWG at CCTF**
- **Single List of Recommended Frequencies (LoR)**
- **Terms of Reference for the FSWG**

1. To make recommendations to the CCL for radiations to be used for the realization of the definition of the metre and to make recommendations to the CCTF for radiations to be used as secondary representations of the second;
2. To maintain together with the BIPM the list of recommended frequency standard values and wavelength values for applications including the practical realization of the definition of the metre and secondary representations of the second;

- **Recommendations of 4 optical frequencies for the new list of frequencies**

APPENDIX 1

Secondary representations of the second

The following frequencies from the list of frequencies have been recommended by the CIPM (CI 1 - 2006) on proposition by the CCTF to be used as secondary representations of the second.

Frequency / Hz	Uncertainty	Atomic species	Reference / Section 1
6 834 682 610.904 324	3×10^{-15}	^{87}Rb	1.19
429 228 004 229 877	1.5×10^{-14}	^{87}Sr	1.12
444 779 044 095 484	7×10^{-15}	$^{88}Sr^{+}$	1.11
688 358 979 309 308	9×10^{-15}	$^{171}Yb^{+}$	1.4
1 064 721 609 899 145	3×10^{-15}	$^{199}Hg^{+}$	1.3

Activities II (2007)

- **Confirmation of FSWG by CCL**
- **Amended Terms of Reference for the FSWG**

3. To take responsibility for key comparisons of standard frequencies such as CCL-K11;
4. To respond to future needs of both the CCL and CCTF concerning standard frequencies relevant to the respective communities;

Activities III (Report to the CCU)

On a New Definition of the Second

In response to CCU suggestion:
for redefinition as early as 2015

P. Gill, F. Riehle

- Cs Clock as the Primary Realization of the Second
- Concept of Secondary Representations of the Second
- List of Recommended Standard Frequencies
- Options for a New Definition
- Constraints for a New Definition

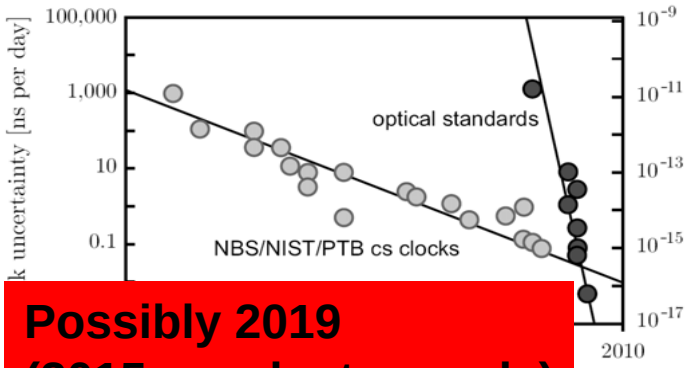
Paris, CCU, 26 May 2009

Work in Progress

- **Different optical transitions are investigated in different institutes and strategic cooperations**
  - Coordinated research of Sr lattice clock in EMRP iMERA Plus
  - Collaborations with external partners (ESA, Centres, etc.)
- **Novel concepts of time and frequency transfer suitable for optical clocks are explored**
  - Optical fibre links (tests are under way)
  - ACES on ISS (planned for 2013)
  - Time transfer by laser light (T2L2)
  - Transportable optical clocks (activities under way)
- **CCTF closely watches the scene**
  - JWG – Secondary representaions of the second
  - Inclusion of optical clocks into TAI possible
  - New WG on novel techniques of Time and Frequency Transfer

On the Way to a New Definition

- Cs definition serves for some time industry's needs
- Secondary Representations serve Science's needs
- There is currently no argument for decision between atom and ion
  - Work has to continue for a consensus
  - It might be better if different laboratories work on the same kind of clock
- Time will be right when
  - Progress with optical standards slows down
  - Transfer problem will be solved



Possibly 2019
(2015 may be too early)

Summary

- Optical clocks are superior to the best primary Cs clocks w/r to stability and accuracy. It is presently not clear what will be the best approach
  - Single trapped ions or
  - Neutral atoms in an optical lattice
- The CIPM, CCTF and CCL have established a Working Group that recommends secondary realizations of the second
- Novel methods for time and frequency transfer are needed
- One of these standards may lead to a New Definition of the Second

Response of the CCU

- CCU strongly encourages the laboratories to work on optical frequency standards for a new definition of the second (in 2019 ?)
- CCU encourages the FSWG to evaluate optical frequency ratios
- New definition of the SI base units kg, A, mol, K will also lead to a new phrasing of the definition of the metre and the second

  (e.g. The metre as the base unit of length is defined such that the speed of light is 299 792 458 m/s;

  e.g. The second as the base unit of time is defined such that the hyperfine transition in ^{133}Cs is 9 192 631 770 Hz)

Terms of reference for the FSWG

On the request of the CIPM the procedure for the appointment of the chairperson of each WG should be defined in the ToR

5. The chairperson is appointed jointly by the CCL and CCTF chairpersons for a period of four years (or at least two consecutive committee meetings) with the possibility of a second term.

^{87}Sr transition lattice clock (update)

^{87}Sr, $5s^2\ {}^1S_0 - 5s5p\ {}^3P_0$ transition

secondary representation of the second;

previous relative uncertainty: 1.5×10^{-14}

JILA $f = 429\ 228\ 004\ 229\ 873.65\ (0.37)$ Hz

G. K. Campbell, A. D. Ludlow, S. Blatt, J. W. Thomsen, M. J. Martin, M. H. G. d. Miranda, T. Zelevinsky, M. M. Boyd, J. Ye, S. A. Diddams, T. P. Heavner, T. E. Parker, and S. R. Jefferts, Metrologia 45, 539 (2008)

SYRTE $f = 429\ 228\ 004\ 229\ 873.6\ (1.1)$ Hz

X. Baillard, M. Fouché, R. Le Targat, P. G. Westergaard, A. Lecallier, F. Chapelet, M. Abgrall, G. D. Rovera, P. Laurent, P. Rosenbusch, S. Bize, G. Santarelli, A. Clairon, P. Lemonde, G. Grosche, B. Lipphardt, and H. Schnatz, Eur. Phys. J. D 48, 11 (2008)

Tokyo $f = 420\ 228\ 004\ 229\ 874.1\ (2.4)$ Hz

F.-L. Hong, M. Musha, M. Takamoto, H. Inaba, S. Yanagimachi, A. Takamizawa, K. Watabe, T. Ikegami, M. Imae, Y. Fujii, M. Amemiya, K. Nakagawa, K. Ueda, and H. Katori, Opt. Lett. 34, 692 (2009)

Recommendation: Weighted mean:

$f_{^{87}Sr} = 429\ 228\ 004\ 229\ 873.65$ Hz

1×10^{-15}

^{88}Sr transition lattice clock (new)

SYRTE f = 429 228 066 418 009 (32) Hz

Xavier Baillard, Mathilde Fouché, Rodolphe Le Targat, Philip G. Westergaard, Arnaud Lecallier, Yann Le Coq, Giovanni D. Rovera, Sebastien Bize, and Pierre Lemonde, Opt. Lett. **32** 1812 (2007)

U. Tokyo f = 62 188 138.4 (1.3) Hz

(Isotope shift); T. Akatsuka, M. Takamoto and H. Katori, Nature Phys. 4, 954 (2008)

by using the weighted mean from ^{87}Sr (recommendation)

This gives

f = 429 228 066 418 012.05 (1.3455) Hz

From these values a weighted mean was derived as:

f_{88Sr} = 429 228 066 418 012.045 (1.34) Hz

Recommendation (Increase uncertainty by 3 times)

f_{88Sr} = 429 228 066 418 012 Hz

($\pm$1 x 10^{-14})

$^{40}Ca^{+}$ transition ($^{2}S_{1/2} - {}^{2}D_{5/2}$) (new)

The values f = 411 042 129 776 393.2 Hz (+-2.4 x 10^{-15})
(Innsbruck)

M. Chwalla, J. Benhelm, K. Kim, G. Kirchmair, T. Monz, M. Riebe, P. Schindler, A. S. Villar, W. Hänsel, C. F. Roos, R. Blatt, M. Abgrall, G. Santarelli, G. D. Rovera, and Ph. Laurent, Phys. Rev. Lett. 102, 023002 (2009)

f = 411 042 129 776 385 Hz (+-4.4 x 10^{-14})
(NICT)

K. Matsubara, K. Hayasaka, Y. Li, H. Ito, S. Nagano, M. Kajita, M. Hosokawa, Appl. Phys. Expr. **1**, 067011 (2008)

f = 411 042 129 776 390 Hz (+-1.7 x 10^{-14})
(NICT)

Proc. of the Asia-Pacific Workshop on Time and Frequency (2008)
(Has not been used since it is not a peer-reviewed paper)

Recommended:
Weighted mean: 411 042 129 776 393 Hz
7 x 10^{-15} (enlarged by 3 times)

$^{171}Yb^{+}$ transition (update)

$^{2}S_{1/2}$ (F = 0, m_F = 0) – $^{2}F_{7/2}$ (F = 3, m_F = 0)

The value f = 642 121 496 772 657 (12) Hz ($\pm$ 2 x 10^{-14})

K. Hosaka, S. A. Webster, A. Stannard, B. R. Walton, H. S. Margolis, and P. Gill, Phys. Rev. A **79** 033403 (2009)

Recommended:
f = 642 121 496 772 657 Hz $\pm$ 6 x 10^{-14}
(enlarged by 3 times)

^{171}Yb transition (new)

$^1S_0(F = 1/2) – {}^3P_0(F = 1/2)$

NMIJ $f = 518\ 295\ 836\ 590\ 864\ (28)$ Hz

F.-L. Hong, M. Musha, M. Takamoto, H. Inaba, S. Yanagimachi, A. Takamizawa, K. Watabe, T. Ikegami, M. Imae, Y. Fujii, M. Amemiya, K. Nakagawa, K. Ueda, and H. Katori, Opt. Lett. 34, 692 (2009)

f = 518 295 836 590 864 Hz

1.6×10^{-13} (expanded uncertainty by 3 times)

List of recommended frequencies

- New entries into the LoR ($^{40}Ca^{+}$, ^{171}Yb, ^{88}Sr)
- Update of a value in the LoR ($^{171}Yb^{+}$)
- Update of the value and uncertainty of a secondary realisation of the second (^{87}Sr)
- No new secondary representations of the second
- No new realisation of the definition of the metre

Other actions / subgroups

- To set up guidelines how to deal with new values
  - Refereed publications
  - Coverage factor
  - etc.

  (NPL, PTB, NMIA, BIPM)
- To develop a protocol for traceability of the metre directly from the Cs clock (comb validation)

  (BEV,NPL, NMIJ, NRC, INRIM, NMIA, BIPM)
- To evaluate the implications of (optical) frequency ratios e.g. for inclusion in the LoR

  (NIST, NRC, SYRTE, NMIJ, PTB, NPL)
- To set up a questionnaire about possible new BIPM activity in supporting comb validations

  (BEV, NPL, BIPM)

Proposal to the CCTF and CCL for modified Terms of reference for the FSWG

1. to maintain and update, together with the BIPM, a list of recommended frequency standard values and wavelength values for the realisation of the definition of the metre, for secondary representations of the second, and for other applications;

2. to make recommendations to:
- CCL for radiations to be used for the realization of the definition of the metre
- CCTF for radiations to be used as secondary representations of the second;

Terms of reference for the FSWG (Rec CCL2 from 2007)

1. To make recommendations to the CCL for radiations to be used for the realization of the definition of the metre and to make recommendations to the CCTF for radiations to be used as secondary representations of the second;
2. To maintain together with the BIPM the list of recommended frequency standard values and wavelength values for applications including the practical realization of the definition of the metre and secondary representations of the second;

•the following Terms of Reference have been drafted by the CCL-CCTF Frequency Standards Working Group (CCL-CCTF FS WG) at their 2007 meeting:

3. To take responsibility for key comparisons of standard frequencies such as CCL-K11;
4. To respond to future needs of both the CCL and CCTF concerning standard frequencies relevant to the respective communities;

•item 3 of Terms of Reference of the CCL-CCTF FS WG is particularly relevant to the conduction of the CCL-K11 key comparison;

Recommendation 1 of CIPM 2006

- the CCL-*Mise en Pratique* WG and CCL/CCTF JWG be combined into a single CCL-CCTF frequency standards working group,
- the *Mise en Pratique*-CCL list of Recommended Radiations and CCTF Secondary Representation list be combined into a single new list of “Recommended values of standard frequencies for applications including the practical realization of the metre and secondary representations of the second”,
- other frequencies may be proposed, evaluated and maintained on the frequency standards list by the CCL-CCTF frequency standards WG, not all of which are adopted as CCL-preferred radiations or CCTF-accepted representations,
- the CCTF consider and recommends those frequencies which it proposes the CIPM to accept as secondary representations of the second,
- the CCL considers and recommends those frequencies which it deems important for use in high accuracy length metrology, and
- the frequency values list is maintained on the BIPM website.

Recommendation 2 of CIPM 2006

- the unperturbed ground-state hyperfine quantum transition of ^{87}Rb with a frequency of f (^{87}Rb) = 6 834 682 610.904 324 Hz
  and an estimated relative standard uncertainty of 3×10^{-15},
- the unperturbed optical $5d^{10}\,6s\ ^2S_{1/2}$ (F = 0) – $5d^9\,6s^2\ ^2D_{5/2}$ (F =2) transition of the $^{199}Hg^+$ ion with a frequency of
  f ($^{199}Hg^+$) = 1 064 721 609 899 145 Hz
  and a relative standard uncertainty of 3×10^{-15},
- the unperturbed optical $5\ ^2S_{1/2} – 4\ ^2D_{5/2}$ transition of the $^{88}Sr^+$ ion with a frequency of f ($^{88}Sr^+$) = 444 779 044 095 484 Hz
  and a relative uncertainty of 7×10^{-15},
- the unperturbed optical $6s\ ^2S_{1/2}$ (F = 0) – $5d\ ^2D_{5/2}$ (F =2) transition of the $^{171}Yb^+$ ion
  with a frequency of f ($^{171}Yb^+$) = 688 358 979 309 308 Hz
  and a relative standard uncertainty of 9×10^{-15},
- the unperturbed optical transition $5s2\ ^1S_0 – 5s5p\ ^3P_0$ ^{87}Sr neutral atom with a frequency of f (^{87}Sr) = 429 228 004 229 877 Hz
  and a relative standard uncertainty of 1.5×10^{-14}.

Structure of the list of frequencies (I)

- Due to the large number of modifications and the new function of the list a complete list shall be published in Metrologia

- The form of this list follows in general the outline of the last complete list (Quinn, Metrologia 2003, based on the results from the 2001 CCL meeting

- modifications in order to reflect the structure of the list of frequencies on the BIPM website

Structure of the list of frequencies (II)

- Introduction and historical perspective
- List of frequencies
    - Part 1 (“living” list)
    - Part 2 (“frozen” list incl. lamps)
- Appendix 1 (Secondary representations of the second)
- Appendix 2 (Commonly used frequency standards for the realization of the definition of the metre)
- Appendix 3 (Source data and frequency differences)

Excerpt of the list of frequencies

“The list is divided into two parts.
The first part includes radiations of high accuracy
that are of utility to the realization of optical frequencies
and vacuum wavelengths. For up-to-date values
and their uncertainties please refer to the BIPM website.

The second part of the list includes radiations
that are still deemed of utility for various applications
but may have larger uncertainties
and which will in general have
no future updates of their values.”

APPENDIX 1

Secondary representations of the second

The following frequencies from the list of frequencies have been recommended by the CIPM (CI 1 - 2006) on proposition by the CCTF to be used as secondary representations of the second.

Frequency / Hz	Uncertainty	Atomic species	Reference / Section 1
6 834 682 610.904 324	3×10^{-15}	^{87}Rb	1.19
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1 064 721 609 899 145	3×10^{-15}	$^{199}Hg^{+}$	1.3

App. 2: Frequency standards commonly used for the realization of the definition of the metre

CCL-CCTF FSWG

The following frequencies from the list of frequencies *have been "designated by the CIPM"* based on the proposal by the CCL to be used as high quality standards to be particularly useful for the realization of the metre. Note, however, that according to *Recommendation I (CI-1983)* any other radiation whose frequency is determined by comparison with the frequency of the caesium atomic clock (method b; see Introduction) can be used to realize the definition of the metre.

Frequency / kHz	Fractional Uncertainty	Wavelength / fm	Laser / absorber	Ref. / Sect. 1
473 612 353 604	2.1×10^{-11}	632 991 212.579	HeNe / I_2	1.8
551 580 162 400	4.5×10^{-11}	543 515 663.608	- / I_2	1.7
563 260 223 513	8.9×10^{-12}	532 245 036.104	2 *f* (Nd:YAG) / I_2	1.6