Report of the CCL-CCTF FSWG to CCTF

- Activities of the FSWG
  - List of Recommended Frequencies
  - Optical frequency ratios
  - Protocol for traceability of the metre directly from the Cs clock (K11; comb validation)

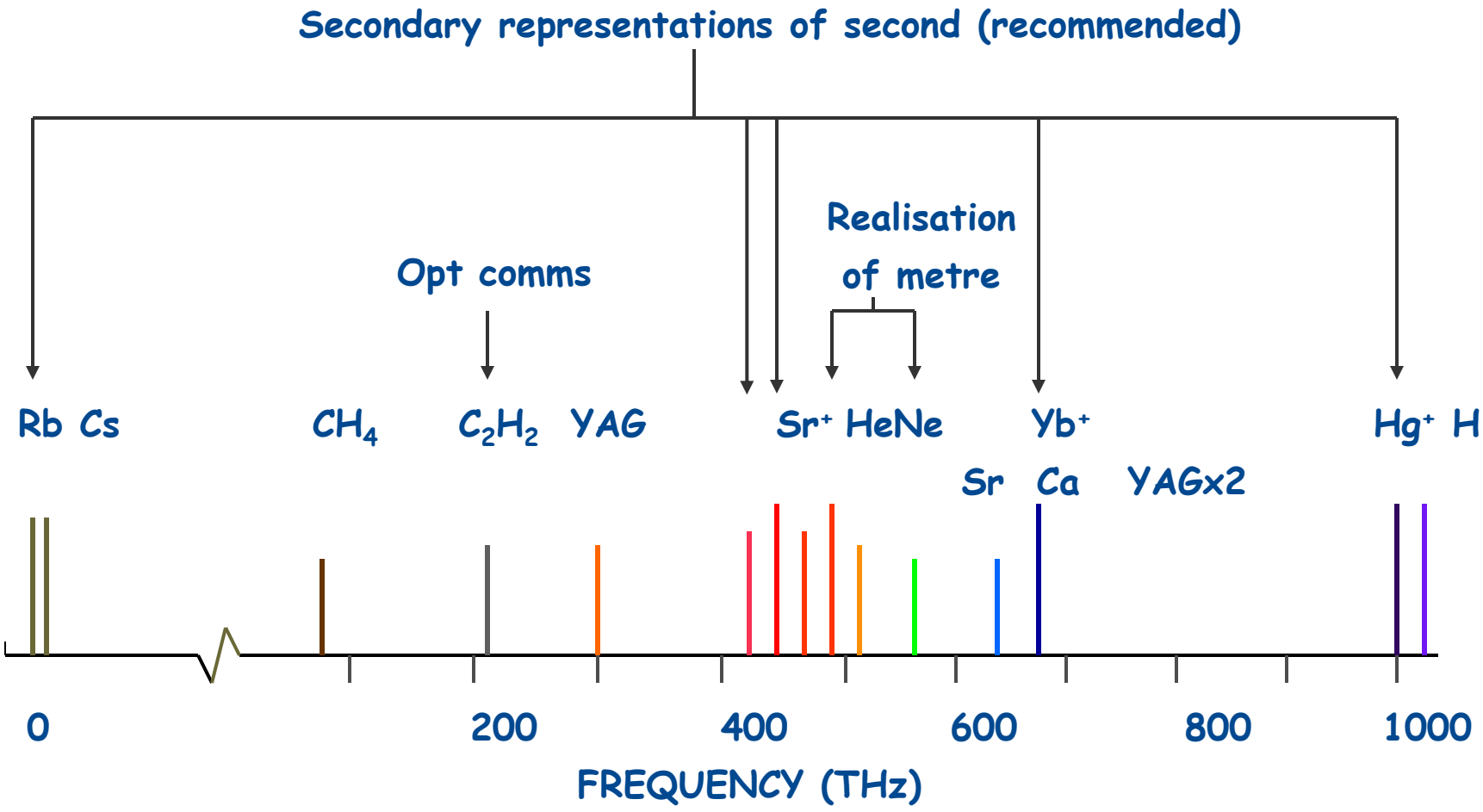
- Recommendations to the CCTF
  - Entries in the List of Recommended Frequencies (from 10/11 September 2012)

Prepared by F. Riehle (PTB) and Patrick Gill (NPL) for the CCTF on 13/14 September 2012

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;
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;

Recommended Standard Frequencies



http://www.bipm.org/en/publications/mep.html

BIPM - recommended frequencies - Windows Internet Explorer bereitgestellt von PTB

http://www.bipm.org/en/publications/mep.html

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> You are here: publications > recommended frequencies

Recommended values of standard frequencies

Version française

Summary

- Proceedings of CGPM, CIPM and CC meetings
- SI brochure
- Director's Reports
- BIPM Bulletins
- *Metrologia*
- Guides in metrology
- Scientific publications in the open literature
- *Rapports* BIPM
- Reports of BIPM Workshops
- *Monographies* BIPM
- Other *Monographs*
- Recommended values of standard frequencies
- *Mise en pratique* for the definition of the kelvin
- ITS-90 documents
- BIPM Annual Report on Time Activities
- Report of the CIPM *ad hoc* Working Group on Materials Metrology
- BIPM *Working Party Notes*
- Other miscellaneous publications

Related articles

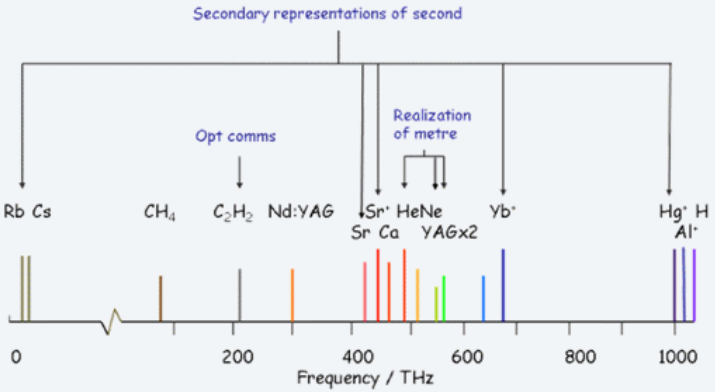
- Definition of the metre
- Definition of the second
- Consultative Committee for Length (CCL)
- Consultative

- **Values recommended by the CIPM for applications including the practical realization of the metre (MeP) and secondary representations of the second (SRS):**

Page last updated: 9 September 2010

698 nm (87Sr [SRS])

Graphical summary:



Background:

The list of recommended radiations was first published by the CIPM in 1983 (see CI-1983, Recommendation 1) in the *mise en pratique* of the definition of the metre. This specified that the metre should be realized by one of the following methods:

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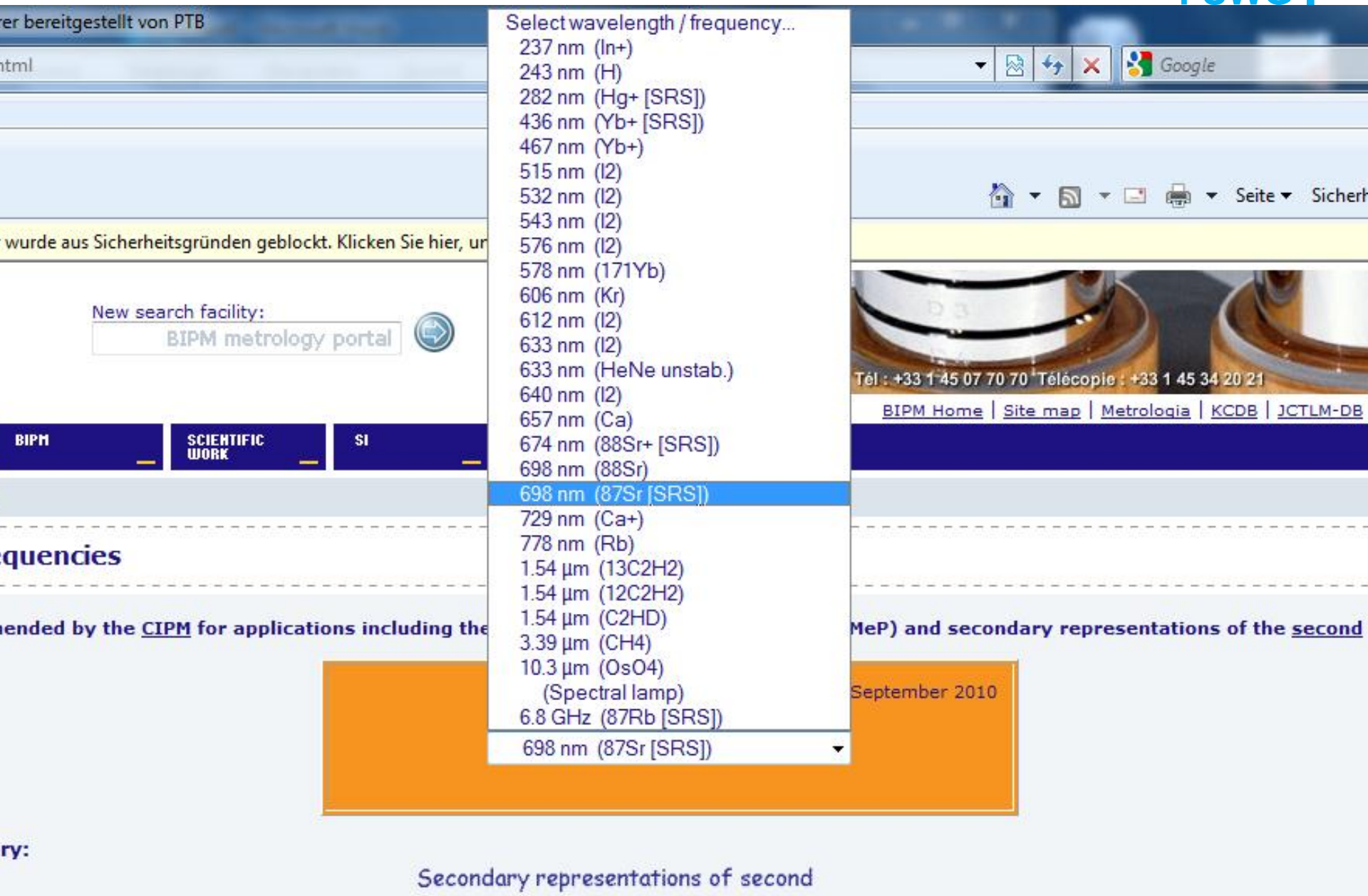
http://www.bipm.org/en/publications/mep.html



Publication in Metrologia

- Due to the large modifications and the new function of the list a complete list shall be published in Metrologia
- The form will follow the general 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
- Existing draft to be amended by
  - Recommendations of this CCTF
  - Discussion of the issue about the uncertainties of the entries in the list
  - A paragraph on frequency ratios
- Submission of final manuscript expected: end of 2012

Adaptation of CCL-K11 protocol to include comb-based calibrations of laser frequencies

CCL-CCTF FSWG

- **Discussions at 2009 FSWG and CCL/CCTF meetings over the need for protocol revision**
- **Set-up of FSWG sub-group to suggest revisions**
- **Changes drafted in line with adopted processes for K11**
- **Campaigns already completed within period 2009-12**
- **Draft protocol now on FSWG document site**
  (Minor modifications have been discussed this week and will be included)

Issues raised with respect to draft as is

- **Calibration via combs at "higher level of accuracy"**

  i.e. relative uncertainties < 10^{-11}

  Self-confirmation via peer-reviewed publication is sufficient for demonstration of capability for Key Comparison and associated CMC statements only if supported by equivalence of measurements with other NMIs.

- **Use of a transportable frequency stable laser as a comb capability validation device**

  if sufficient reproducibility and reliability is e.g. referenced to an atomic/molecular line

Optical frequency ratios (f/r)

- **Discussions at 2009 FSWG and CCL/CCTF meetings to deal with frequency ratios**
  - **Direct measurements limited by Cs realization**
  - **But optical frequency ratio measurements < 10^{-17}**
- **Set-up of FSWG sub-group to suggest utilizations (sub group led by NIST)**
- **Results**
  - **f/r for synthesized frequencies (already used !)**
  - **f/r for consistency checks ($(f1/f2)_1$ / $(f1/f2)_2$ = 1?)**
  - **all meas. vs. Cs and f/r in matrix (long term goal)**

Optical frequency ratios (f/r)

CCL-CCTF
FSWG

	Al^+	Be	Ca^+	Cs	Hg	Hg^+
Al^+	$u = 2.5\times10^{-17}$ Ref: Cho2010			$u = 5.4\times10^{-15}$ Ref: Ros2007		$u = 5.3\times10^{-17}$ Ref: Ros2008
Be						
Ca^+				$u = 2.5\times10^{-15}$ Ref: Chw2009		
Cs						
Hg				$u = 1.1\times10^{-13}$ Ref: Pet2008		
Hg^+	$u = 5.3\times10^{-17}$ Ref: Ros2008					

For the filled matrix use standard algorithms

Issue of f/r to be discussed in Metrologia paper

List of recommended frequencies (LoR)

CCL-CCTF
FSWG

- New entries into the LoR
  ($^{27}Al^+$,^{199}Hg)
- Update of a value in the LoR
  ($^{171}Yb^+$ octupole, $^{171}Yb^+$ quadrupole, $^{88}Sr^+$, $^{40}Ca^+$, ^{1}H)
- Update of the value and uncertainty of a secondary realisation of the second
  (^{87}Sr, $^{88}Sr^+$, $^{199}Hg^+$, $^{171}Yb^+$ quadrupole, ^{87}Rb microwave)
- New secondary representations of the second
  ($^{171}Yb^+$ octupole, ^{171}Yb, $^{27}Al^+$)
- No new realisation of the definition of the metre

$^{27}Al^{+}$ transition ($^{1}S_0 \leftrightarrow {}^{3}P_0$) (new)

f_{Al+} = 1 121 015 393 207 851(6) Hz

(NIST) **T. Rosenband et al PRL 98, 220801 (2007)**

f_{Al+} = 1 121 015 393 207 857.4(7) Hz)

(NIST) **T. Rosenband et al, *Science 319, 1808 (2008)***

(This value was derived from f_{Al+} / f_{Hg+} x f_{Hg+})

Recommended value (weighted mean):
1 121 015 393 207 857.3 Hz
(1.9×10^{-15}) (enlarged by 3 times)

^{199}Hg transition $^1S_0 - {}^3P_0$ (new)

SYRTE f = 1 128 575 290 808 162 (6.4) Hz

McFerran et al , PRL 108, 183004 (2012)

Recommended value:
1 128 575 290 808 162 Hz
(1.7×10^{-14}) (expanded uncertainty by 3 times)

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

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

Recommendation: 642 121 496 772 657 (6×10^{-14})

f = 642 121 496 772 657 (12) Hz

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

f = 642 121 496 772 646.22 (67) Hz

S.A. King et al , **New J. Phys. 14 013045 (2012)**

f = 642 121 496 772 645.15 (52) Hz

Huntemann et al, **PRL 108, 090801 (2012)**

Recommended value (weighted mean):
f = 642 121 496 772 645.57 Hz
(1.3×10^{-15}) (enlarged by 2 times)

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

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

Recommendation: 688 358 979 309 308 Hz (9 x 10^{-15})

PTB f = 688 358 979 309 307.65 (2.14) Hz.

CCL document 2005, Report **CCL-CCTF/06-11**

Corrected to f = 688 358 979 309 308(2.14) Hz (@ 0 K)

PTB f = 688 358 979 309 306.62(73) Hz (@ 300 K)

Tamm PHYSICAL REVIEW A 80, 043403 2009

Corrected to f = 688 358 979 309 306.97(73) Hz (@ 0 K)
with negligible contribution to the uncertainty

NPL f = 688 358 979 309 310(9) Hz

Webster et al, IEEE Trans. UIFFC **57**, 592 (2010)

Recommended (weighted mean):
***f* = 688 358 979 309 307.1**
(3 x 10^{-15}) (enlarged by 3 times)

$^{88}Sr^{+}$ transition ($^{2}S_{1/2} - {}^{2}D_{5/2}$) (update)

Recommendation: 444 779 044 095 484 Hz (7×10^{-15})

f = 444 779 044 095 484.6 (1.5) Hz

(NPL) Margolis et al Science 306 19 (2004) 1355

f = 444 779 044 095 484 (15) Hz

(NPL) Madej et al, **PHYSICAL REVIEW A 70, 012507 (2004), Dube et al PRL 95, 033001 (2005)**

f = 444 779 044 095 485.6 (9) Hz

(NPL) Madej et al, **PRL (accepted)**

Recommended (weighted mean):
444 779 044 095 485.3 Hz
(4.0×10^{-15}) (enlarged by 2 times)

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

Recommendation: 411 042 129 776 393 Hz (4×10^{-14})

f = 411 042 129 776 393.2 Hz (2.4×10^{-15})

M. Chwalla, et al, Phys. Rev. Lett. 102, 023002 (2009)

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

((not used because of order of magnitude larger uncertainty))

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

f = 411 042 129 776 398.4 Hz (2.9×10^{-15})

(NICT) Matsubara et al, Opt. Express 2012 (accepted)

f = 411 042 129 776 393.0 Hz (3.9×10^{-15})

(NICT) Y. Huang, Phys. Rev. A 85, 030503(R) (2012)

Recommended (weighted mean):
411 042 129 776 395 Hz
(1.5×10^{-14}) (enlarged by 3 times (inconsistencies))

^{1}H transition 1S – 2S (update)

Recommendation: 1 233 030 706 593. 55 kHz (2.0×10^{-13})

f = 1 233 030 706 593 515(5) Hz (4×10^{-15})

Parthey et al, **PRL 107, 203001 (2011)**

It was deemed that the determined centre frequency would only be based upon the most recent series of published results.
This was done considering the significant reduction in scatter for the line centre values due to improved laser system and the reduced systematic uncertainty associated with the evaluation with the second order Doppler shift uncertainty and by mapping the velocity distribution.

Recommended:
f = = 1 233 030 706 593 515 Hz (1.2×10^{-14})
(enlarged by 3 times)

This frequency is that of a laser stabilized to the two-photon transition

^{87}Sr transition (lattice clock; update)

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

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Recommendation (SRS): 429 228 004 229 873.7 (1×10^{-15})

JILA f = 429 228 004 229 873.65 (37) Hz

G. K. Campbell et al, Metrologia 45, 539 (2008)

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

X. Baillard et al, Eur. Phys. J. D 48, 11 (2008)

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

F.-L. Hong et al., Opt. Lett. 34, 692 (2009)

PTB f = 429 228 004 229 872.9 (5) Hz

S. Falke et al, Metrologia 48, 399 (2011)

NMIJ f = 429 228 004 229 873.9 (1.4) Hz

A. Yamaguchi et al, Appl. Phys. Express 5, 022701 (2012)

Recommendation (weighted mean):

$f_{^{87}Sr}$ = 429 228 004 229 873.4 Hz

(1×10^{-15}) (uncertainty kept)

^{171}Yb transition lattice clock (update)

$6s^2\ {}^1S_0 - 6s6p\ {}^3P_0$ transition

Recommendation: 518 295 836 590 864 (1.6×10^{-13})

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

T. Kohno et al, *Applied Physics Express* 2, 072501-1-3 (2009).

NMIJ f = 518 295 836 590 863.1(2.0) Hz

Yasuda et al, Appl. Phys. Express (2012) accepted

NIST f = 518 295 836 590 865.2(7) Hz

N. Lemke et al, Phys. Rev. Lett. 103 063001 (2009)

Recommendation (weighted mean):
f_{171Yb} = 518 295 836 590 865.0 Hz
(2.7×10^{-15})

Recommmended as Sec. Rep. of the Second

^{87}Rb microwave transition (update)

Recommendation (SRS): 6 834 682 610.904 324 (3×10^{-15})

- **Rb HF transition**

  was the first Secondary Representation of the Definition of the Second

- **Continuous comparisons between Cs and Rb HF were performed by LNE-SYRTE**

- **In 2011/12 SYRTE presented data to be included in Circular T**

- **The WGPFS investigated the data and the reports from SYRTE in 2012**

^{87}Rb microwave transition (update)

… the WGPFS recommends that the BIPM accept the SYRTE data for publication in Circular T.

It is evident from the data in the SYRTE reports that the Rb frequency for a secondary standard needs to be revised.

The WGPFS recommends

that the CCL-CCTF Frequency Standards WG consider revising the Rb frequency.

In the meantime the WGPFS recommends

that the SYTRE Rb reports be published in Circular T,

but not yet used in the steering of TAI.

^{87}Rb microwave transition (update)

Recommendation (SRS): 6 834 682 610.904 324 (3×10^{-15})

SYRTE f = 6 834 682 610.904 314 (4) Hz

J. Guena, et al, IEEE Trans. UFFC 57, 647 (2010)

An improved evaluation of the dual fountain at SYRTE was reported

J. Guena, et al, IEEE Trans. UFFC 59, 391 (2012)

SYRTE f = 6 834 682 610.904 312 (3) Hz

CCTF_12-18-LNE-SYRTE_Report, data from Feb 2012 – August 2012

An independent evaluation by the BIPM using the values of Circular T related to the Cs fountain ensemble was consistent within the uncertainty.

Recommendation:
f = 6 834 682 610.904 312 Hz
(1.3×10^{-15}) (expanded 3 times)

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)

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;

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.

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}.

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

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