Report of the CCL-CCTF WGFS to CCTF

- Activities of the CCL-CCTF WGFS
  - Meetings since last CCTF
  - New approach to include frequency ratios and absolute frequency measurements into the CIPM List of Recommended Frequencies (LoF)

- Recommendations to the CCTF
  - Updated entries in the CIPM List of Recommended Frequencies (from 3/4 May and 6 June 2017)
  - Recommendations for operating, comparing and reporting frequency standards as Secondary Representations of the Second in preparation for a redefinition of the second by optical transitions

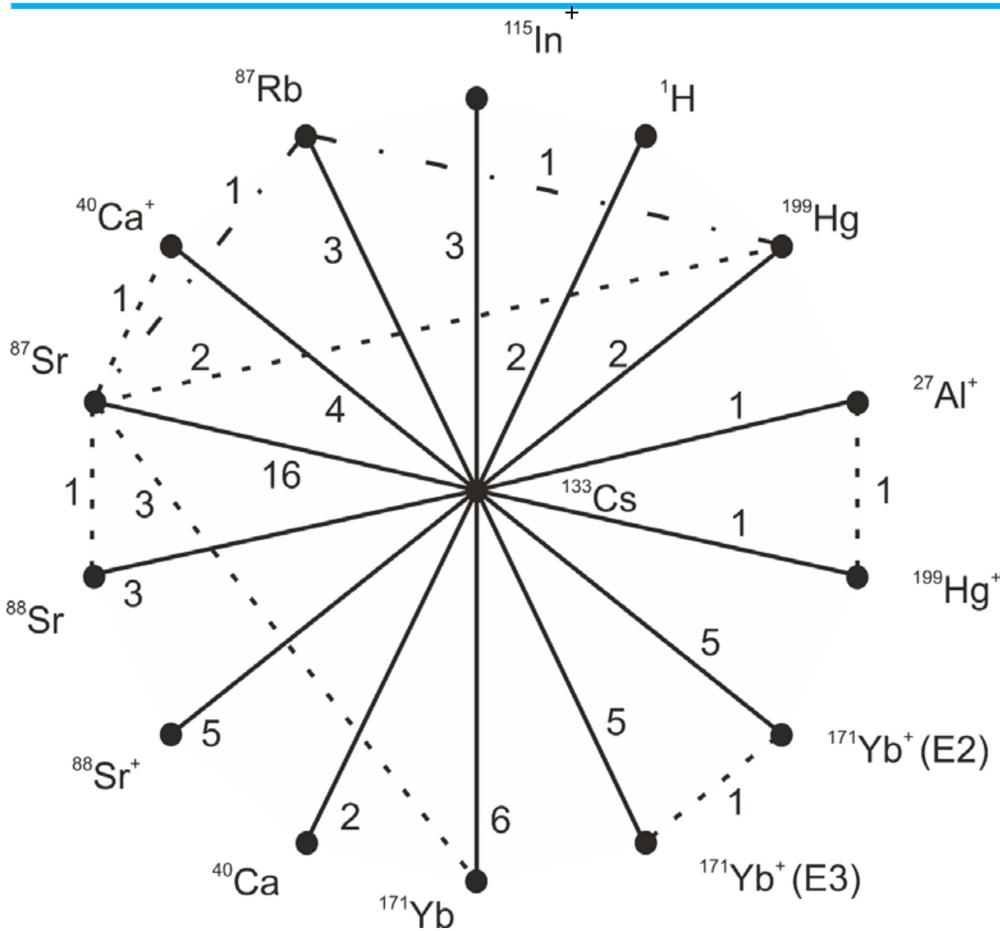
Prepared by F. Riehle (PTB) and Patrick Gill (NPL) for the CCTF on 8 June 2017

Activities of the CCL-CCTF WGFS

Meetings

- 2016 York at the EFTF
  - New schedule for preparing recommendations
  - Establishment of a WGFS Subgroup
- WGFS Subgroup work started January 2017
- 2017-05-3/4 at the BIPM
  - Discussion and preparation of WGFS rcommendations 2017
    - Frequency values and ratios
    - Status of optical frequency standards
- 2017-06-6 at the BIPM
  - Morning session jointly with WGPSFS
  - Afternoon: Evaluation of new frequency values for the CIPM LoF

Frequency and frequency ratio measurements



- Over-determined set of clock comparison data
- Use a least-squares adjustment procedure, to provide a self-consistent set of recommended values

Margolis, H. S. & Gill, P.: Least-squares analysis of clock frequency comparison data to deduce optimized frequency and frequency ratio values; *Metrologia,* 2015*,* **52**, 628-634

Robertsson, L.: On the evaluation of ultra-high-precision frequency ratio measurements: examining closed loops in a graph theory framework; *Metrologia,* 2016*, 53*, 1272-1280

Oates, Ch., private commun. 2017

Riehle, F., Gill, P., Arias, F., Robertsson, L.: Recommended frequency standard values for applications including the practical realisation of the metre and secondary representations of the second; in preparation for *Metrologia*

Source data file (I)

$^{115}In^{+}$

q1	nu1	1267402452899920.0 Hz	690.0	[vonZanthier2000]
q2	nu1	1267402452901265.0	256.0	[Wang2007a]
~~q3~~	~~nu1~~	~~1267402452900967.0~~	~~63.0~~	~~[Wang2007b]~~
q4	nu1	1267402452901049.9	20.7	[Ohtsubo2017 accepted]

^{1}H

q5	nu2	1233030706593517.5	5.0	[Parthey2011]
q6	nu2	1233030706593509 5.5	5.1	[Matveev2013]

^{199}Hg

q7	nu3	1128575290808155.1	6.4	[McFerran2012, corr. 2015]
q8	nu3	1128575290808154.62	0.41	[Tyumenev2016]

$^{27}Al^{+}$

q9	nu4	1121015393207851.0	6.0	[Rosenband2007]

$^{199}Hg^{+}$

q10	nu5	1064721609899145.30	0.69	[Stalnaker2007]

Source data file (II)

$^{171}Yb^{+}$(E2 or quadrupole)

q11	nu6	688358979309308.0	2.14	[12thCCL]
q12	nu6	688358979309306.97	0.73	[Tamm2009BBRcorrected]
q13	nu6	688358979309310.0	9.0	[Webster2010]
q14	nu6	688358979309307.82	0.36	[Tamm2014]
q15	nu6	688358979309308.42	0.42	[Godun2014]
~~q16~~	~~nu6~~	~~688358979309308.02~~	~~0.23~~	~~[PTBInPreparation]~~

(removed because value is not published yet)

$^{171}Yb^{+}$(E3 or octupole)

q17	nu7	642121496772657.0	12.0	[Hosaka2009]
q18	nu7	642121496772645.15	0.52	[Huntemann2012]
q19	nu7	642121496772646.22	0.67	[King2012]
q20	nu7	642121496772644.91	0.37	[Godun2014]
q21	nu7	642121496772645.36	0.25	[Huntemann2014]
~~q22~~	~~nu7~~	~~642121496772645.14~~	~~0.29~~	~~[NPLUnpublished]~~
~~q23~~	~~nu7~~	~~642121496772645.13~~	~~0.16~~	~~[PTBInPreparation]~~

(removed because value is not published yet)

Source data file (III)

^{171}Yb

q24	nu8	518295836590864.0	28.0	[Kohno2009]
q25	nu8	518295836590863.1	2.0	[Yasuda2012]
q26	nu8	518295836590865.2	0.7	[Lemke2009]
q27	nu8	518295836590863.5	8.1	[Park2013]
q28	nu8	518295836590863.59	0.31	[Pizzocaro2017]
q29	nu8	518295836590863.38	0.57	[Kim2017]

^{40}Ca

q30	nu9	455986240494144.0	5.3	[Degenhardt2005]
q31	nu9	455986240494135.8	3.4	[Wilpers2006, 2007]

$^{88}Sr^{+}$

q32	nu10	444779044095484.6	1.5	[Margolis2004]
q33	nu10	444779044095484.0	15.0	[Dube2005]
q34	nu10	444779044095485.5	0.9	[Madej2012]
q35	nu10	444779044095486.71	0.24	[Barwood2014]
q36	nu10	444779044095485.27	0.75	[Dube2017]

^{88}Sr

q37	nu11	429228066418009.0	32.0	[Baillard2007]
q38	nu11	429228066418008.3	2.1	[Morzynski2015SrI]
q39	nu11	429228066418007.3	2.9	[Morzynski2015SrII]

Source data file (IV)

^{87}Sr

q40	nu12	429228004229874.0	1.1	[Boyd2007]
q41	nu12	429228004229873.65	0.37	[Campbell2008]
q42	nu12	429228004229873.6	1.1	[Baillard2008]
q43	nu12	429228004229874.1	2.4	[Hong2009]
q44	nu12	429228004229872.9	0.5	[Falke2011]
q45	nu12	429228004229873.9	1.4	[Yamaguchi2012]
q46	nu12	429228004229872.0	1.6	[Akamatsu2014b]
q47	nu12	429228004229873.56	0.49	[Tanabe2015]
q48	nu12	429228004229873.7	1.4	[Lin2015]
q49	nu12	429228004229873.13	0.17	[Falke2014]
q50	nu12	429228004229873.10	0.13	[LeTargat2013]
q51	nu12	429228004229872.92	0.12	[Lodewyck2016]
q52	nu12	429228004229872.97	0.16	[Grebing2016(Oct14)]
q53	nu12	429228004229873.04	0.11	[Grebing2016(Jun15)]
q54	nu12	429228004229872.97	0.40	[Hachisu2017]
q55	nu12	429228004229872.99	0.18	[Hachisu2017b]

Source data file (V)

$^{40}Ca^{+}$

q56	nu13	411042129776393.2	3.0	[Chwalla2009]
q57	nu13	411042129776398.4	1.2	[Matsubara2012]
q58	nu13	411042129776400.5	1.2	[Huang2015,2012value]
q59	nu13	411042129776401.7	1.1	[Huang2015, 2014/15 val.]

^{87}Rb

q60	nu14	6834682610.904312	3.0e-6	[SYRTE TAI data; MJD 55954-57867 i.e. Jan 2012 – April 2017]
q61	nu14	6834682610.9043070	3.1e-6	[Ovchinnikov2015]
q62	nu14	6834682610.9043125	2.1e-6	[Guena2017]

Source data file (VI; frequency ratios)

^{199}Hg /^{87}Sr

q63	nu3_over_nu12 [Yamanake2015]	2.62931420989890960	2.2e-16
q64	nu3_over_nu12 [Tyumenev2016]	2.62931420989890915	4.6e-16

^{199}Hg /^{87}Rb

q65	nu3_over_nu14 [Tyumenev2016]	165124.754879997258	6.2e-11

^{27}Al^{+}/^{199}Hg^{+}

q66	nu4_over_nu5 [Rosenband2008]	1.052871833148990438	5.5e-17

^{171}Yb^{+}(E2 or quadrupole)/ ^{171}Yb^{+}(E3 or octupole)

q67	nu6_over_nu7 [Godun2014]	1.07200737363420630	3.6e-16
~~q68~~	~~nu6_over_nu7~~	~~1.07200737363420543~~	~~1.5e-1 [PTBInPreparation]~~

^{171}Yb^{+}(E3 or octupole)/ ^{87}Sr

~~q69~~	~~nu7_over_nu12~~	~~1.495991618544900642~~	~~3.5e-17 [PTBInPreparation]~~

Source data file (VII; frequency ratios)

^{171}Yb /^{87}Sr

q70 nu8_over_nu12 1.207507039343412 1.7e-15
[Akamatsu2014aErrata]

q71 nu8_over_nu12 1.2075070393433776 2.9e-16
[Takamoto2015]

q72 nu8_over_nu12 1.20750703934333749 5.5e-17
[Nemitz2016]

~~q73 nu8_over_nu12 1.2075070393433841 3.4e-16~~
~~[PTB/INRIMInPreparation]~~ (removed because value is not published yet)

^{88}Sr /^{87}Sr

q74 nu11_over_nu12 1.000001448836827727 23.0e-18
[Takano accepted]

^{87}Sr/$^{40}Ca^{+}$

q75 nu12_over_nu13 1.0442433345296416 2.5e-15
[Matsubara2012]

^{87}Sr/^{87}Rb

q76 nu12_over_nu14 62801.453800512435 2.1e-11
[Lodewyck2016]

No changes proposed

^{1}H

CIPM rec.: f(^{1}H) = 1 233 030 706 593 514 Hz + - 9 x 10^{-15}

Recalculation: f(^{1}H) = 1 233 030 706 593 513.6538 Hz + - 3.7 Hz

No update (since no new data available)

$^{27}Al^{+}$

CIPM rec.: f(^{27}Al) = 1 121 015 393 207 857.3 Hz + - 1.9 x 10^{-15}

Recalculation: f(^{27}Al) = 1 121 015 393 207 857.3031 Hz +- 0.7235 Hz

No update (since no new data available)

$^{199}Hg^{+}$

CIPM rec.: f($^{199}Hg^{+}$) = 1 064 721 609 899 145.30 Hz + - 1.9 x 10^{-15}

Recalculation: f($^{199}Hg^{+}$) = 1 064 721 609 899 145.2122 Hz +- 0.6850 Hz

In principle, the recommended value ought to be 0.1 Hz lower, i.e. ...145.2, but since this difference is negligible compared to the recommended uncertainty and since there are no new data available → No update

No changes proposed

$^{171}Yb^+$(E2 or quadrupole)

CIPM rec.: $f(^{171}Yb^+, E2)$ = 688 358 979 309 308.3 + - 6×10^{-16}

Recalculation: $f(^{171}Yb^+, E2)$ = 688 358 979 309 308.3180 Hz +- 0.2176 Hz

No update (since no new data available)

$^{171}Yb^+$(E3 or octupole)

CIPM rec.: $f(^{171}Yb^+, E3)$ = 642 121 496 772 645.0 + - 6×10^{-16}

Recalculation: $f(^{171}Yb^+, E3)$ = 642 121 496 772 645.0259 Hz +- 0.1623 Hz

No update (since no new data available)

^{40}Ca

CIPM rec.: $f(^{40}Ca)$ = 455 986 240 494 140 Hz + - 1.8×10^{-14}

Recalculation: $f(^{40}Ca)$ = 455 986 240 494 138.1907 Hz +- 2.862 Hz

In principle, the recommended value ought to be 1.8 Hz lower, i.e. ...138.2, but since this difference is negligible compared to the recommended uncertainty and since there are no new data available → No update

$^{115}In^{+}$ transition $5s^2\ ^1S_0 – 5s5p\ ^3P_0$

q1	nu1	1267402452899920.0	690.0	[vonZanthier2000]
q2	nu1	1267402452901265.0	256.0	[Wang2007a]
~~q3~~	~~nu1~~	~~1267402452900967.0~~	~~63.0~~	~~[Wang2007b]~~
	(removed because of inconsistency)			
q4	nu1	1267402452901049.9	20.7	[Ohtsubo2017 accept.]

CIPM 2003: 1267402452899920 Hz + - 3.6 x 10^{-13}

Recalculation: 1267402452901050.2866 Hz + - 20.62 Hz

The four values available are inconsistent as Wang2007a and Wang7b have very different uncertainties but result from the same data set and there is not a clear explanation for this difference. It was decided to keep the measurement with the larger uncertainty [Wang2007a]. From the least square procedure it turned out that the uncertainty of [vonZanthier2000] is not compatible with the other data. Thus the uncertainty given in the original publication [vonZanthier2000] was increased to 690 Hz to make it statistically more consistent. [Ohtsubo2017] has an uncertainty that is more than ten times smaller than the other ones and this uncertainty was enlarged by a factor of 3 to 20.7 Hz in the calculation.

The adopted value of $f(^{115}In)$ is 1267402452901050 Hz $u_c/y = 1.6 \times 10^{-14}$

^{199}Hg transition 6s^2 $^1S_0$ – 6s6p $^3P_0$ (update)

q7	nu3	1128575290808155.1	6.4	[McFerran2012, corr.2015]
q8	nu3	1128575290808154.62	0.41	[Tyumenev2016]

^{199}Hg /^{87}Sr

q63	nu3_over_nu12	2.62931420989890960	2.2e-16 [Yamanaka2015]
q64	nu3_over_nu12	2.62931420989890915	4.6e-16 [Tyumenev2016]

^{199}Hg /^{87}Rb

q65	nu3_over_nu14	165124.754879997258	6.2e-11 [Tyumenev2016]

CIPM LoF: 1128575290808154.8 Hz +- 6 x 10^{-16}

Recalculation: 1128575290808154.4163 Hz +- 0.1419 Hz (1.3x10^{-16})

The adopted value of $f(^{199}\text{Hg})$ 1128575290808154.4 Hz u_c/y = 5 x 10^{-16}

has been calculated by the methods presented in * with the data from the source table attached below. The estimated standard uncertainty of 5 x 10^{-16} takes into account the uncertainty of the ^{87}Sr value of 4 x 10^{-16} governing the evaluation procedure and quantitatively unknown contributions of the correlations between the data of [Tyumenev2016].

* [Margolis, Gill 2015, Robertsson 2015, Oates 2017, Riehle et al 2017]

^{171}Yb transition 6s^2 $^1S_0$ – 6s5p $^3P_0$; latt. clock

q24	nu8	518295836590864.0	28.0	[Kohno2009]
q25	nu8	518295836590863.1	2.0	[Yasuda2012]
q26	nu8	518295836590865.2	0.7	[Lemke2009]
q27	nu8	518295836590863.5	8.1	[Park2013]
q28	nu8	518295836590863.59	0.31	[Pizzocaro2017]
q29	nu8	518295836590863.38	0.57	[Kim2017]

^{171}Yb /^{87}Sr

q70	nu8_over_nu12	1.207507039343412	1.7e-15	[Akamatsu2014aErrata]
q71	nu8_over_nu12	1.2075070393433776	2.9e-16	[Takamoto2015]
q72	nu8_over_nu12	1.20750703934337749	5.5e-17	[Nemitz2016]

CIPM LoF: $f(^{171}\text{Yb})$ = 518 295 836 590 864.0 + - 2×10^{-15}

Recalculation: $f(^{171}\text{Yb})$ = 518 295 836 590 863.6440 Hz +- 0.0609 Hz

The adopted value of $f(^{171}\text{Yb})$ 518 295 836 590 863.6 Hz u_c/y = 5 x 10^{-16}

has been calculated by the methods presented in * with the data from the source table attached below. The estimated standard uncertainty of 5 x 10^{-16} takes into account the uncertainty of the ^{87}Sr value of 4 x 10^{-16} governing the evaluation procedure and also takes into account the smaller database.

* [Margolis, Gill 2015, Robertsson 2015, Oates 2017, Riehle et al 2017]

$^{88}Sr^{+}$ transition (5s $^{2}S_{1/2}$ – 4d $^{2}D_{5/2}$) (update)

q32	nu10	444779044095484.6	1.5	[Margolis2004]
q33	nu10	444779044095484.0	15.0	[Dube2005]
q34	nu10	444779044095485.5	0.9	[Madej2012]
q35	nu10	444779044095486.71	0.24	[Barwood2014]
q36	nu10	444779044095485.27	0.75	[Dube2017]

CIPM LoF: $f(^{88}Sr^{+})$ = 444 779 044 095 486.6 Hz + - 1.6×10^{-15}

Recalculation: $f(^{88}Sr^{+})$ = 444 779 044 095 486.4697 Hz +- 0.219 Hz

The adopted value of $f(^{88}Sr^{+})$ 444 779 044 095 486.5 Hz $u_c/y = 1.5 \times 10^{-15}$

has been calculated by the methods presented in * with the data from the source table attached below. Since the result is largely dominated by a single measurement ([Barwood2014]), the final uncertainty has been increased by a factor of three.

* [Margolis, Gill 2015, Robertsson 2015, Oates 2017, Riehle et al 2017]

^{88}Sr 5s^2 $^1S_0$ – 5s5p $^3P_0$ (update)

q37	**nu11**	**429228066418009.0**	**32.0**	**[Baillard2007]**
q38	**nu11**	**429228066418008.3**	**2.1**	**[Morzynski2015SrI]**
q39	**nu11**	**429228066418007.3**	**2.9**	**[Morzynski2015SrII]**

^{88}Sr /^{87}Sr

q74	**nu11_over_nu12**	**1.0000001448836827727**	**23e-18**	**[Takano2017 Accepted]**

CIPM LoF: **$f(^{88}\mathrm{Sr})$ = 429 228 066 418 012 Hz + - 1 x 10^{-14}**

Recalculation: **$f(^{88}\mathrm{Sr})$ = 429 228 066 418 007. 0377 Hz +- 0.048 Hz**

The adopted value of $f(^{88}\mathrm{Sr})$ 429 228 066 418 007.0 Hz **$u_c/y = 6 \times 10^{-16}$**

has been calculated by the methods presented in * with the data from the source table attached below. Given that the calculated uncertainty is dominated by the uncertainty of the frequency ratio [Takano2017], the CCTF enlarged the recommended uncertainty to 6 x 10^{-16}, which is the fractional uncertainty of the best realisation of the ^{88}Sr standard today [Takano2017].

* [Margolis, Gill 2015, Robertsson 2015, Oates 2017, Riehle et al 2017]

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

q40	nu12	429228004229874.0	1.1	[Boyd2007]
q41	nu12	429228004229873.65	0.37	[Campbell2008]
q42	nu12	429228004229873.6	1.1	[Baillard2008]
q43	nu12	429228004229874.1	2.4	[Hong2009]
q44	nu12	429228004229872.9	0.5	[Falke2011]
q45	nu12	429228004229873.9	1.4	[Yamaguchi2012]
q46	nu12	429228004229872.0	1.6	[Akamatsu2014b]
q47	nu12	429228004229873.56	0.49	[Tanabe2015]
q48	nu12	429228004229873.7	1.4	[Lin2015]
q49	nu12	429228004229873.13	0.17	[Falke2014]
q50	nu12	429228004229873.10	0.13	[LeTargat2013]
q51	nu12	429228004229872.92	0.12	[Lodewyck2016]
q52	nu12	429228004229872.97	0.16	[Grebing2016(Oct14)]
q53	nu12	429228004229873.04	0.11	[Grebing2016(Jun15)]
q54	nu12	429228004229872.97	0.40	[Hachisu2017]
q55	nu12	429228004229872.99	0.18	[Hachisu2017b]

$^{87}Sr/^{40}Ca^+$

q75	nu12_over_nu13	1.0442433345296416	2.5e-15	[Matsubara2012]

$^{87}Sr/^{87}Rb$

q76	nu12_over_nu14	62801.453800512435	2.1e-11	[Lodewyck2016]

^{87}Sr transition 5s^2 $^1S_0$ – 5s5p $^3P_0$ (update)

CIPM LoF: 429228004229873.2 Hz + - 5 x 10^{-16}

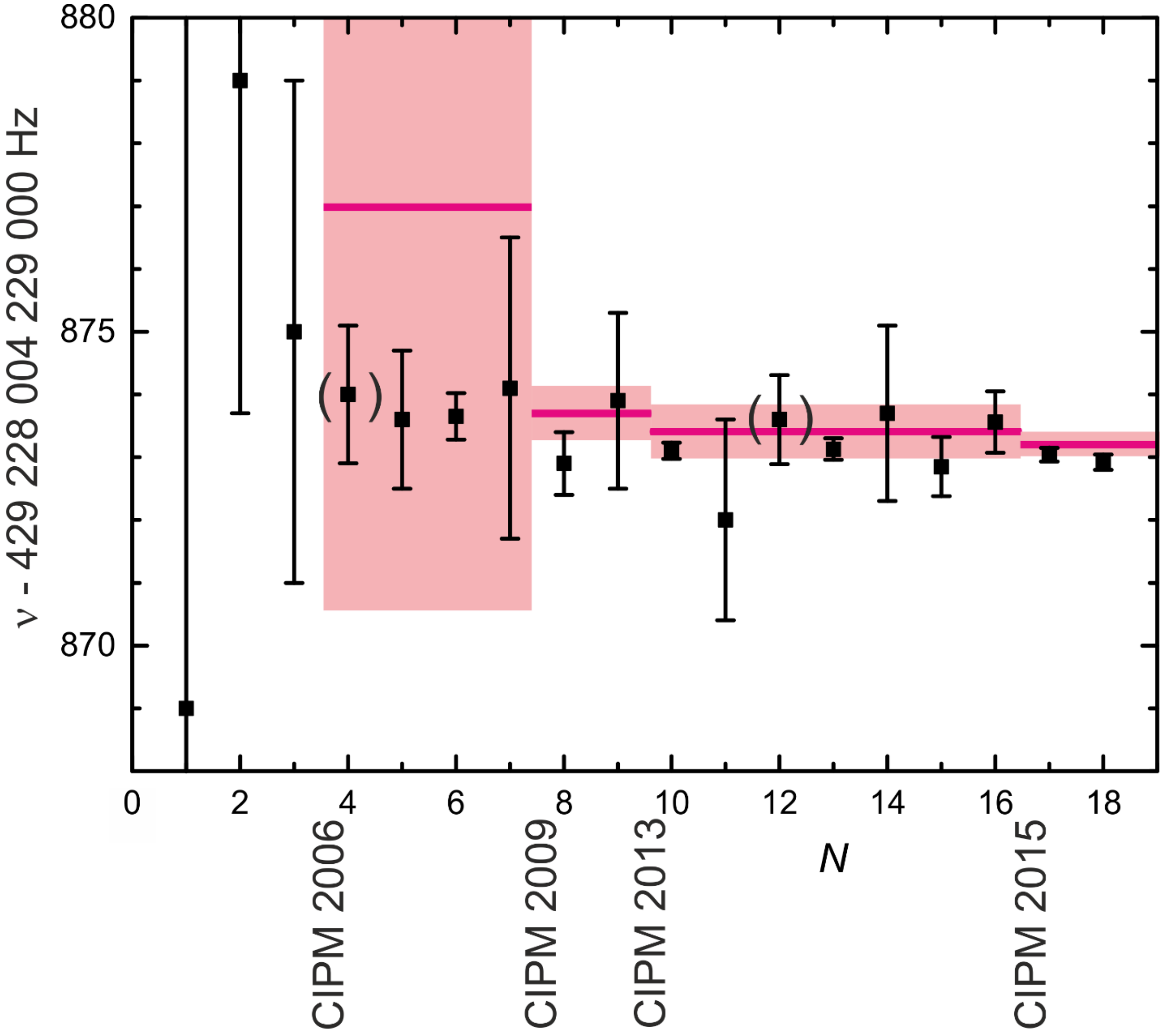
Recalculation: 429228004229873.0356 Hz +- 0.047 Hz

The adopted value of $f(^{87}Sr)$ 429228004229873.0 Hz u_c/y = 4 x 10^{-16}

has been calculated by the methods presented in * with the data from the source table attached below. The recommended uncertainty is the same as that of the most accurate comparison between the Cs PFS at LNE-SYRTE and PTB via an optical fibre link [Guena2017] i.e. 4 x 10^{-16}.

* [Margolis, Gill 2015, Robertsson 2015, Oates 2017, Riehle et al 2017]

Frequency measurements of ^{87}Sr



$^{40}Ca^+$ transition 4s $^2S_{1/2}$ – 3d $^2D_{5/2}$ (update)

q56	nu13	411042129776393.2	3.0	[Chwalla2009]
q57	nu13	411042129776398.4	1.2	[Matsubara2012]
q58	nu13	411042129776400.5	1.2	[Huang2015,2012value]
q59	nu13	411042129776401.7	1.1	[Huang2015,2014/15value]

CIPM LoF: $f(^{40}Ca^+)$ = 411 042 129 776 398.4 Hz + - 1.2 x 10^{-14}

Recalculation: $f(^{40}Ca^+)$ = 411 042 129 776 399.7963 Hz ± 0.5458 Hz.

The adopted value of $f(^{40}Ca^+)$ = 411 042 129 776 399.8 Hz **$u_c/y = 2.4 \times 10^{-15}$**

has been calculated by the methods presented in * with the data from the source table attached below. Since [Chwalla2009] is not compatible with the other data, the uncertainty given in the original publication was increased to 3 Hz to make it statistically more consistent. This value has very little effect, and so the recommended frequency value comes essentially only from measurements made by two labs. Thus the final $^{40}Ca^+$ uncertainty was enlarged by a factor of 2.

* [Margolis, Gill 2015, Robertsson 2015, Oates 2017, Riehle et al 2017]

^{87}Rb microwave transition (update)

q60	nu14	6834682610.9043129 Hz	3.0e-6 Hz	[SYRTE TAI data; MJD 55954-57867 i.e. Jan 2012 – April 2017]
q61	nu14	6834682610.9043070 Hz	3.1e-6 Hz	[Ovchinnikov2015]
q62	nu14	6834682610.9043125 Hz	2.1e-6 Hz	[Guena2017]

CIPM LoF: $f(^{87}\mathrm{Rb})$ = 6 834 682 610.904 310 Hz +- 7 x 10^{-16}

Recalculation: $f(^{87}\mathrm{Rb})$ = 6 834 682 610.904 312 5645 Hz +- 1.177 x 10^{-06} Hz

The adopted value of $f(^{87}\mathrm{Rb})$ = 6 834 682 610.904 312 6 Hz **u_c/y = 6 x 10^{-16}**
has been calculated by the methods presented in * with the data from the source table attached below. Given that there are only two contributors and the result is heavily influenced by the LNE-SYRTE Rb standard by both direct frequency and frequency ratio measurements, which have a total uncertainty of 3.1 x 10^{-16}, the CCTF multiplied the total uncertainty by a factor of 2 to give 6.2 x 10^{-16} and rounded it to 6 x 10^{-16}.

* [Margolis, Gill 2015, Robertsson 2015, Oates 2017, Riehle et al 2017]

^{199}Hg transition $6s^2\ {}^1S_0 – 6s6p\ {}^3P_0$: New SRS

The recommended frequency of the ^{199}Hg lattice clock transition

$f(^{199}\mathrm{Hg}) = 1\ 128\ 575\ 290\ 808\ 154.4$ Hz $\qquad u_c/y = 5 \times 10^{-16}$

has now an uncertainty that is comparable to that of primary caesium fountain clocks. The CCTF therefore recommends this standard as a new Secondary Representation of the Second with a fractional standard uncertainty of 5×10^{-16}.

CCL-CCTF WGFS procedure for updating the CIPM List of Frequencies