Report of the CCL-CCTF Frequency Standards Working Group (WGFS) to the CCTF 2017

Since the CCTF 2015 the WGFS has met twice. The first meeting took place at the EFTF 2016 at York on 7 April 2016 and the second one on 3/4 May at the BIPM. There will be a third meeting on 6 June 2017 at the BIPM prior to the CCTF 2017.

At York on April 7, 2016 the WGFS decided on a new procedure for arriving at the recommendations to the CCTF because of the decision by the CIPM to break the three-year cycle of CCTF meetings collocated with the CCL meetings and the paradigm change how to arrive at the recommendations. The latter one was necessary as the increasing number of frequency measurements and optical frequency ratio measurements asked for longer evaluation periods. A subgroup with the members Sebastien Bize (LNE-SYRTE), Helen Margolis (NPL), Chris Oates (NIST), Fritz Riehle (PTB), Lennart Robertsson (BIPM) started the preparation of possible recommendations about half a year before the CCTF. A Questionnaire was sent out to the National Metrology Institutes about four months before the CCTF and six answers were received. The subgroup has investigated these answers as well as the general literature. Three independent programs have been developed and used to make an adjustment of the frequencies for recommendation in an overdetermined system of frequency measurements and frequency ratio measurements. In preparation of the second meeting the subgroup has made suggestions for the recommendations based on a list of frequency measurements.

At the BIPM on May 3 and 4, 2017 thirteen optical and one microwave standard were discussed and the following preliminary recommendations to the CCTF were prepared (see below). The final discussion during the third WGFS meeting on 6 June at the BIPM may lead to very small modifications of these recommendations.
Dr Riehle gave a presentation of the paper on the list of recommended frequencies for submission to Metrologia which contains a historical perspective from the Mise en pratique of the definition of the metre to the current list of recommended frequencies, the new approach to determine frequencies in an overdetermined system, the procedures applied by the WGFS to derive the values of the recommended frequencies, and the possible route to a new definition of the second by an optical frequency.
The WGFS discussed the influence of correlations between the different measurements used for the recommendations that could underestimate the final uncertainty. Several test examples have been calculated and it was found that this influence is currently small but already detectable and will become more and more important in the future. Hence, the WGFS will prepare a guideline on how to report on measurements of optical frequencies and frequency ratios. A draft is expected to be discussed at the third meeting of the WGFS on 6 June 2017.

1. The following frequencies have been discussed but no update is suggested

^{1}H

CIPM recommendation: **$f(^{1}H) = 1\ 233\ 030\ 706\ 593\ 514$ Hz + - 9×10^{-15}**

New calculation: **$f(^{1}H) = 1\ 233\ 030\ 706\ 593\ 513.6538$ Hz + - 3.7 Hz**

Proposed Recommendation: **$f(^{1}H) = 1\ 233\ 030\ 706\ 593\ 514$ Hz +- 9×10^{-15}**

No update (since no new data available)

$^{27}Al^{+}$

CIPM recommendation: **$f(^{27}Al) = 1\ 121\ 015\ 393\ 207\ 857.3$ Hz + - 1.9×10^{-15}**

New calculation: **$f(^{27}Al) = 1\ 121\ 015\ 393\ 207\ 857.3031$ Hz +- 0.7235 Hz**

Proposed Recommendation: **$f(^{27}Al) = 1\ 121\ 015\ 393\ 207\ 857.3$ Hz + - 1.9×10^{-15}**

No update (since no new data available)

$^{199}Hg^{+}$

CIPM recommendation: **$f(^{199}Hg^{+}) = 1\ 064\ 721\ 609\ 899\ 145.30$ Hz + - 1.9×10^{-15}**

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

Proposed Recommendation: **$f(^{199}Hg^{+}) = 1\ 064\ 721\ 609\ 899\ 145.2$ Hz + - 1.9×10^{-15}**

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

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

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

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

Proposed Recommendation: **$f(^{171}Yb^{+}, E2) = 688\ 358\ 979\ 309\ 308.3$ Hz +- 6×10^{-16}**

No update (since no new data available)

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

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

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

Proposed Recommendation: **$f(^{171}Yb^{+}, E3) = 642\ 121\ 496\ 772\ 645.0$ Hz +- 6×10^{-16}**

No update (since no new data available)

^{40}Ca

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

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

Proposed Recommendation: $f(^{40}Ca) = 455\,986\,240\,494\,140$ Hz + - 1.8×10^{-14}

No update (since no new data available)

2. The following frequencies have been discussed and are recommended for an update

$^{115}In^{+}$

CIPM recommendation: $f(^{115}In^{+}) = 1\,267\,402\,452\,899\,920$ Hz + - 3.6×10^{-13}

New calculation: $f(^{115}In^{+}) = 1\,267\,402\,452\,901\,050.2866$ Hz + - 20.62 Hz

Proposed Recommendation: $f(^{115}In^{+}) = 1\,267\,402\,452\,901\,050$ Hz +- 1.6×10^{-14}

^{199}Hg

CIPM recommendation: $f(^{199}Hg) = 1\,128\,575\,290\,808\,154.8$ Hz + - 6×10^{-16}

New calculation: $f(^{199}Hg) = 1\,128\,575\,290\,808\,154.4163$ Hz +- 0.1423 Hz

Proposed Recommendation: $f(^{199}Hg) = 1\,128\,575\,290\,808\,154.4$ Hz + - 5×10^{-16}

^{171}Yb

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

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

Proposed Recommendation: $f(^{171}Yb) = 518\,295\,836\,590\,863.6$ Hz + - 5×10^{-16}

$^{88}Sr^{+}$

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

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

Proposed Recommendation: $f(^{88}Sr^{+}) = 444\,779\,044\,095\,486.5$ Hz + - 1.5×10^{-15}

^{88}Sr

CIPM recommendation: $f(^{88}Sr) = 429\,228\,066\,418\,012$ Hz + - 1×10^{-14}

New calculation: $f(^{88}Sr) = 429\,228\,066\,418\,007.0377$ Hz +- 0.048 Hz

Proposed Recommendation: $f(^{88}Sr) = 429\,228\,066\,418\,007.0$ Hz +- 1×10^{-15}

This uncertainty has not been discussed yet finally by the WGFS. The low uncertainty of the calculated value depends entirely on the estimated uncertainty of the Takano 2017 standard

which is much less solid than the bulk of the ^{87}Sr data. It therefore seems prudent to enlarge the final ^{88}Sr uncertainty by a factor of 2.5 with respect to the ^{87}Sr data. (To be discussed on 6 June)

^{87}Sr

CIPM recommendation: **$f(^{87}Sr) = 429\ 228\ 004\ 229\ 873.2\ Hz + - 5 \times 10^{-16}$**

New calculation: **$f(^{87}Sr) = 429\ 228\ 004\ 229\ 873.0357\ Hz +/- 0.047\ Hz$**

Proposed Recommendation: **$f(^{88}Sr) = 429\ 228\ 004\ 229\ 873.0\ Hz + - 4 \times 10^{-16}$**

$^{40}Ca^{+}$

CIPM recommendation: **$f(^{40}Ca^{+}) = 411\ 042\ 129\ 776\ 398.4\ Hz + - 1.2 \times 10^{-14}$**

New calculation: **$f(^{40}Ca^{+}) = 411\ 042\ 129\ 776\ 399.7934\ Hz +- 0.5458\ Hz$**

Proposed Recommendation: **$f(^{40}Ca^{+}) = 411\ 042\ 129\ 776\ 399.8\ Hz + - \ 2.4 \times 10^{-15}$**

This uncertainty has not been discussed yet finally by the WGFS. The previously included value of Chwalla2009 value now has very little effect and so the recommended frequency value comes essentially only from measurements made by two labs. It therefore seems prudent to enlarge the final $^{40}Ca^{+}$ uncertainty by a factor of 2. (To be discussed on 6 June)

^{87}Rb

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

New calculation: **$f(^{87}Rb) = 6\ 834\ 682\ 610.904\ 312\ 5645\ Hz +- 1.177 \times 10^{-06}\ Hz$**

Proposed Recommendation: **$f(^{87}Rb) = 6\ 834\ 682\ 610.904\ 312\ 6\ Hz + - \ 7 \times 10^{-16}$**

This uncertainty has not been discussed yet by the WGFS since the SYRTE data was not available previously. The final uncertainty has been kept to roughly include the NPL value as the mean goes away from that value.

3. New Secondary Representations of the Second

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

$f(^{199}Hg) = 1\ 128\ 575\ 290\ 808\ 154.4\ Hz + - 5 \times 10^{-16}$

has now an uncertainty which is comparable to that of primary caesium fountain clocks. The WGFS on request of SYRTE therefore suggests a recommendation of this standard as a new **Secondary Representation of the Second** with the estimated fractional standard uncertainty of 5×10^{-16}.

4. PROPOSED RECOMMENDATION CCTF (2017)

Recommended frequency standard values for applications including the practical realisation of the metre and secondary representations of the second

The Consultative Committee for Time and Frequency,
considering

- that a list of Secondary Representations of the Second (SRS) has been maintained following the recommendations of the CIPM;
- that different optical SRS have estimated uncertainties of the unperturbed line centre with nearly two orders of magnitude lower uncertainty than the best Cs primary standards;
- the improvement in uncertainty associated with optical frequency standards is ongoing;
- that the Working Group on Strategic Planning of the CCTF has prepared a roadmap for a future redefinition of the second using optical frequency standards

recommends that:

- the institutes put effort into operating their frequency standards as secondary representations of the second in such a way that they routinely contribute to TAI via reporting to the BIPM
- that the best optical standards be compared with uncertainties that are comparable to the uncertainties of the standards themselves
- that the institutes measure the frequencies of their SRS with the lowest uncertainty with the best primary caesium standards as a necessary requirement for a possible future redefinition of the second in terms of an optical transition
- that formal milestones for a redefinition are identified and the CIPM be informed about the current process

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