# 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 List of Recommended Frequencies (LoR)

- Recommendations to the CCTF
  - Entries in the List of Recommended Frequencies (from 13 September 2015)

Prepared by F. Riehle (PTB) and Patrick Gill (NPL) for the CCTF on 17 September 2015

# Activities of the CCL-CCTF WGFS

## Meetings

- 2013 Praque at the EFTF
  - Discussion: How to deal with frequency ratios
    - Direct measurements limited by Cs realization
    - But optical frequency ratio measurements < $10^{-17}$
  - Status of optical frequency standards

- 2014 Neuchatel at the EFTF
  - Discussion and preparation of WGFS 2015
    - First attempts to deal with frequency values and ratios
    - Status of optical frequency standards
      - Established subgroups for ions and neutral atom clocks

- 2015 Paris, BIPM
  - Evaluation of new frequency values for the LoR

# List of recommended frequencies (LoR)



- No new entries into the LoR at this time,
  but requests from CCL under consideration

- Update of values in the LoR
  ($^{171}Yb^+$ octupole, $^{171}Yb^+$ quadrupole, $^{88}Sr^+$, $^{40}Ca^+$,
  $^{87}Sr$, $^{171}Yb$, $^{199}Hg$, $^{1}H$, $^{87}Rb$ microwave)

- Update of the value and uncertainty of a secondary realisation of the second
  ($^{87}Sr$, $^{171}Yb$, $^{199}Hg$, $^{171}Yb^+$ octupole, $^{171}Yb^+$ quadrupole,
  $^{88}Sr^+$, $^{87}Rb$ microwave)

- No new secondary representations of the second

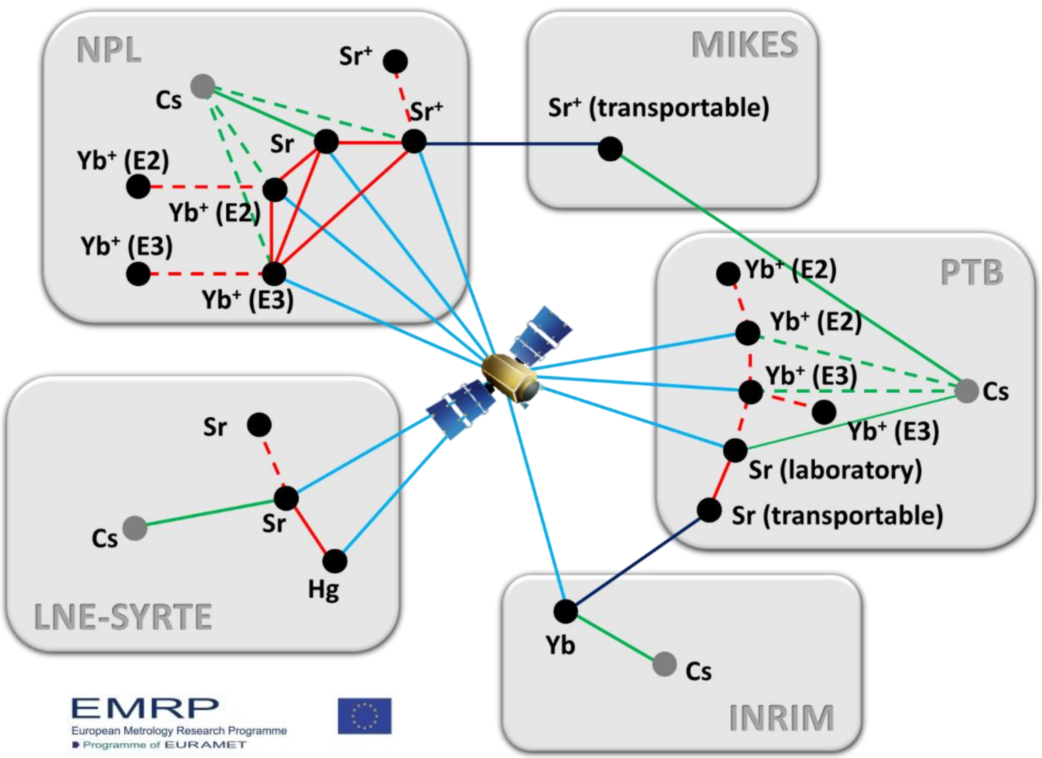
- No new realisation of the definition of the metre

# Recommended values of standard frequencies



**Almost all data considered so far by the WGFS comes from absolute frequency measurements relative to Cs primary standards**

**Future information about reproducibility of optical standards will come mainly from direct optical frequency ratio measurements**




## International Timescales with Optical Clocks (ITOC)

NPL National Physical Laboratory; CMI; INRiM Istituto Nazionale di Ricerca Metrologica; LNE Le progrès, une passion à partager; MIKES Centre for metrology and accreditation; l'Observatoire de Paris SYRTE; PTB; Leibniz Universität Hannover; CNRS; UPMC Sorbonne Universités

**www.optical-time.eu**

EMRP
European Metrology Research Programme
Programme of EURAMET
The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

# Over-determined sets of clock comparison data

It will be possible to deduce some frequency ratios from several different measurements

For example, $\nu_{Yb+} / \nu_{Sr}$ could be measured either directly, or indirectly by combining two or more other frequency ratio measurements,

e.g. $\nu_{Yb+} / \nu_{Sr} = (\nu_{Yb+} / \nu_{Yb})(\nu_{Yb} / \nu_{Sr})$

or $\nu_{Yb+} / \nu_{Sr} = (\nu_{Yb+} / \nu_{Cs})(\nu_{Cs} / \nu_{Sr})$

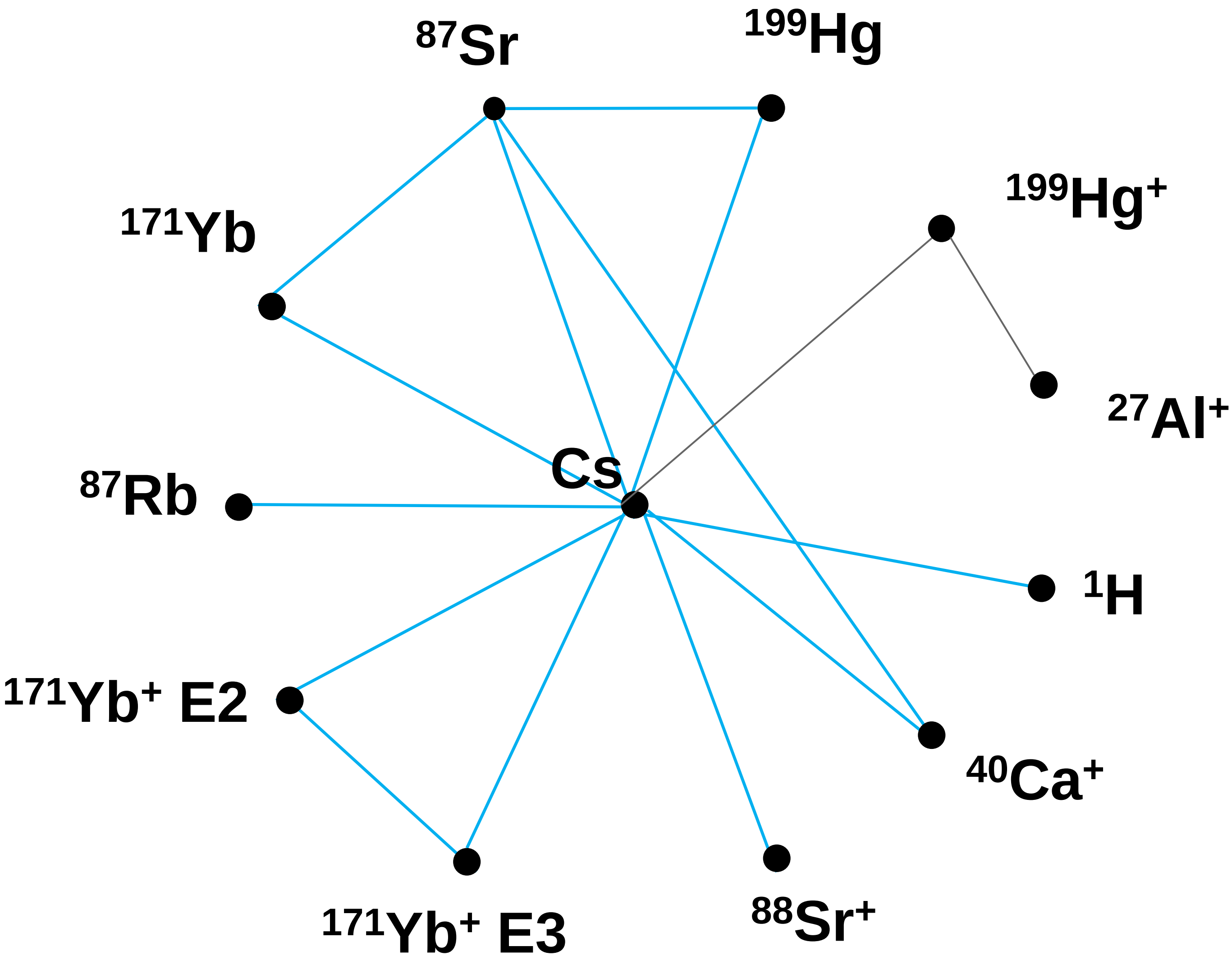
or $\nu_{Yb+} / \nu_{Sr} = (\nu_{Yb+} / \nu_{Sr+})(\nu_{Sr+} / \nu_{Yb})(\nu_{Yb} / \nu_{Sr})$

etc.

Multiple routes to deriving each frequency ratio value mean that it will no longer be possible to treat each optical clock in isolation when considering the available data

# The situation today

## Five direct optical frequency ratio measurements



# Analysis of the frequency ratio matrix



- **Aim: to develop methods for analysing all available data from clock comparison experiments**
  a) **To check the level of internal self-consistency**
  b) **To derive optimal values for the ratios between their operating frequencies**

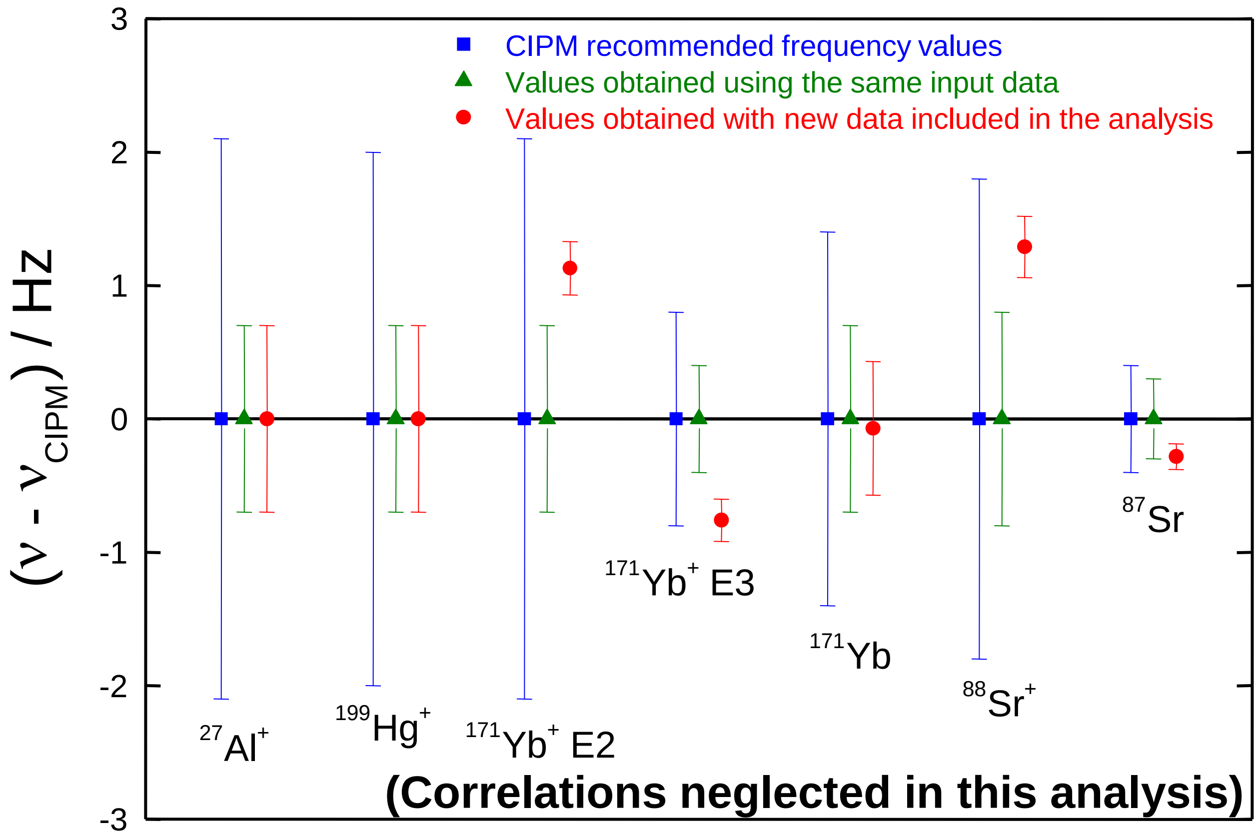
- **Use a least-squares adjustment procedure, based on the approach used by CODATA to provide a self-consistent set of recommended values of the physical constants**
  **[Mohr & Taylor, Rev. Mod. Phys. 72, 351–495 (2000)]**

- **All data stored as frequency ratios (optical frequency ratios, microwave frequency ratios or optical-microwave frequency ratios)**

**H. S. Margolis and P. Gill, Metrologia 52, 628–634 (2015)**

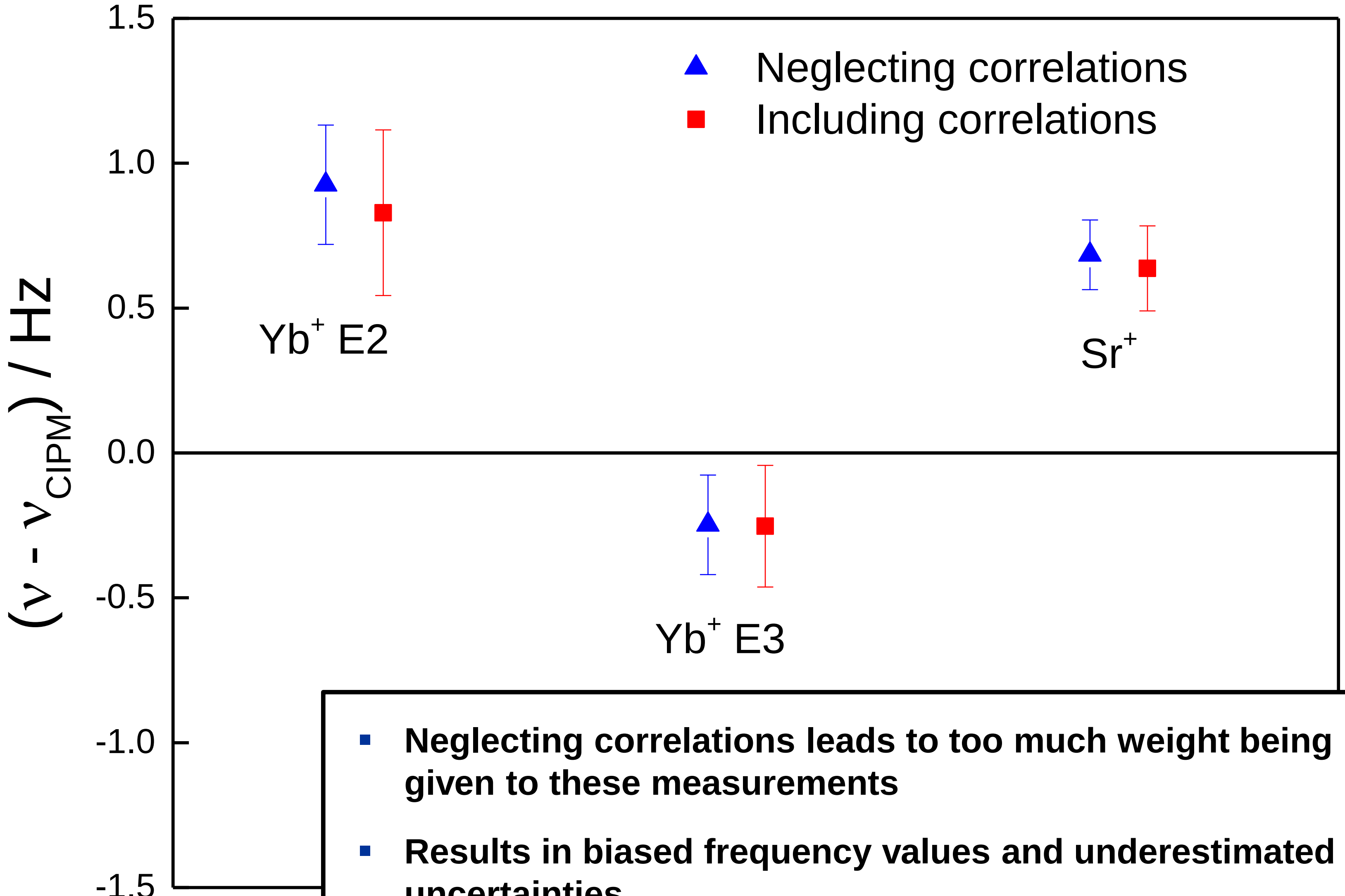
# Software analysis test, with inclusion of new clock comparison data (up to January 2015)






- **Reproduces CIPM 2013 recommended frequency values**
- **Uncertainties are smaller, due to prudent approach of WGFS**
- **But significant changes observed for some values**
- **Prudent approach adopted by the WGFS proves to be justified**

# Effect of correlations




- **Neglecting correlations leads to too much weight being given to these measurements**
- **Results in biased frequency values and underestimated uncertainties**

# Application of the analysis methods

- Can be used to determine a self-consistent set of frequency ratios between high accuracy standards, based on all available experimental data and including correlations among the data
- Analysis checked against classical treatment of weighted means
- As number of direct optical frequency ratio measurements increases, could be used
  - To provide valuable information about relative performance of different candidates for an optical redefinition of the SI second
  - To determine optimized values and uncertainties for absolute frequencies of each optical standard relative to the current definition of the SI second (special cases of frequency ratios)
- Optimized values and uncertainties are required to maximise the potential contribution of optical clocks to international timescales prior to any redefinition

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

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

**CIPM2013 429 228 004 229 873.4 Hz (1 x $10^{-15}$)**

| | | |
|---|---|---|
| 429 228 004 229 873.65 Hz | 0.37 Hz | G.K. Campbell et al, Metrologia 45, 539 (2008) |
| 429 228 004 229 873.6 | 1.1 | X. Baillard et al, Eur. Phys. J. D 48, 11 (2008) |
| 429 228 004 229 874.1 | 2.4 | F.-L. Hong et al, Opt. Lett. 34, 692 (2009) |
| 429 228 004 229 872.9 | 0.5 | S. Falke et al, Metrologia 48, 399 (2011) |
| 429 228 004 229 873.9 | 1.4 | A. Yamaguchi et al, Appl. Phys. Expr. 5, 022701 (2012) |
| **429 228 004 229 873.10** | **0.13** | **Le Targat et al, Nature Com. 4, 2109 (2013)** |
| **429 228 004 229 873.13** | **0.17** | **S. Falke et al, New J. Phys 16, 073023 (2014)** |
| ~~429 228 004 229 873.60~~ | ~~0.71~~ | ~~H. Hachisu et al, Opt. Lett. 39, 4072 (2014)~~ * |
| **429 228 004 229 872.0** | **1.6** | **D. Akamatsu et al, Appl. Phys. Expr. 7, 012401 (2014)** |
| **429 228 004 229 873.56** | **0.49** | **T. Tanabe et al, Journal: J. Phys. Soc. Jpn., accepted** |
| **429 228 004 229 873.7** | **1.4** | **Y.-G. Lin et al, Chin. Phys. Lett. 32, 090601 (2015)** |
| **429 228 004 229 872.85** | **0.47** | **H. Hachisu and T. Ido, Jap. J. Appl. Phys. accepted** |

**Recommended value (weighted mean):**
**$f_{87Sr}$ = 429 228 004 229 873.2 Hz (5 x $10^{-16}$) (uncertainty limited essentially by Cs clock)**

*** Removed because based on value of S. Falke et al (correlation)**

# $^{199}$Hg transition $^1S_0$ – $^3P_0$ (update)

**CIPM2013 $6s^2\ ^1S_0 - 6s6p\ ^3P_0$ 1 128 575 290 808 162 $1.7 \times 10^{-14}$**

SYRTE $f$ = 1 128 575 290 808 155.1 (6.4) Hz

J.J. McFerran et al , PRL 108, 183004 (2012) corrected for gravitational potential

Katori Lab, Tokyo $f_{199Hg} / f_{87Sr}$ = 2.62931420989890960(22)

M. Takamoto, et al, C. R. Physique, 6, 489-498 (2015) and
K. Yamanaka et al, Phys. Rev. Lett. 114, 230801 (2015)

**Recommended value: 1 128 575 290 808 154.8 Hz ($6 \times 10^{-16}$)**
**(frequency ratio uncertainty expanded by 3 times)**

# $^{1}H$ transition 1S – 2S (update)

**CIPM2013 1S – 2S 1 233 030 706 593 518 Hz ($1.2 \times 10^{-14}$)**

$f$ = 2 466 061 413 187 035 (10) Hz ($4 \times 10^{-15}$)

C. Parthey et al, **Phys. Rev. Lett. 107, 230001 (2011)**

$f$ = 2 466 061 413 187 018 (11) Hz ($4 \times 10^{-15}$)

A. Matveev et al, **Phys. Rev. Lett. 110, 230801 (2013)**

**Recommended value:**
***f*** **= 1 233 030 706 593 514 Hz (11 Hz - $4.5 \times 10^{-15}$)**
**(weighted mean; uncertainty enlarged by 3 times)**

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

# $^{171}$Yb transition (SRS; lattice clock; update)

## $6s^2\ ^1S_0 – 6s6p\ ^3P_0$ transition

**CIPM2013 518 295 836 590 865.0 Hz (2.7 x $10^{-15}$)**

| | | |
|---|---|---|
| 518 295 836 590 864 | 28 | T. Kohno et al, Appl. Phys. Express 2, 072501 (2009) |
| 518 295 836 590 863.1 | 2.0 | M.Yasuda, Appl. Phys. Express 5, 102401 (2012) |
| 518 295 836 590 865.2 | 0.7 | N. Lemke et al, Phys. Rev. Lett. 103, 063001 (2009) |
| 518 295 836 590 863.5 | 8.1 | C. Park et al, Metrologia 50,119 (2013) |
| (1.207 507 039 343 337 76) | 29 | M. Takamoto et al, C. R. Physique 16, 489 (2015) |
| (1.207507039343412) | 17 | D. Akamatsu et al, Opt. Express 22(7), 7898 (2014). |

**Recommended value (weighted mean):**
**$f_{171Yb}$ = 518 295 836 590 864 Hz (2 x $10^{-15}$)**
**(uncertainty limited essentially by Cs clock)**

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



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

**CIPM2013** 688 358 979 309 307.1 Hz (3 x $10^{-15}$)

| | | |
|---|---|---|
| 688 358 979 309 308 | 2.14 | Document CCL-CCTF/06-11 |
| 688 358 979 309 306.97 | 0.73 | C. Tamm et al, Phys. Rev. A 80, 043403 (2009) |
| 688 358 979 309 310 | 9 | S. Webster et al, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 57, 592 (2010) |
| 688 358 979 309 308.42 | 0.42 | R. Godun et al, Phys. Rev. Lett. 113, 210801 (2014) |
| 688 358 979 309 307.82 | 0.36 | C. Tamm et al, Phys. Rev. A 89, 023820 (2014) |
| (0.932 829 404 530 964 65) | 31 | R. Godun et al, Phys. Rev. Lett. 113, 210801 (2014) |

**Recommended value (weighted mean):**
**$f$ = 688 358 979 309 308.3 (6 x $10^{-16}$)**
**(uncertainty enlarged by 2-3 times)**

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



## 6s2 $^2S_{1/2}$ (F = 0, $m_F$ = 0) – $^2F_{7/2}$ (F = 3, $m_F$ = 0)

**CIPM2013 642 121 496 772 645.6 Hz (1.3 x $10^{-15}$)**

| | | |
|---|---|---|
| 642 121 496 772 657 | 12.00 | K. Hosaka et al, Phys. Rev. A 79, 033403 (2009) |
| 642 121 496 772 645.15 | 0.52 | N. Huntemann et al; Phys. Rev. Lett. 108, 090801 (2012) |
| 642 121 496 772 646.22 | 0.67 | S.A. King et al, New Journal of Physics 14, 013045 (2012) |
| 642 121 496 772 644.91 | 0.37 | R. Godun et al, Phys. Rev. Lett. 113, 210801 (2014) |
| 642 121 496 772 645.36 | 0.25 | N. Huntemann et al, Phys. Rev. Lett. 113, 210802 (2014) |
| (0.932 829 404 530 964 65) | 31 | R. Godun et al, Phys. Rev. Lett. 113, 210801 (2014) |

**Recommended value (weighted mean):**
**$f$ = 642 121 496 772 645.0 Hz (6 x $10^{-16}$)**
**(uncertainty enlarged by 3 times because of the different Individual uncertainties)**

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



**CIPM2013** **444 779 044 095 485.3 Hz (4 x $10^{-15}$)**

| | | |
|---|---|---|
| 444 779 044 095 484.6 | 1.50 | H.S. Margolis et al, Science 306, 1355 (2004) |
| 444 779 044 095 484 | 15.00 | P. Dubé et al, Phys. Rev. Lett. 95, 033001 (2005) |
| 444 779 044 095 485,5 | 0.9 | A.A. Madeij et al, Phys. Rev. Lett. 109, 203002 (2012) and P. Dubé et al, Phys. Rev. A 87, 023806 (2013) |
| **444 779 044 095 486.71** | **0.24** | **G.P. Barwood et al, Phys. Rev. A 89, 050501(R) (2014)** |

**Recommended value (weighted mean):**
**444 779 044 095 486.6 Hz (1.6 x $10^{-15}$ )**
**(uncertainty enlarged by 3 times**
**because of very different values with lowest uncertainties)**

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



**CIPM2013** **411 042 129 776 39 Hz (1.5 x $10^{-14}$)**

| | | |
|---|---|---|
| 411 042 129 776 393.2 | 1.0 | M. Chwalla et al, Phys. Rev. Lett. 102, 023002 (2009) |
| ~~411 042 129 776 393.0~~ | ~~1.6~~ | ~~Y. Huang et al, Phys. Rev. A 85, 030503(R) (2012) and K. Gao, Chinese Science Bulletin 58, 853 (2013)~~ |
| 411 042 129 776 398.4 | 1.2 | K. Matsubara et al, Opt. Expr. 20, 22034 (2012) |
| **411 042 129 776 400.5** | **1.2** | **Y. Huang et al, Report to CCL-CCTF WGFS** |
| **411 042 129 776 401.7** | **1.1** | **Y. Huang et al, Report to CCL-CCTF WGFS** |

**Recommended value (unweighted mean):**
**411 042 129 776 398.4 Hz (1.2 x $10^{-14}$)**
**(uncertainty enlarged by 10 times**
**due to the continuing inconsistencies)**

# $^{87}Rb$ microwave transition (update)

**CIPM2013** 6 834 682 610.904 312 Hz ($1.3 \times 10^{-15}$)

| | | |
|---|---|---|
| 6 834 682 610.904 312 Hz | $3 \times 10^{-6}$ Hz | J. Guéna et al, Metrologia 51, 108 (2014) |
| 6 834 682 610.904 307 Hz | $3.1 \times 10^{-6}$ Hz | Y. B. Ovchinnikov et al, Metrologia 52, 595 (2015) |

**Recommended value:**
$f$ = 6 834 682 610.904 310 Hz ($7 \times 10^{-16}$)
(uncertainty expanded 2 times and rounded)

# Requests from CCL for additions to LoR

- NPL would like included in the WGFS LoR frequencies of hydrogen cyanide [H13C14N] transitions (at around 1530 nm to 1565 nm) for absolute distance meas interferometry using frequency-swept lasers
  - Need for defined freqs, pressure shift & broadening coeffs, etc.

- NMIJ would like included in the LoR a particular saturated absorption crossover resonance at 384 THz (780 nm) in the $^{85}Rb$ D2 line
  - Previous publication with ± 3 kHz (~ 1 in $10^{11}$) reproducibility
  - Crossover line relevant to NMIJ gauge block interferometer
  - Query over validation of 780 nm commercial stabilised laser

- NMIJ would like included in the LoR a particular saturated absorption in $^{127}I_2$ at 531 nm, which is used to stabilise a compact frequency-doubled 1092 DFB laser. The laser system has application as wavemeter reference, a laser gravimeter, and as an absolute frequency marker for an astro-comb
  - Absolute frequency, pressure / power / modulation width data have been measured for the system

# Requests from CCL for LoR additions II

WGFS has set up a study group comprising P Gill, F Riehle, F.-L. Hong and K. Hosaka to evaluate these requests:

- Considering the data available for the doubled DFB laser stabilised to $^{127}I_2$ at 531 nm, it seems likely that the WGFS will be ready to report at the CCL 2015 meeting

- It is considered unlikely that the WGFS will be ready to report to the CCL 2015 on the $^{85}Rb$ crossover absorption for stabilising a commercial 780 nm laser due to lack of sufficient knowledge of the performance characteristics of the system at this time

- Improved characterisation of the frequencies of a set of HCN transitions in the range 1530 nm – 1565 nm, complete with pressure shift and broadening coefficients does not appear viable without significant additional R&D. Currently we are unaware of whether such R&D has been carried out over and above early NIST data that is normally used to provide the reference data

# Next steps

- WGFS asks CCTF for approving the updated frequencies for the LoR and will provide a recommendation of the CCTF to the CIPM

- WGFS will pass this recommendation to CCL for approving the updated frequencies for the LoR next week and ask to support this recommendation to the CIPM