CCL-CCTF/06-11

Questionnaire previous to the 2006 meeting of the CCL/CCTF Joint Working Group

Summary of the previous meetings

The CCTF on its 16th meeting in April 2004 recommended that the unperturbed ground-state hyperfine quantum transition of ^{87}Rb may be used as a secondary representation of the second with a frequency of f_{Rb}= 6 834 682 610.904 324 Hz and an estimated relative standard uncertainty (1σ) of 3×10^{-15}, and submitted this recommendation to the CIPM.

The 2005 CCL/CCTF JWG adopted three optical frequency standards for recommendation to the CCTF as secondary representations of the second:

> The trapped and cooled mercury ion ^{199}Hg$^+$, 5d^{10} 6s $^2S_{1/2}$ (F = 0) — 5d^9 6s^2 $^2D_{5/2}$ (F = 2), $\Delta m_F = 0$ transition for which the value f = 1 064 721 609 899 145 Hz with a relative standard uncertainty of 3×10^{-15}, applies to the unperturbed quadrupole transition.
>
> The trapped and cooled strontium ion ^{88}Sr$^+$, 5s $^2S_{1/2}$ – 4d $^2D_{5/2}$ transition for which the value f = 444 779 044 095 484.6 Hz with a relative standard uncertainty of 7×10^{-15}, applies to the radiation of a laser stabilized to the unperturbed transition and to the centre of the Zeeman multiplet.
>
> The trapped and cooled ytterbium ion ^{171}Yb$^+$, 6s $^2S_{1/2}$ (F = 0, m_F = 0) — 5d $^2D_{3/2}$ (F =2, m_F = 0) transition for which the value f = 688 358 979 309 308 Hz with a relative standard uncertainty of 9×10^{-15}, applies to the unperturbed quadrupole transition.

1. Frequency sources in the microwave domain

1.1. Have you made or are you aware of new absolute frequency measurements of the Rb hyperfine transition?

Yes [✓ **No**]

If yes, please list the values and uncertainties obtained and refer to the publication in which they may be found. Please be sure to include measurements made in other laboratories.

1.2. Are you aware of absolute frequency measurements of other microwave standards that should be proposed as secondary representations of the second?

Yes [✓ **No**]

If yes, please list the values and uncertainties obtained and the method used and refer to the publication in which they may be found. Please be sure to include measurements made in other laboratories in your country.

1.3. Are you currently developing new frequency sources in the microwave domain?

Yes [✓ **No**]

If yes, please give a brief description of your experiment.

2. Frequency sources in the optical domain

2.1. Have you made or are you aware of new absolute frequency measurements of the three optical transitions adopted by the 2005 CCL/CCTF JWG?

[✓ **Yes**] No

If yes, please list the values and uncertainties obtained and refer to the publication in which they may be found. Please be sure to include measurements made in other laboratories. **(see Appendix 1. Note: *The uncertainties given there might be reduced prior to the CCL/CCTF JWG meeting as a result of a reduced uncertainty of PTB's Cs fountain clock*)**

2.2. Have you made or are you aware of new absolute optical frequency measurements suitable to serve as secondary representations of the second?

Yes [✓ **No**]

If yes, please list the values and uncertainties obtained and refer to the publication in which they may be found.

2.3. Are you currently developing new frequency sources in the optical domain?

[✓ **Yes**] No

If yes, please give a brief description of your experiment.
(see Appendix 2: Optical Frequency Standards with Neutral Atoms)

P.S.: In your response please would you attach a pdf copy of the publication, preprint or internal report which describes the relevant information to assess the final values and uncertainties provided, as this is extremely useful for the JWG deliberation.

NAME: Fritz Riehle, Optics Division

INSTITUTE: Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

Appendix 1:

Report on recent frequency measurements of the 435 nm $^2S_{1/2}(F=0)$ - $^2D_{3/2}(F=2)$ transition of $^{171}Yb^+$

(i) General conditions of measurement

In an extension of earlier work [1-3], five frequency measurements of the 688 THz (435 nm) transition of $^{171}Yb^+$ were performed in July and August 2005 and in June 2006. The output of a frequency-doubled diode laser was locked to the $^2S_{1/2}(F=0)$ - $^2D_{3/2}(F=2)$ transition of a single $^{171}Yb^+$ ion confined in a Paul trap. The diode laser frequency was compared to the caesium fountain clock CSF1 of PTB using a frequency comb generator based on a Er^{3+}-doped fiber laser [4].

Immediately before the measurement of Aug. 9, 2005, two $^{171}Yb^+$ traps were operated simultaneously as described in [5] in order to compare the transition frequencies of the trapped ions for various orientations of the magnetic field. The results of this comparison confirm the results reported in [5].

The $^{171}Yb^+$ trap was operated at room temperature (T=297 K). The $^{171}Yb^+$ transition frequency values reported here include the frequency shift due to the ambient blackbody radiation. Tabulated oscillator strength data and the atomic polarizability measurements described in [5,6] indicate that the blackbody AC Stark shift of the Yb^+ reference transition is -0.37(5) Hz at T=300 K.

(ii) Measurement results and uncertainty contributions

Notation: $\nu_i(Yb^+) = 688\,358\,979\,309\,000$ Hz + x_i Hz, i: number of measurement

i	Starting Date	x_i / Hz	u_{Ai} / Hz	$u_B(Cs)$ / Hz	$u_B(Yb^+)$ / Hz
1	05.07.05	307.84	3.43	1.82	1.05
2	06.07.05	307.51	0.46	1.82	1.05
3	09.08.05	307.49	1.01	1.82	1.05
4	10.08.05	307.07	0.64	1.82	1.05
5	22.06.06	307.70	0.44	1.82	1.05

Weighted mean of measured $^{171}Yb^+$ $^2S_{1/2}(F=0)$ - $^2D_{3/2}(F=2)$ transition frequencies:

$\nu(Yb^+) = 688\,358\,979\,309\,307.65$ Hz

(Weighting proportional to $(u_{Ai}^2 + u_{Bi}^2(Cs) + u_{Bi}^2(Yb^+))^{-1}$.
Earlier results [2,3] are included with <0.05 Hz effect on the mean.)

Type A uncertainty of $\nu(Yb^+)$, including earlier results:

$u_A = (\Sigma u_{Ai}^{-2})^{-1/2}$ **= 0.34 Hz**

Type B uncertainty of $\nu(Yb^+)$, recent measurements:

$u_B = (u_B^2(Cs) + u_B^2(Yb^+))^{1/2}$ **= 2.10 Hz**

Combined uncertainty of ν**(Yb⁺)**:
u(combined) = $(u_A^2 + u_B^2)^{1/2}$ **= 2.14 Hz**

(iii) Comments on some type B uncertainty contributions (see also enclosed GUM worksheet)

(1) The value u_B(Cs) = 1.82 Hz (corresponding to a fractional uncertainty of $2.65 \cdot 10^{-15}$) takes into account an unresolved issue associated with the operation of CSF1 at increased microwave power (see 2006 report of PTB to CCTF, Sec. 1).

(2) The assumed quadrupole shift contribution to $u_B(\mathrm{Yb}^+)$ is a factor of two larger than the statistical uncertainty of the trap-trap-comparison measurements described in [4]. These comparisons did not show any statistically significant quadrupole or tensorial Stark shifts.

(3) The $u_B(\mathrm{Yb}^+)$ contributions taking into account the trap field-induced Stark shift and the relativistic Doppler shift correspond to a stray-field induced micromotion amplitude that is a factor of two larger than the maximum amplitude which might remain undetected with the employed compensation scheme for electrostatic stray fields [5,6]. The amplitude of the thermal secular motion is much smaller than the assumed micromotion amplitude.

(4) The blackbody shift contribution to $u_B(\mathrm{Yb}^+)$ is an estimate of possible deviations of the AC Stark shift from the purely scalar shift caused by isotropic 300 K blackbody radiation. Such deviations could be caused by spurious thermal radiation sources near the trap and by laser stray light. Tests of the mechanical shutters which block the cooling and repumping laser light during the clock laser pulse were carried out during the trap-trap comparison experiments (separate shutters are used for the two trap setups).

(5) The $u_B(\mathrm{Yb}^+)$ contribution taking into account the quadratic Zeeman shift caused by the rf trap drive current is based on an estimate of the displacement current through one octant of the trap electrode structure and of the resulting magnetic field. In a perfectly symmetric trap, the magnetic field contributions of all octants would add up to zero at trap center. The field produced by other rf conductors in the setup is expected to be smaller than the assumed field since these conductors are located sufficiently far from trap center.

References

[1] J. Stenger, Chr. Tamm, N. Haverkamp, S. Weyers, H.R. Telle, Opt. Lett. **26**, 1589 (2001).
[2] T. Quinn, Metrologia **40**, 103 (2003)
[3] E. Peik, B. Lipphardt, H. Schnatz, T. Schneider, Chr. Tamm, Phys. Rev. Lett. **93**, 170801 (2004).
[4] Ph. Kubina, P. Adel, G. Grosche, Th. W. Hänsch, R. Holzwarth, B. Lipphardt, H. Schnatz, Opt. Express 904 (2005)
[5] T. Schneider, E. Peik, Chr. Tamm, Phys. Rev. Lett. **94**, 230801 (2005).

[6] T. Schneider, PhD thesis, Univ. Hannover (2005).

GUM worksheet:
^{171}Yb^{+} frequency standard, July/Aug. 2005 and June 2006 measurements, corrections and systematic uncertainty contributions

Model Equation:

$$f_{YbCorr} = f_{2ndZeem} + f_{grav} + \delta QShift + \delta Servo + \delta StarkBBDev + \delta StarkTrap + \delta relDopp;$$

$$f_{2ndZeem} = f_{ZeemDC} + f_{ZeemAC};$$

$$f_{ZeemDC} = s0*(B_{DC})\hat{}2;$$

$$f_{ZeemAC} = (s0/2)*(B_{AC})\hat{}2;$$

$$f_{grav} = s3*h_{refminusYb}$$

List of Quantities:

Quantity	Unit	Definition
f_{YbCorr}	Hz	corrections to f_{Yb} due to interactions of trapped ion
$f_{2ndZeem}$	Hz	time average of second-order Zeeman shift
f_{grav}	Hz	gravitational shift of measured frequency
δQShift	Hz	uncertainty due to stray-field induced quadrupole shift of Yb frequency
δServo	Hz	uncertainty due to servo errors and spectral asymmetry of probe laser
δStarkBBDev	Hz	uncertainty due to deviation of the AC Stark shift from 300 K-blackbody shift; includes shift due to laser stray light
δStarkTrap	Hz	uncertainty due to quadratic Stark shift caused by secular motion and by excessive micromotion
δrelDopp	Hz	uncertainty due to relativistic Doppler shift caused by secular motion and by excessive micromotion
f_{ZeemDC}	Hz	second-order Zeeman shift due to applied static magnetic field
f_{ZeemAC}	Hz	time average of second-order Zeeeman shift due to magnetic field associated with rf trap drive
s0	Hz/T^2	sensitivity coefficient of quadratic Zeeman shift
B_{DC}	T	static magnetic field at trap center
B_{AC}	T	amplitude of rf magnetic field at trap center
s3	Hz/m	gravitational shift coefficient of measured frequency

Quantity	Unit	Definition
$h_{refminusYb}$	m	elevation difference of Cs reference and Yb+ standard

f_{YbCorr}: Result

total systematic shift of Yb+ single-ion standard

$f_{2ndZeem}$: Interim Result

f_{grav}: Interim Result

gravitational redshift difference due to different elevation of Cs clock and Yb+ standard

δQShift: Stray-field induced quadrupole shift

Type B normal distribution
Value: 0 Hz
Expanded Uncertainty: 1 Hz
Coverage Factor: 1

δServo: Servo error

Type B normal distribution
Value: 0 Hz
Expanded Uncertainty: 0.1 Hz
Coverage Factor: 1

δStarkBBDev: AC Stark shift minus 300 K blackbody shift

Type B normal distribution
Value: 0 Hz
Expanded Uncertainty: 0.3 Hz
Coverage Factor: 1

δStarkTrap: Stark shift due to trap field

Type B rectangular distribution
Value: 0 Hz
Halfwidth of Limits: 0.03 Hz

δrelDopp: Relativistic Doppler shift due to micromotion and secular motion

Type B rectangular distribution
Value: -0.01 Hz
Halfwidth of Limits: 0.01 Hz

f_{ZeemDC}: Interim Result

f_{ZeemAC}: Interim Result

s0: Coefficient for quadratic Zeeman shift

Type B normal distribution
Value: $520 \cdot 10^8$ Hz/T^2
Expanded Uncertainty: $26 \cdot 10^8$ Hz/T^2
Coverage Factor: 1

B_{DC}: Applied static magnetic field

Type B normal distribution
Value: $3.09 \cdot 10^{-6}$ T (in 2005); $2.76 \cdot 10^{-6}$ T (in 2006)
Expanded Uncertainty: $0.1 \cdot 10^{-6}$ T
Coverage Factor: 1

B_{AC}: AC magnetic field amplitude
Type B rectangular distribution
Value: $2 \cdot 10^{-8}$ T
Halfwidth of Limits: $2 \cdot 10^{-8}$ T

s3: Proportionality factor for gravitational redshift
Type B rectangular distribution
Value: 0.0688 Hz/m (used in 2005); 0.0750 Hz/m (corrected, used in 2006)
Halfwidth of Limits: $1 \cdot 10^{-6}$ Hz/m

$h_{refminusYb}$: Height Fountain- height Yb+
Type B rectangular distribution
Value: -0.75 m
Halfwidth of Limits: 0.01 m

Uncertainty Budget (2005 measurements):

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Sensitivity Coefficient	Uncertainty Contribution	Index
$f_{2ndZeem}$	0.4965 Hz	0.0406 Hz				
f_{grav}	-0.051600 Hz	$397 \cdot 10^{-6}$ Hz				
δQShift	0.0 Hz	1.00 Hz	50	1.0	1.0 Hz	90.7 %
δServo	0.0 Hz	0.100 Hz	50	1.0	0.10 Hz	0.9 %
δStarkBBDev	0.0 Hz	0.300 Hz	50	1.0	0.30 Hz	8.2 %
δStarkTrap	0.0 Hz	0.0173 Hz	∞	1.0	0.017 Hz	0.0 %
δrelDopp	-0.01000 Hz	$5.77 \cdot 10^{-3}$ Hz	∞	1.0	$5.8 \cdot 10^{-3}$ Hz	0.0 %
f_{ZeemDC}	0.4965 Hz	0.0406 Hz				
f_{ZeemAC}	$10.4 \cdot 10^{-6}$ Hz	$12.0 \cdot 10^{-6}$ Hz				
s0	$52.00 \cdot 10^{9}$ Hz/T^2	$2.60 \cdot 10^{9}$ Hz/T^2	50	$9.5 \cdot 10^{-12}$	0.025 Hz	0.1 %
B_{DC}	$3.090 \cdot 10^{-6}$ T	$100 \cdot 10^{-9}$ T	50	$320 \cdot 10^{3}$	0.032 Hz	0.1 %
B_{AC}	$20.0 \cdot 10^{-9}$ T	$11.5 \cdot 10^{-9}$ T	∞	not valid!	$12 \cdot 10^{-6}$ Hz	0.0 %
s3	0.068800000 Hz/m	$577 \cdot 10^{-9}$ Hz/m	∞	-0.75	$-430 \cdot 10^{-9}$ Hz	0.0 %
$h_{refminusYb}$	-0.75000 m	$5.77 \cdot 10^{-3}$ m	□	0.069	$400 \cdot 10^{-6}$ Hz	0.0 %
f_{YbCorr}	0.4 Hz	1.05 Hz	60			

Result:

Quantity: $\mathbf{f_{YbCorr}}$
Value: 0.4 Hz
Expanded Uncertainty: ±2.1 Hz
Coverage Factor: 2.0
Coverage: t-table 95%

Uncertainty Budget (2006 measurement):

Quantity	**Value**	**Standard Uncertainty**	**Degrees of Freedom**	**Sensitivity Coefficient**	**Uncertainty Contribution**	**Index**
$f_{2ndZeem}$	0.3961 Hz	0.0349 Hz				
f_{grav}	-0.056250 Hz	$433\cdot10^{-6}$ Hz				
δQShift	0.0 Hz	1.00 Hz	50	1.0	1.0 Hz	90.8 %
δServo	0.0 Hz	0.100 Hz	50	1.0	0.10 Hz	0.9 %
δStarkBBDev	0.0 Hz	0.300 Hz	50	1.0	0.30 Hz	8.2 %
δStarkTrap	0.0 Hz	0.0173 Hz	∞	1.0	0.017 Hz	0.0 %
δrelDopp	-0.01000 Hz	$5.77\cdot10^{-3}$ Hz	∞	1.0	$5.8\cdot10^{-3}$ Hz	0.0 %
f_{ZeemDC}	0.3961 Hz	0.0349 Hz				
f_{ZeemAC}	$10.4\cdot10^{-6}$ Hz	$12.0\cdot10^{-6}$ Hz				
s0	$52.00\cdot10^{9}$ Hz/T^2	$2.60\cdot10^{9}$ Hz/T^2	50	$7.6\cdot10^{-12}$	0.020 Hz	0.0 %
B_{DC}	$2.760\cdot10^{-6}$ T	$100\cdot10^{-9}$ T	50	$290\cdot10^{3}$	0.029 Hz	0.1 %
B_{AC}	$20.0\cdot10^{-9}$ T	$11.5\cdot10^{-9}$ T	∞	not valid!	$12\cdot10^{-6}$ Hz	0.0 %
s3	0.075000000 Hz/m	$577\cdot10^{-9}$ Hz/m	∞	-0.75	$-430\cdot10^{-9}$ Hz	0.0 %
$h_{refminusYb}$	-0.75000 m	$5.77\cdot10^{-3}$ m	∞	0.075	$430\cdot10^{-6}$ Hz	0.0 %
f_{YbCorr}	0.3 Hz	1.05 Hz	60			

Result:
Quantity: $\mathbf{f_{YbCorr}}$
Value: 0.3 Hz
Expanded Uncertainty: ±2.1 Hz
Coverage Factor: 2.0
Coverage: t-table 95%

Appendix 2:

Optical Frequency Standards with Neutral Atoms

Calcium:
We have published a detailed analysis of the uncertainty and the stability that can be achieved with the 657 nm $^1S_0$ – $^3P_1$ transition (f = 455.986 THz) when interrogating ultracold ($T \approx 15$ µK) ballistically expanding atomic clouds [deg05a]. We estimate to reach an possible uncertainty of $2 \cdot 10^{-15}$ and an instability of $\sigma_y \approx 6 \cdot 10^{-16} (\tau/s)^{-1/2}$ in the measurements that are currently underway. Frequency shifts due to non-ideal characteristics of acousto-optic modulators were identified [deg05].

Ultrastable Lasers:
With the pulsed excitation, the frequency noise the interrogation laser limits the achievable stability even with a 1-Hz laser-linewidth [stoe06]. As the noise is due to the coupling of vibrations to the reference cavity, we have developed a novel, vibration insensitive mounting configuration that reduced the influence by at least one order of magnitude [naz06].

Strontium:
We believe that for further progress can using freely expanding absorbers will require unreasonable efforts. Thus the future work concentrates on using strontium atoms for an optical lattice clock.
So far we obtain about 10^7 ^{88}Sr atoms a 1 µK within a cooling time of a few milliseconds. The laser for the optical lattice is available and the 698 nm clock laser is currently being set up. We expect first frequency measurements within the year 2006.

deg05a C. Degenhardt, H. Stoehr, C. Lisdat, G. Wilpers, H. Schnatz, B. Lipphardt, T. Nazarova, P. Pottie, U. Sterr, J. Helmcke and F. Riehle, *Calcium optical frequency standard with ultracold atoms: Approaching 10^{-15} relative uncertainty,* Phys. Rev. A **72**, 062111-1-17 (2005)

deg05 C. Degenhardt, T. Nazarova, C. Lisdat, H. Stoehr, U. Sterr and F. Riehle, *Influence of Chirped Excitation Pulses in an Optical Clock with Ultracold Calcium Atoms*, IEEE Trans. Instrum. Meas. **54**, 771-775 (2005)

sto06 H. Stoehr, F. Mensing, J. Helmcke and U. Sterr, *Diode Laser with 1 Hz Linewidth*, Opt. Lett. **31**, 736-738 (2006)

naz06 T. Nazarova, F. Riehle and U. Sterr, *Vibration-Insensitive Reference Cavity for an Ultra-Narrow Laser*, Appl. Phys. B **83**, 531-536 (2006)