Questionnaire previous to the 2007 meeting of the CCL-CCTF Frequency Standards Working Group

Note: Results will be considered only if there is a publication or at least acceptance for publication at the date of the meeting.

1. Have you made absolute frequency measurements of radiations included in the CCL list of recommended radiations (Mise en Pratique 2005)?

Yes [X] No [ ]

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

1-1

Measurements have been performed in 2006 on the $^{171}Yb^{+}$ single ion transition with a frequency of 688 THz. These measurements have been reported to the CCTF in 2006. The results are given in Appendix 1.

1-2

PTB's primary laser PTB-HeNe 03/86 was calibrated in May 2007 by use of a frequency comb. The laser was operated according to the recommendation of the mise en pratique. The frequency was determined to be

$$f_{\text{PTB-HeNe 03/86}} = 473\,612\,353\,601.8 \cdot \text{kHz} \pm 5.4\ \text{kHz}$$

Uncertainty budget

Measurand	Value	Standard uncertainty	Degree of freedom	Sensitivity coefficient	Uncertainty	Index
f_{CIPM}	473.612353604· 10^9 kHz					
f_{mess}	2.08 kHz	1.06 kHz	50	1.0	1.1 kHz	3.9 %
T	25.00 °C	5.00 °C	50	0.50	2.5 kHz	21.5 %
s12	0.500 kHz/°C	0.100 kHz/°C	50	0.0	0.0 kHz	0.0 %
Θ	15.000 °C	0.150 °C	50	-23	-3.4 kHz	39.3 %
s01	-15.00 kHz/°C	1.00 kHz/°C	50	0.0	0.0 kHz	0.0 %
$mod_{amplitude1}$	6.000 MHz	0.300 MHz	50	10	3.0 kHz	30.9 %
s11	10.00 kHz/MHz	2.00 kHz/MHz	50	0.0	0.0 kHz	0.0 %
$P1_{out}$	0.10500 mW	$4.50 \cdot 10^{-3}$ mW	50	120	0.55 kHz	1.0 %
Transmittance 1	0.014					
P_{int1}	7.500 mW	0.321 mW				

Measurand	Value	Standard uncertainty	Degree of freedom	Sensitivity coefficient	Uncertainty	Index
s21	1.700 kHz/mW	0.400 kHz/mW	50	-2.5	-1.0 kHz	3.4 %
$f_{pressure}$	0.0	3.38				
f_{power}	-4.25	1.14				
f_{mod}	0.0	3.00				
f_{shift1}	-4.25 kHz	5.29 kHz				
f_{offset}	-2.17	5.39				
f_{laser}	$473.6123536018 \cdot 10^9$ kHz	5.39 kHz	170			

1-3
Measurements of the Sr lattice clock of LNE-SYRTE have been performed in autumn 2006 with PTB's transportable frequency comb. The results should be reported by LNE-SYRTE.

1.1. If yes, indicate for each one whether you think that any of these measurements should modify the current value and uncertainty already on the list.

Yes [X] No [ ]

(add as many lines as necessary)

2. Have you made absolute frequency measurements of radiations included in the CCTF list of secondary representations of the second?

Yes [X] No [ ]

See above

2.1. If yes, please list the values and uncertainties obtained and the methods 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.

(see appendix 1)

2.2. If yes, indicate for each one whether you think that any of these measurements should be proposed as an update of existing value and uncertainty to be considered at the next CCL-CCTF Joint WG meeting just prior to the CCTF (2008/2009).

Yes [ ] No [X]

(add as many lines as necessary)

3. Have you made absolute frequency measurements of other radiations not included in these lists?

Yes [X] No [ ]

If yes, please list the values and uncertainties obtained and the methods 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.

3-1 In a cooperation with Hannover University and PTB the transition frequencies of the D lines in several potassium isotopes and potassium molecules have been measured: Stephan Falke, Eberhard Tiemann, Christian Lisdat, Harald Schnatz and Gesine Grosche: *The transition frequencies of the D lines in ^{39}K, ^{40}K, and ^{41}K measured with a femtosecond frequency comb*, Phys. Rev. A **74** 032503-1 – 9 (2006)

TABLE IV. Hyperfine-free transition frequencies ν of the D_1 and D_2 lines.

Isotope	Source	$\nu(D_1)$ in MHz	$\nu(D_2)$ in MHz
^{39}K	fs comb	389 286 058.716(62)	391 016 170.03(12)
	Wavelength meter	389 286 068(40)	391 016 190(40)
	I_2	389 285 980(100)	
	[14]	389 286 078(20)	391 016 188(20)
	[10,11]	389 285 580.908(50)	391 015 578.04(11)
^{40}K	This work	389 286 184.353(73)	391 016 296.050(88)
^{41}K	This work	389 286 294.205(62)	391 016 406.21(12)

and
I. Sherstov, S. Liu, Ch. Lisdat, H. Schnatz, S. Jung, H. Knöckel, and E. Tiemann: *Frequency measurements in the $b\,^3\Pi(0_u^+) - X\,^1\Sigma_g^+$ system of K_2*, Eur. Phys. J. D **41**, 485–492 (2007)

Table 1. Results of absolute frequency measurements for two molecular lines. Always the hyperfine component with highest frequency is observed. The numbers in brackets give the 1σ standard deviation. If the density of the atoms was switched between records, the number of records for each experimental situation is given by the two numbers in column 6.

Molecular line	Absolute frequency, MHz: high density of atoms ν_{hi}	Absolute frequency, MHz: low density of atoms ν_{lo}	$\nu_{lo} - \nu_{hi}$ kHz	^{39}K atoms deflected %	Number of scans averaged
R(24) (27-0) $F - J = +2$	366 287 448.092(12)				7
	366 287 448.092(5)				5
	366 287 448.090(14)	366 287 448.080(10)	−10	83.6	14+14
	366 287 448.085(9)	366 287 448.085(11)	0	82.5	12+12
R(25) (27-0) $F - J = +3$	366 284 992.046(5)				3
	366 284 992.047(26)				3
	366 284 992.042(40)				2
	366 284 992.039(11)				4
	366 284 992.054(12)				6
	366 284 992.026(35)				3
	366 284 992.036(5)				3
	366 284 992.035(13)	366 284 992.031(13)	−4	81.8	5+5
	366 284 992.039(20)	366 284 992.050(14)	11	82.1	3+3
	366 284 992.039(11)	366 284 992.040(11)	1	82.7	15+15

3-2 In a cooperation between the Max-Planck-Institut für Kernphysik, Heidelberg, the Institut für Physik, Mainz, the Max-Planck-Institut für Quantenoptik, Garching (all Germany) and the University of Manitoba, Canada, absolute frequency measurements of iodine transitions were performed.
S. Reinhardt, G. saathoff, S. Karpuk, C. Novotny, G. Huber, M. Zimmermann, R. Holzwarth, T. Udem, T.W. Hänsch, G. Gwinner: *Iodine hyperfine structure and absolute frequency measurements at 565, 576, and 585 nm*, Opt. Commun. 261, 282-290 (2006)

Both absolute frequency measurements are limited to 70 kHz by the reproducibility of the laser stabilization and result in

$\nu_{a10} = (530\,222\,434\,295 \pm 70)$ kHz

for the a_{10} component of P(80)21-1 and

$\nu_{a15} = (512\,671\,028\,075 \pm 70)$ kHz

for the a_{15} component of P(10)14-1.

4. Conclusion

The absolute frequencies of the P(80)21-1 a_{10} and the P(10)14-1 a_{15} components are determined as $\nu_{a10} = (530\,222\,434\,295 \pm 70)$ kHz and $\nu_{a15} = (512\,671\,028\,075 \pm 70)$ kHz. The latter is also confirmed by measurements of the frequency distance of this line to the previously calibrated R(99)15-1 a_{13} component. A heterodyne method

Table 6
Summary of the absolute frequency of P(10)14-1 a_{15} obtained with different methods

Method	Frequency (kHz)
Relative frequency, AOM technique	512671028042 ± 150
Relative frequency, heterodyne	512671028067 ± 73
Frequency comb	512671028075 ± 70

3-3 In a cooperation with Hannover University and PTB the transition frequency of the magnesium intercombination transition $^1S_0 \rightarrow {}^3P_1$ was measured to be

$$f_{Mg} = 655\,659\,923\,839.6 \text{ kHz} \pm 1.6 \text{ kHz.}$$

Jan Friebe, Andre Pape, Matthias Riedmann, Karsten Moldenhauer, Tanja Mehlstäubler, Nils Rehbein, Ernst M. Rasel, Wolfgang Ertmer, Harald Schnatz, Gesine Grosche, and Burghard Lipphardt, *Absolute frequency measurement of the magnesium intercombination transition* $^1S_0 \rightarrow {}^3P_1$, to be published

3.1. If yes, indicate if any of these sources should be included in a updated list of "Recommended values of standard frequencies for applications including the practical realization of the metre and secondary representations of the second, and present your arguments for a positive assessment.

Recommended for the MeP:

Yes [ ] No [X]

Recommended for secondary representation of the second

Yes [ ] No [X]

(add as many lines as necessary)

4. Are you currently developing new frequency sources or are you aware of such sources developed in your country?

Yes [X] No [ ]

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

4-1
A Sr stabilized optical lattice clock is currently being developed at PTB. ^{88}Sr atoms can now be loaded in an optical dipole trap. The clock laser is currently set up in a similar way to the 1 Hz laser used for the Ca frequency standard.
(T. Nazarova, F. Riehle and U. Sterr, Appl. Phys. **B 83**, 2006, 531-536)

4-2
An indium single ion frequency standard is being developed in Prof. Dr. Lijun Wang's group in the Institute of Optics, Information, and Photonics / Max-Planck Research Group in Erlangen, Germany.

NAME: Fritz Riehle
INSTITUTE: Physikalisch-Technische Bundesanstalt

Appendix 1:

Physikalisch-Technische Bundesanstalt, Germany July 2006

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 $\nu(\mathbf{Yb^+})$, including earlier results:
$\mathbf{u_A} = (\Sigma u_{Ai}^{-2})^{-1/2}$ **= 0.34 Hz**

Type B uncertainty of $\nu(\mathbf{Yb^+})$, recent measurements:
$\mathbf{u_B} = (u_B^2(Cs) + u_B^2(Yb^+))^{1/2}$ **= 2.10 Hz**

Combined uncertainty of $\nu(\mathbf{Yb^+})$:

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 $u_B(Yb^+)$ 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 $u_B(Yb^+)$ 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 $u_B(Yb^+)$ 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 $u_B(Yb^+)$ 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
$h_{refminusYb}$	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	$433 \cdot 10^{-6}$ 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	$5.77 \cdot 10^{-3}$ Hz	∞	1.0	$5.8 \cdot 10^{-3}$ Hz	0.0 %
f_{ZeemDC}	0.3961 Hz	0.0349 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	$7.6 \cdot 10^{-12}$	0.020 Hz	0.0 %
B_{DC}	$2.760 \cdot 10^{-6}$ T	$100 \cdot 10^{-9}$ T	50	$290 \cdot 10^{3}$	0.029 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	0.075000000 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	∞	0.075	$430 \cdot 10^{-6}$ 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%