RECOMMENDATION 1 (CI-2002): Revision of the practical realization of the definition of the metre

The International Committee for Weights and Measures,

recalling

- that in 1983 the 17th General Conference (CGPM) adopted a new definition of the metre;
- that in the same year the CGPM invited the International Committee (CIPM)
  - to draw up instructions for the practical realization of the metre,
  - to choose radiations which can be recommended as standards of wavelength for the interferometric measurement of length and draw up instructions for their use,
  - to pursue studies undertaken to improve these standards and in due course to extend or revise these instructions;
- that in response to this invitation the CIPM adopted Recommendation 1 (CI-1983) (*mise en pratique* of the definition of the metre) to the effect
  - that the metre should be realized by one of the following methods:

  (a) by means of the length l of the path travelled in vacuum by a plane electromagnetic wave in a time t; this length is obtained from the measured time t, using the relation $l = c_0 \cdot t$ and the value of the speed of light in vacuum c_0 = 299 792 458 m/s,

  (b) by means of the wavelength in vacuum λ of a plane electromagnetic wave of frequency f; this wavelength is obtained from the measured frequency f using the relation $\lambda = c_0 / f$ and the value of the speed of light in vacuum c_0 = 299 792 458 m/s,

  (c) by means of one of the radiations from the list below, whose stated wavelength in vacuum or whose stated frequency can be used with the uncertainty shown, provided that the given specifications and accepted good practice are followed;

- that in all cases any necessary corrections be applied to take account of actual conditions such as diffraction, gravitation or imperfection in the vacuum;
- that in the context of general relativity, the metre is considered a unit of proper length. Its definition, therefore, applies only within a spatial extent sufficiently small that the effects of the non-uniformity of the gravitational field can be ignored (note that, at the surface of the Earth, this effect in the vertical direction is about 1 part in 10^{16} per metre). In this case, the effects to be taken into account are those of special relativity only. The local methods for the realization of the metre recommended in (b) and (c) provide the proper metre but not necessarily that given in (a). Method (a) should therefore be restricted to lengths l which are sufficiently short for the effects predicted by general relativity to be negligible with respect to the uncertainties of realization. For advice on the interpretation of measurements in which this is not the case, see the report of the Consultative Committee for Time and Frequency (CCTF) Working Group on the Application of General Relativity to Metrology (Application of general relativity to metrology, *Metrologia*, 1997, **34**, 261-290);

- that the CIPM had already recommended a list of radiations for this purpose;

recalling also that in 1992 and in 1997 the CIPM revised the practical realization of the definition of the metre;

considering

- that science and technology continue to demand improved accuracy in the realization of the metre;
- that since 1997 work in national laboratories, in the BIPM and elsewhere has identified new radiations and methods for their realization which lead to lower uncertainties;
- that there is an increasing move towards optical frequencies for time-related activities, and that there continues to be a general widening of the scope of application of the recommended radiations of the *mise en pratique* to cover not only dimensional metrology and the realization of the metre, but also high-resolution spectroscopy, atomic and molecular physics, fundamental constants and telecommunication;
- that a number of new frequency values with reduced uncertainties for radiations of high-stability cold atom and ion standards already listed in the recommended radiations list are now available, that the frequencies of

radiations of several new cold atom and ion species have also recently been measured, and that new improved values with substantially reduced uncertainties for a number of optical frequency standards based on gas cells have been determined, including the wavelength region of interest to optical telecommunications;

- that new femtosecond comb techniques have clear significance for relating the frequency of high-stability optical frequency standards to that of the frequency standard realizing the SI second, that these techniques represent a convenient measurement technique for providing traceability to the International System of Units (SI) and that comb technology also can provide frequency sources as well as a measurement technique;

recognizes comb techniques as timely and appropriate, and recommends further research to fully investigate the capability of the techniques;

welcomes validations now being made of comb techniques by comparison with other frequency chain techniques;

urges national metrology institutes and other laboratories to pursue the comb technique to the highest level of accuracy achievable and also to seek simplicity so as to encourage widespread application;

recommends

- that the list of recommended radiations given by the CIPM in 1997 (Recommendation 1 (CI-1997)) be replaced by the list of radiations given below, including
  - updated frequency values for cold Ca atom, H atom and the trapped Sr^+ ion,
  - frequency values for new cold ion species including trapped Hg^+ ion, trapped In^+ ion and trapped Yb^+ ion,
  - updated frequency values for Rb-stabilized lasers, I_2-stabilized Nd:YAG and He-Ne lasers, CH_4-stabilized He-Ne lasers and OsO_4-stabilized CO_2 lasers at 10 μm,
  - frequency values for standards relevant to the optical communications bands, including Rb- and C_2H_2-stabilized lasers.

CIPM list of approved radiations for the practical realization of the metre, 2002: frequencies and vacuum wavelengths

This list replaces those published in *BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1983, **51**, 25-28, 1992, **60**, 141-144, 1997, **65**, 243-252 and *Metrologia*, 1984, **19**, 165-166, 1993/94, **30,** 523-525, 1999, **36**, 211-215.

In this list, the values of the frequency f and of the vacuum wavelength λ should be related exactly by the relation $\lambda \cdot f = c_0$, with c_0 = 299 792 458 m/s but the values of λ are rounded.

The data and analysis used for the compilation of this list are set out in the associated Appendix L 2 of the Consultative Committee for Length (CCL): Source data for the list of recommended radiations, 2001.

It should be noted that for several of the listed radiations, few independent values are available, so the estimated uncertainties may not reflect all sources of variability.

Each of the listed radiations can be replaced, without degrading the accuracy, by a radiation corresponding to another component of the same transition or by another radiation, when the frequency difference is known with sufficient accuracy. Such radiations are listed in Appendix L 3 of the CCL: Absolute frequency of the other transitions related to those adopted as recommended and frequency intervals between transitions and hyperfine components.

It should be also noted that to achieve the uncertainties given here it is not sufficient just to meet the specifications for the listed parameters. In addition, it is necessary to follow the best good practice concerning methods of stabilization as described in numerous scientific and technical publications. References to appropriate articles, illustrating accepted good practice for a particular radiation, may be obtained by application to a member laboratory of the CCL[(1)] or to the BIPM.

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(1) At its 1997 meeting, the CIPM changed the name of the Consultative Committee for the Definition of the Metre (CCDM) to that of Consultative Committee for Length (CCL).

1 Recommended radiations of stabilized lasers

1.1 Absorbing ion $^{115}In^+$, $5s^2\ ^1S_0 - 5s5p\ ^3P_0$ transition

The values f = 1 267 402 452 899.92 kHz

λ = 236 540 853.549 75 fm

are associated with a relative standard uncertainty of 3.6×10^{-13}.

1.2 Absorbing atom ^1H, 1S–2S two-photon transition

The values f = 1 233 030 706 593.55 kHz

λ = 243 134 624.626 04 fm

with a relative standard uncertainty of 2.0×10^{-13} apply to the laser frequency stabilized to the two-photon transition in a cold hydrogen beam, corrected to zero laser power, and for atoms which are effectively stationary, i.e. the values are corrected for second-order Doppler shift.

1.3 Absorbing 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

The values f = 1 064 721 609 899 143 Hz

λ = 281 568 867.591 969 fm

with a relative standard uncertainty of 1.9×10^{-14} are corrected for the second-order Zeeman shift.

1.4 Absorbing ion $^{171}Yb^+$, $6s\ ^2S_{1/2}$ (F = 0, $m_{F\,=}$ 0) – $5d\ ^2D_{3/2}$ (F = 2, $m_F = 0$) transition

The values f = 688 358 979 309 312 Hz

λ = 435 517 610.739 69 fm

are associated with a relative standard uncertainty of 2.9×10^{-14}.

1.5 Absorbing ion $^{171}Yb^+$, $^2S_{1/2}$ (F = 0, m_F = 0) – $^2F_{7/2}$ (F = 3, m_F = 0) transition

The values f = 642 121 496 772.6 kHz

λ = 466 878 090.061 fm

with a relative standard uncertainty of 4.0×10^{-12} are corrected for the AC Stark shift and second-order Zeeman shift.

1.6 Absorbing molecule $^{127}I_2$, a_{10} component, R(56) 32-0 transition[2]

The values f = 563 260 223 513 kHz

λ = 532 245 036.104 fm

with a relative standard uncertainty of 8.9×10^{-12} apply to the radiation of a frequency-doubled Nd:YAG laser, stabilized with an iodine cell external to the laser, having a cold-finger temperature of –15 °C.

1.7 Absorbing molecule $^{127}I_2$, a_{16}, or f, component, R(127) 11-5 transition

The values f = 473 612 353 604 kHz

λ = 632 991 212.58 fm

with a relative standard uncertainty of 2.1×10^{-11} apply to the radiation of a He-Ne laser with an internal iodine cell, stabilized using the third harmonic detection technique, subject to the conditions:

- cell-wall temperature (25 ± 5) °C [3];
- cold-finger temperature (15.0 ± 0.2) °C;
- frequency modulation width, peak-to-peak, (6.0 ± 0.3) MHz;
- one-way intracavity beam power (i.e. the output power divided by the transmittance of the output mirror) (10 ± 5) mW for an absolute value of the power shift coefficient ≤ 1.0 kHz/mW.

These conditions are by themselves insufficient to ensure that the stated standard uncertainty will be achieved. It is also necessary for the optical and electronic control systems to be operating with the appropriate technical performance. The iodine cell may also be operated under relaxed conditions, leading to the larger uncertainty specified in Appendix L 2 of the CCL.

1.8 Absorbing atom ^{40}Ca, $^1S_0 - {}^3P_1$; $\Delta m_J = 0$ transition

The values f = 455 986 240 494 150 Hz

λ = 657 459 439.291 67 fm

with a relative standard uncertainty of 1.1×10^{-13} apply to the radiation of a laser stabilized to Ca atoms. The values correspond to the mean frequency of

(2) All transitions in I_2 refer to the $B^3\Pi\, 0_u^+ - X^1\Sigma_g^+$ system from now on.

(3) For the specification of operating conditions, such as temperature, modulation width and laser power, the symbols ± refer to a tolerance, not an uncertainty.

the two recoil-split components for atoms which are effectively stationary, i.e. the values are corrected for the second-order Doppler shift.

1.9 Absorbing ion $^{88}Sr^{+}$, 5 $^{2}S_{1/2}$ – 4 $^{2}D_{5/2}$ transition

The values f = 444 779 044 095.5 kHz

λ = 674 025 590.8631 fm

with a relative standard uncertainty of 7.9 × 10^{-13} apply to the radiation of a laser stabilized to the transition observed with a trapped and cooled strontium ion. The values correspond to the centre of the Zeeman multiplet.

1.10 Absorbing atom ^{85}Rb, 5$S_{1/2}$ (F_g = 3) – 5$D_{5/2}$ (F_e = 5) two-photon transition

The values f = 385 285 142 375 kHz

λ =778 105 421.23 fm

with a relative standard uncertainty of 1.3 × 10^{-11} apply to the radiation of a laser stabilized to the centre of the two-photon transition. The values apply to a rubidium cell at a temperature below 100 °C and are corrected to zero laser power.

1.11 Absorbing molecule $^{13}C_2H_2$, P(16) (ν_1+ν_3) transition

The values f = 194 369 569.4 MHz

λ = 1 542 383 712 fm

with a provisional relative standard uncertainty of 5.2 × 10^{-10} apply to the radiation of a laser stabilized with an external $^{13}C_2H_2$ cell at a pressure range from 1.3 Pa to 5.3 Pa.

1.12 Absorbing molecule CH_4, $F_2^{(2)}$ component, P(7) ν_3 transition

1.12.1 The values f = 88 376 181 600.18 kHz

λ = 3 392 231 397.327 fm

with a relative standard uncertainty of 3 × 10^{-12} apply to the radiation of a He-Ne laser stabilized to the central component, (7-6) transition, of the resolved hyperfine-structure triplet. The values correspond to the mean frequency of the two recoil-split components for molecules which are effectively stationary, i.e. the values are corrected for second-order Doppler shift.

1.12.2 The values f = 88 376 181 600.5 kHz

λ = 3 392 231 397.31 fm

with a relative standard uncertainty of 2.3×10^{-11} apply to the radiation of a He-Ne laser stabilized to the centre of the unresolved hyperfine-structure of a methane cell, within or external to the laser, held at room temperature and subject to the following conditions:

- methane pressure ≤ 3 Pa;
- mean one-way intracavity surface power density (i.e., the output power density divided by the transmittance of the output mirror) ≤ 10^4 W m^{-2};
- radius of wavefront curvature ≥ 1 m;
- inequality of power between counter-propagating waves ≤ 5 %;
- servo-referenced to a detector placed at the output facing the laser tube.

1.13 Absorbing molecule OsO_4, transition in coincidence with the $^{12}C^{16}O_2$, R(10) $(00^01) - (10^00)$ laser line

The values f = 29 054 057 446 579 Hz

λ = 10 318 436 884.460 fm

with a relative standard uncertainty of 1.4×10^{-13} apply to the radiation of a CO_2 laser stabilized with an external OsO_4 cell at a pressure below 0.2 Pa. This laser line is selected due to its reduced sensitivity to pressure shifts and other effects, in comparison with the previously selected R(12) laser line.

2 Recommended values for radiations of spectral lamps and other sources

2.1 ^{86}Kr spectral lamp radiation, $5d_5 - 2p_{10}$ transition

The value λ = 605 780 210.3 fm

with a relative expanded uncertainty $U = 3.9 \times 10^{-9}$, where $U = ku_c$ ($k = 3$), u_c being the combined standard uncertainty, applies to the radiation emitted by a discharge lamp. The radiation of ^{86}Kr is obtained by means of a hot-cathode discharge lamp containing ^{86}Kr, of a purity not less than 99 %, in sufficient quantity to assure the presence of solid krypton at a temperature of 64 K, this lamp having a capillary with an inner diameter from 2 mm to 4 mm and a wall thickness of about 1 mm.

It is estimated that the wavelength of the radiation emitted by the positive column is equal, to within 1 part in 10^8, to the wavelength corresponding to the transition between the unperturbed levels, when the following conditions are satisfied:

- the capillary is observed end-on from the side closest to the anode;
- the lower part of the lamp, including the capillary, is immersed in a cold bath maintained at a temperature within one degree of the triple point of nitrogen;
- the current density in the capillary is (0.3 ± 0.1) $A \cdot cm^{-2}$.

2.2 ^{86}Kr, ^{198}Hg and ^{114}Cd spectral lamp radiations

Vacuum wavelengths, λ, for ^{86}Kr, ^{198}Hg and ^{114}Cd transitions

Atom	Transition	λ / pm
^{86}Kr	$2p_9 - 5d'_4$	645 807.20
^{86}Kr	$2p_8 - 5d_4$	642 280.06
^{86}Kr	$1s_3 - 3p_{10}$	565 112.86
^{86}Kr	$1s_4 - 3p_8$	450 361.62
^{198}Hg	$6^1P_1 - 6^1D_2$	579 226.83
^{198}Hg	$6^1P_1 - 6^3D_2$	577 119.83
^{198}Hg	$6^3P_2 - 7^3S_1$	546 227.05
^{198}Hg	$6^3P_1 - 7^3S_1$	435 956.24
^{114}Cd	$5^1P_1 - 5^1D_2$	644 024.80
^{114}Cd	$5^3P_2 - 6^3S_1$	508 723.79
^{114}Cd	$5^3P_1 - 6^3S_1$	480 125.21
^{114}Cd	$5^3P_0 - 6^3S_1$	467 945.81

For ^{86}Kr, the above values with a relative expanded uncertainty $U = 2 \times 10^{-8}$, where $U = ku_c$ ($k = 3$), apply to radiations emitted by a lamp operated under conditions similar to those specified in Section 2.1.

For ^{198}Hg, the above values with a relative expanded uncertainty $U = 5 \times 10^{-8}$, where $U = ku_c$ ($k = 3$), apply to radiations emitted by a discharge lamp when the following conditions are met:

- the radiations are produced using a discharge lamp without electrodes containing ^{198}Hg, of a purity not less than 98 %, and argon at a pressure from 0.5 mm Hg to 1.0 mm Hg (66 Pa to 133 Pa);

- the internal diameter of the capillary of the lamp is about 5 mm, and the radiation is observed transversely;
- the lamp is excited by a high-frequency field at a moderate power and is maintained at a temperature less than 10 °C;
- it is preferred that the volume of the lamp be greater than 20 cm^3.

For ^{114}Cd, the above values with a relative expanded uncertainty $U = 7 \times 10^{-8}$, where $U = ku_c$ ($k = 3$), apply to radiations emitted by a discharge lamp under the following conditions:

- the radiations are generated using a discharge lamp without electrodes, containing ^{114}Cd of a purity not less than 95 %, and argon at a pressure of about 1 mm Hg (133 Pa) at ambient temperature;
- the internal diameter of the capillary of the lamp is about 5 mm, and the radiation is observed transversely;
- the lamp is excited by a high-frequency field at a moderate power and is maintained at a temperature such that the green line is not reversed.

2.3 Absorbing molecule $^{127}I_2$, a_3 component, P(13) 43-0 transition

The values $f = 582\ 490\ 603.38$ MHz

$\lambda = 514\ 673\ 466.4$ fm

with a relative standard uncertainty of 2.5×10^{-10} apply to the radiation of an Ar^+ laser stabilized with an iodine cell external to the laser, having a cold-finger temperature of (–5 ± 2) °C.

2.4 Absorbing molecule $^{127}I_2$, a_9 component, R(12) 26-0 transition

The values $f = 551\ 579\ 482.97$ MHz

$\lambda = 543\ 516\ 333.1$ fm

with a relative standard uncertainty of 2.5×10^{-10} apply to the radiation of a frequency stabilized He-Ne laser with an external iodine cell having a cold-finger temperature of (0 ± 2) °C.

2.5 Absorbing molecule $^{127}I_2$, a_1 component, P(62) 17-1 transition

The values $f = 520\ 206\ 808.4$ MHz

$\lambda = 576\ 294\ 760.4$ fm

with a relative standard uncertainty of 4×10^{-10} apply to the radiation of a dye laser (or frequency-doubled He-Ne laser) stabilized with an iodine cell, within or external to the laser, having a cold-finger temperature of (6 ± 2) °C.

2.6 Absorbing molecule $^{127}I_2$, a_7 component, R(47) 9-2 transition

The values f = 489 880 354.9 MHz

λ = 611 970 770.0 fm

with a relative standard uncertainty of 3×10^{-10} apply to the radiation of a He-Ne laser stabilized with an iodine cell, within or external to the laser, having a cold-finger temperature of (–5 ± 2) °C.

2.7 Absorbing molecule $^{127}I_2$, a_9 component, P(10) 8-5 transition

The values f = 468 218 332.4 MHz

λ = 640 283 468.7 fm

with a relative standard uncertainty of 4.5×10^{-10} apply to the radiation of a He-Ne laser stabilized with an internal iodine cell having a cold-finger temperature of (16 ± 1) °C and a frequency modulation width, peak-to-peak, of (6 ± 1) MHz.