Approved by the CIPM in October 2007

RECOMMENDED VALUES OF STANDARD FREQUENCIES FOR APPLICATIONS INCLUDING THE PRACTICAL REALIZATION OF THE METRE AND SECONDARY REPRESENTATIONS OF THE SECOND

ACETYLENE ($\lambda \approx 1.54$ µm)

Absorbing molecule $^{13}C_2H_2$, P(16) ($\nu_1+\nu_3$) transition

1. CIPM recommended values

The values f = 194 369 569 384 kHz
λ = 1 542 383 712.38 fm

- with a relative standard uncertainty of 2.6×10^{-11} apply to the radiation of a laser stabilized using the third harmonic detection technique to an external $^{13}C_2H_2$ cell within an enhancement cavity and subject to the following conditions:

- C_2H_2-pressure (3 ± 2) Pa;
- frequency modulation width, peak-to-peak (1 ± 0.5) MHz[1];
- one-way intracavity beam power density of (25 ± 20) W cm^{-2}

2. Source data

Adopted value :	f = 194 369 569 384 (5) kHz	$u_c/y = 2.6 \times 10^{-11}$
	for which:	
	λ = 1 542 383 712.38 (4) fm	$u_c/y = 2.6 \times 10^{-11}$

calculated from

f / kHz	u_c/y	source data
194 369 569 384.875	1.4×10^{-11}	[1]
194 369 569 383.5	6.7×10^{-12}	[2]
194 369 569 386.4	5.7×10^{-12}	[3]
194 369 569 384	1.3×10^{-11}	[4]

In order to combine these measurements which were carried out with a variety of acetylene cell pressures, the values were converted to a common 3 Pa cell pressure by use of the pressure shift coefficients measured for each particular system, leading to the following values:

f / kHz	u_c/y	source data
194 369 569 384.6	1.4×10^{-11}	[1]
194 369 569 383.3	6.7×10^{-12}	[2]
194 369 569 385.5	5.7×10^{-12}	[3]
194 369 569 384	1.3×10^{-11}	[4]
Unweighted mean:	f = 194 369 569 384.3 kHz	

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

The recommended value by the CCL is the unweighted mean of these last four values, rounded to the nearest kHz. Given the good agreement between the different laboratories, the CCL decided to reduce the uncertainty from the 10 kHz 2003 value to 5kHz (2.6×10^{-11}), which corresponds approximately to the quadrature sum of the quoted uncertainties, then rounded up.

3. Frequency intervals of the other transitions of the band related to the recommended value

Table 1 replaces that published in BIPM Com. Cons. Long., 2001, **10**, 177, and in *Metrologia*, 2003, **40**, 124.

- The notation for the transitions is that used in the source references. The values adopted for the frequency intervals were determined from the unweighted mean of the values given by three laboratories in references [1, 2, 3, 4], where available.
- The uncertainties were determined from the square root of the quadrature sum of individual line uncertainties divided by the number of laboratories contributing and then rounded.
- u_c represents the estimated combined standard uncertainty (1 σ).

Table 1

$\lambda \approx 1.54$ µm $^{13}C_2H_2$ ($\nu_1 + \nu_3$) band

J	f (P(J))- f (P(16)/kHz	u_c /kHz	J	f (R(J))- f (P(16)/kHz	u_c /kHz
31	–1 236 727 330	5	0	1 219 093 122	1
30	–1 149 564 562	4	1	1 284 956 011	1
29	–1 063 105 009	3	2	1 350 174 198	1
28	–977 244 288	3	3	1 414 736 584	1
27	–892 105 380	1	4	1 478 632 192	1
26	–807 638 070	1	5	1 541 851 517	1
25	–723 847 084	1	6	1 604 387 136	1
24	–640 721 967	1	7	1 666 233 736	1
23	–558 275 721	1	8	1 727 380 519	1
22	–476 502 654	1	9	1 787 844 397	1
21	–395 402 8867	1	10	1 847 604 826	1
20	–314 976 290	1	11	1 906 665 847	1
19	–235 222 731	1	12	1 965 025 956	1
18	–156 142 106	1	13	2 022 683 714	1
17	–77 734 397	1	14	2 079 635 680	1
16	0.0	—	15	2 135 883 116	1
15	77 063 007	1	16	2 191 421 970	1
14	153 451 226	1	17	2 246 250 502	1
13	229 165 964	1	18	2 300 366 567	1
12	304 206 524	1	19	2 353 767 928	1
11	378 572 272	1	20	2 406 452 321	1
10	452 257 032	1	21	2 458 417 492	1
9	525 279 212	1	22	2 509 661 432	1
8	597 619 759	1	23	2 560 176 324	1
7	669 287 337	1	24	2 609 973 044	1
6	740 285 116	1	25	2 659 039 015	1
5	810 618 380	1	26	2 707 376 844	1
4	880 294 498	1	27	2 754 934 187	1
3	949 322 304	1	28	2 801 831 908	2
2	1 017 710 757	1	29	2 847 963 516	2
1	1 085 467 073	1			

Frequency referenced to P(16) $\nu_1 + \nu_3$, $^{13}C_2H_2$: f = 194 369 569 384 kHz

Refs. [2, 3, 4, 5]

4. Absolute frequencies of transitions in other bands

Data were reported by only one laboratory. Consequently, the corresponding uncertainties were increased by a factor of three. In the following tables, the quoted uncertainty associated with each transition is the higher value of either the calculated uncertainty or the adopted uncertainty for the recommended transition P16 (5 kHz).

Table 2

$\lambda \approx 1.54$ µm $^{13}C_2H_2$ ($\nu_1 + \nu_3 + \nu_4 + \nu_5$) band

J	f (P(J))/kHz	u_c /kHz	J	f (R(J))/kHz	u_c /kHz
22	194 307 400 767	5	0	195 984 590 791	5
21	194 387 420 760	7	1	196 050 630 476	6
20	194 466 700 977	5	2	196 116 121 548	5
19	194 545 255 871	14	3	196 181 059 390	5
18	194 623 100 111	8	4	196 245 438 197	5
17	194 700 248 978	5	5	196 309 250 959	5
16	194 776 717 968	5	6	196 372 489 471	5
15	194 852 522 485	8	7	196 435 144 317	6
14	194 927 677 581	5	8	196 497 204 895	5
13	195 002 197 738	5	9	196 558 659 425	7
12	195 076 096 694	5	10	196 619 494 998	5
11	195 149 387 300	5	11	196 679 697 623	7
10	195 222 081 409	5	12	196 739 252 313	5
9	195 294 189 794	5	13	196 798 143 195	5
8	195 365 722 096	5	14	196 856 353 650	5
7	195 436 686 781	5	15	196 913 866 494	5
6	195 507 091 120	11	16	196 970 664 190	5
5	195 576 941 187	10	17	197 026 729 110	9
4	195 646 241 847	7	18	197 082 043 836	9
3	195 714 996 769	5	19	197 136 591 576	9
2	195 783 208 426	5	20	197 190 355 743	9
1	195 850 878 107	13			

Refs. [3]

Table 3

			$\lambda \approx 1.54$ µm $^{12}C_2H_2$ ($\nu_1 + \nu_3$) band		
J	f (P(J))/kHz	u_c /kHz	J	f (R(J))/kHz	u_c /kHz
31	194 018 374 094	12	0	196 487 319 562	5
30	194 111 459 735	6	1	196 696 652 918	6
29	194 203 815 938	5	2	196 764 884 467	9
28	194 295 440 629	6	3	196 832 341 007	5
27	194 386 332 284	6	4	196 899 021 426	8
26	194 476 488 865	7	5	196 964 924 625	5
25	194 565 910 191	5	6	197 030 049 517	6
24	194 654 593 133	7	7	197 094 395 033	5
23	194 742 536 723	5	8	197 157 960 117	5
22	194 829 739 418	6	9	197 220 743 737	5
21	194 916 199 701	6	10	197 282 744 858	5
20	195 001 916 075	5	11	197 343 962 482	5
19	195 086 887 065	5	12	197 404 395 609	9
18	195 171 111 207	5	13	197 464 043 280	7
17	195 254 587 067	8	14	197 522 904 510	5
16	195 337 313 210	6	15	197 580 978 379	5
15	195 419 288 236	6	16	197 638 263 952	8
14	195 500 510 746	9	17	197 694 760 326	5
13	195 580 979 370	10	18	197 750 466 614	5
12	195 660 692 742	9	19	197 805 381 943	5
11	195 739 649 524	9	20	197 859 505 462	5
10	195 817 848 379	11	21	197 912 836 343	6
9	195 895 288 002	8	22	197 965 373 772	6
8	195 971 967 085	7	23	198 017 116 975	5
7	196 047 884 351	9	24	198 068 064 596	6
6	196 123 038 520	5	25	198 118 217 440	5
5	196 197 428 347	10	26	198 167 573 369	5
4	196 271 052 580	5	27	198 216 132 108	6
3	196 343 910 002	8	28	198 263 892 859	17
2	196 415 999 395	5	29	198 310 855 386	7
1	196 487 319 562	5	30	198 357 019 564	27
			31	198 402 374 897	14

The values in this table have been updated [7] after a recommendation of the CIPM [8] and have replaced the data from [6].

Table 4

			$\lambda \approx 1.54$ μm $^{12}C_2HD$ $(2\nu_1)$ band		
J	f (P(J))/kHz	u_c /kHz	J	f (R(J))/kHz	u_c /kHz
27	195 083 584 556	5	0	197 004 767 626	5
26	195 161 449 715	5	1	197 062 611 545	5
25	195 238 655 952	5	2	197 119 660 023	5
24	195 315 202 227	5	3	197 175 921 813	5
23	195 391 087 967	5	4	197 231 407 145	5
22	195 466 309 716	5	5	197 286 126 795	5
21	195 540 867 837	5	6	197 340 091 336	5
20	195 614 760 669	5	7	197 393 310 618	5
19	195 687 985 368	5	8	197 445 793 469	5
18	195 760 540 274	5	9	197 497 547 587	5
17	195 832 422 908	5	10	197 548 579 273	5
16	195 903 630 364	5	11	197 598 894 432	5
15	195 974 159 502	5	12	197 648 497 165	5
14	196 044 006 224	5	13	197 697 391 167	5
13	196 113 166 245	5	14	197 745 579 093	5
12	196 181 634 239	5	15	197 793 063 418	5
11	196 249 404 477	5	16	197 839 845 665	5
10	196 316 469 424	5	17	197 885 927 073	5
9	196 382 821 148	5	18	197 931 308 538	5
8	196 448 450 320	5	19	197 975 990 084	5
7	196 513 346 479	5	20	198 019 972 926	5
6	196 577 498 143	5	21	198 063 257 107	5
5	196 640 893 107	5	22	198 105 840 645	5
4	196 703 518 964	5	23	198 147 725 370	5
3	196 765 363 848	5	24	198 188 910 239	5
2	196 826 417 377	5	25	198 229 394 675	5
1	196 886 671 626	5	26	198 269 179 255	5
			27	198 308 261 614	6

The values in this table have been added after a recommendation of the CCL [7] and the CIPM [8].

5. References

[1] Balling P., Fischer M., Kubina Ph., Holzwarth R., Absolute Frequency Measurement of Wavelength Standard at 1542 nm: Acetylene-Stabilized DFB Laser, *Opt. Express*, **13** (23), pp. 9196-9201, 2005.

[2] Jiang J., Onae A., Matsumoto H., Hong F.-L., Frequency Measurement of Acetylene-Stabilized Lasers using a Femtosecond Optical Comb Without Carrier-Envelope Offset Frequency Control, *Opt. Express*, **13** (6), pp. 1958-65, 2005.

[3] Edwards C. S., Margolis H. S., Barwood G. P., Lea S. N., Gill P., Rowley W. R. C., High-Accuracy Frequency Atlas of $^{13}C_2H_2$ in the 1.5 µm Region, *Appl. Phys. B*, **80**, pp. 977-83, 2005.

[4] Czajkowski A., Bernard J. E., Madej A. A., Windeler R. S., Absolute Frequency Measurement of Acetylene Transitions in the Region of 1540 nm, *Appl. Phys. B*, **79**, pp. 45-50, 2004.

[5] Madej A. A., Bernard J. E., Alcock A. J., Czajkowski A., Chepurov S., Accurate Absolute Frequencies of the $\nu_1 + \nu_3$ Band of $^{13}C_2H_2$ Determined Using an Infrared Mode-Locked Cr:YAG Laser Frequency Comb, *J. Opt. Soc. Am. B*, **23** (4), pp. 741-49, 2006.

[6] Edwards C. S., Barwood G. P., Margolis H. S., Gill P., Rowley W. R. C., High-precision frequency measurements of the $\nu_1 + \nu_3$ combination band of $^{12}C_2H_2$ in the 1.5 µm region, *J. Mol. Spectr.*, **234**, pp. 143-8, 2005.

[7] Report of the 13th meeting (13 – 14 September 2007) of the Consultative Committee for Length (CCL) to the International Committee for Weights and Measures p. 36 (see e.g. http://www.bipm.org/utils/common/pdf/CCL13.pdf#page=36).

[8] Procès-Verbaux des Séances du Comité International des Poids et Mesures, 96th meeting (2007) 2008, Recommendation 1 (CI-2007): Revision of the *Mise en pratique* list of recommended radiations. p. 185 (see e.g. http://www.bipm.org/utils/en/pdf/CIPM2007-EN.pdf#page=77).