Results from the CII-2004 campaign at the BIPM of the BIPM.L-K11 ongoing key comparison.

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Abstract

Lasers from four national metrological institutes (NMIs) were brought to the BIPM in November 2004 as part of the BIPM.L-K11 ongoing key comparison initiated by the Comité Consultative des Longueurs (CCL) 11th meeting in 2003. The absolute frequency of the f component of the R(127) 11-5 transition was measured for these lasers following the Protocol for BIPM.L-K11. The results of these measurements are compiled in the present paper. The comparison reports, as communicated by each participant, are included as Appendices.

Introduction

The BIPM.L-K10 (K10) key comparison was initiated in 1993 to provide a basis for demonstrating equivalence of national realizations of wavelength-standards used for the realization of the definition of the SI *metre* according to method (c) in the *Mise en Pratique* (MeP) [1]. The K10 took only the 633 nm He-Ne standards into consideration. Such a comparison seemed of particular importance since these lasers were most often used in the whole field of dimensional metrology to provide traceability to the *metre*. The measurand of the comparison was the difference between lasers of the *average* frequency of the components d, e, f, and g in the R(127) 11-5 line as obtained by matrix measurements [2]. The frequency of the reference laser BIPM-4 was used as the key comparison reference value.

During the last few years, the situation for realization of the *metre* has changed due to the introduction of new techniques for absolute frequency measurements. This has opened up the method (b) in the MeP for the realization of wavelength standards traceable to the *second*. The practical consequence of this development is that, at least, two methods are today being used for the realization of the *metre*, and several wavelengths, important for dimensional metrology applications, can now demonstrate traceability with relative ease. Considering these circumstances, the 11th CCL meeting, held in October 2003, decided to close the K10 comparison and initiate a new key comparison named BIPM.L-K11 (K11) [3].

The K11 concerns those wavelengths present in the list of recommended radiations in the MeP, which are used in the field of dimensional metrology. Typical examples would be the 633 nm, 612 nm, 543 nm and 532 nm iodine-stabilized standards but others may also become appropriate to include. The CCL also proposed to include absolute frequency measurements, matrix measurements as well as direct frequency heterodyne measurements in which only the difference in frequency between two standards is measured. Besides being a key comparison, K11 will not only provide reduced uncertainties for the frequencies listed in the MeP but also extend the ways in which participants can claim traceability to the definition of the *metre* to comply with the MRA and the related ISO/IEC 17025 [4].

Measurements

Four NMI's took part in the measurement campaign at the BIPM in the spring of 2004. These institutes are listed in Table 1. The measurements carried out are compatible with both the protocol of K11 and the BIPM quality procedures for such measurements. For these laser standards, all working at 633 nm, the f-component of the 127(R) 11-5 transition in iodine was measured being the reference component recommended in the MeP.

Country	NMI	Contact person	Standard
China	NIM	Qian JIN	NIM-D1
France	LNE-INM	J.-P. Wallerand	INM9
Netherlands	NMi VSL	S. Van den Berg	NMi-5
Sweden	SP	R. Johansson	SP2

Table 1. Participants

The femtosecond comb arrangement used is based on a Kerr-lens mode-locked ring laser with a repetition rate of ~740 MHz, pumped by 5 W of 532 nm radiation from a single frequency Nd:YVO_4 laser [5]. A decimeter long photonic-crystal fiber was used to widen the comb spectrum to more than one octave so as to control the carrier-envelope-offset frequency. A typical signal-to-noise ratio (S/N) of 40 dB to 45 dB in a 300 kHz bandwidth was obtained for the self-referencing signal. All frequency generators and frequency counters used are referenced to a local hydrogen maser providing a 10 MHz (UTC) reference frequency known to within 5 parts in 10^{14} and with a stability better then 2 parts in 10^{13} in 1 s. Both the repetition rate and the carrier-envelope-offset frequency are phase-locked to a local hydrogen maser calibrated against the BIPM's internal time service.

For lasers that are weak in power or stabilized by the third harmonic technique it is advantageous to use a buffer laser, i.e. a laser which simultaneously beats with a comb component and the laser to be measured. The two beats so obtained are mixed and the resulting frequency difference, or sum, is used for counting. The resulting beat had a typical S/N of 35 db in a 300 kHz bandwidth. It should be pointed out that by the introduction of the mixing of these two beat signals, phase-coherence is kept between the comb and the laser subject for the frequency determination. The noise contribution from the buffer laser essentially vanishes. By keeping phase-coherence from the hydrogen maser oscillation all the way up to the optical frequency, noise can be minimized giving a shorter integration time. For the present measurements, light from the buffer-laser was delivered by an optical fiber to the laboratory in which the participating laser standards were kept. Perturbations due to thermal changes, acoustic noise etc. could in this way be minimized. The RF beat signal between the measured laser and the buffer laser was then returned to the comb laboratory for further treatment. Three data records of ~300 samples were taken for each laser using a counter gate time of one second. Table 2 gives the values used for the most important working parameters for each standard. Additional information can be found in Appendices 1-4.

Standard	Power[1] [μW]	I_2 temp.[2] [°C]	Modulation width[3] [MHz]
NIM-D1	92 (2)	14.87(0.1)	6.0(0.1)
INM9	80(2)	15.04(0.01)	5.94(0.10)
NMi	109(2.0)	14.96(0.08)	6.22(0.1)
SP2	115(3.0)	15.06(0.05)	6.0(0.1)

Table 2. Working parameter values for the standards with estimated standard uncertainty in parenthesis as given in the measurement reports included in Appendices 1-4.

[1] Output power when laser stabilised to the f component.
[2] Cold-finger temperature.
[3] Peak to peak modulation width.

Data reduction and results

In Table 3 are listed the recorded data series. The frequencies in column 4 are offset by the value 473 612 353 000 kHz. The file names give date and time for the registration of the record in the format *ddmmyy hhmm*.

Standard	File	N	f [kHz]	$s(f)$ [kHz]
NIM-D1	291104 1506	303	595.249	0.24
	291104 1514	313	594.977	0.23
	291104 1522	305	595.170	0.23
INM9	261104 1515	310	602.346	0.12
	261104 1523	317	602.302	0.11
	261104 1529	306	602.358	0.11
NMi-5	161104 1121	308	597.400	0.21
	161104 1127	303	598.100	0.23
	161104 1133	320	597.475	0.21
SP2	241104 1510	1010	601.569	0.66
	241104 1528	1012	604.124	0.72
	241104 1547	1030	603.075	0.65

Table 3. Absolute frequency measurement data records. N – number of 1 s data samples, f – frequency relative to 473 612 353 000 kHz, and $s(f)$ – the statistical fluctuations of the frequency of the laser standard itself given as one standard deviation of the mean.

Weighted mean values from the data in Table 3 are calculated for each laser using the standard deviation of the mean as the weight of each data record. The uncertainties given in column 5 of Table 3 are the *a priori* uncertainties obtained from the statistical uncertainty in each measurement. It should also be checked that the *posteriori* result is consistent by a reduced χ^2-test. This can reveal unexpected instabilities and possible problems when re-locking the standard. If the presence of such instabilities is detected the individual uncertainties should be inflated so as to obtain a reduced χ^2-value of 1. In Table 4 are listed the final results for each laser.

The *uncertainty* of the determined frequency is composed of two parts, one from the frequency measurement, u_1, and one from the uncertainty in the settings of the working parameters, u_2. The latter, the uncertainties related to the standard itself are to be estimated by each operator in accordance with their quality system and are detailed in Appendices 1-4.

The uncertainty stemming from the measurements, u_1, are estimated by the operator of the experiment or together with personnel involved in the comparison, again in accordance with a quality procedure if one exists. Here u_1 is taken as the root-sum-square (RSS) of the calculated uncertainty (with a reduced χ^2 equal to one) of the weighted mean for the three measurement series for each laser as described above and 25 Hz uncertainty from the frequency reference and finally 20 Hz as a general estimated maximum uncertainty of the comb measurement method.

Institute	Standard	f [kHz]	$u_1(f)$ [kHz]	$u_2(f)$ [kHz]	$u_c(f)$ [kHz]
NIM	NIM-D1	**595.1**	0.09	1.9	**1.9**
LNE-INM	INM9	**602.3**	0.04	1.6	**1.6**
NMi	NMi-5	**597.6**	0.22	2.3	**2.3**
SP	SP2	**602.9**	0.73	6.8	**6.8**

Table 4. Final frequency values f for the standards relative to 473 612 353 000 kHz. u_1 corresponds to standard uncertainty stemming from the measurement. u_2 is the estimated uncertainty propagated from the uncertainty in the values of the working parameters for the standard. u_c is the RSS of u_1 and $u_{2,}$ given at a confidence level of 68% assuming a large number of degrees of freedom.

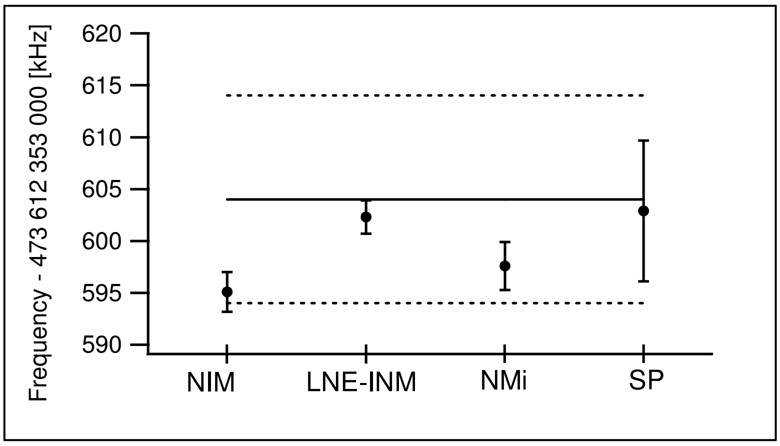

Figure 1. The final frequency values as given in column 3 in Table 4 for each laser. The solid line represents the present recommended value for the 633 nm laser standard and the dotted lines its uncertainty [1].

Conclusion

Frequency measurements have been carried out on 4 primary wavelength standards. Good agreement between the lasers and also with the frequency value recommended in the MeP was found. The uncertainty of the laser frequencies is estimated to be of few kHz, which is considerably smaller than the uncertainty obtained by using the method (c) in the MeP, i.e. 10 kHz.

References

[1] T. J. Quinn, "Practical realization of the definition of the metre, including recommended radiations of other optical frequency standards (2001)", *Metrologia*, vol. 40, pp. 103-133, 2003.

[2] Bayer-Melms F., Chartier J.-M., Helmcke J., Wallard a. J., *PTB-Bericht*, 1977, **PTP-ME 17**, 139-146.

[3] Proceedings from the 11th CCL meeting.

[4] International Organization of Standardization, ISO/IEC 17025, Geneva Switzerland.

[5] L. S. Ma, L. Robertsson, S. Picard, J.-M. Chartier, H. Karlsson, E. Prieto, J. K. Ranka, and R. S. Windeler, "The BIPM laser standards at 633 nm and 532 nm simultaneously linked to the SI second using a femtosecond laser in an optical clock configuration", *IEEE. Trans. Inst. Meas.*, vol. 52, pp. 232-235, 2003.

Appendix 1, NIM.
Comparison report, BIPM.L-K11.

After each series of comparison measurements a copy of this report is to be sent Lennart Robertsson at the BIPM by e-mail for inclusion in the key comparison. Add new lines in the tables as needed and modify names of sensitivity coefficients and operational parameters as relevant for the standard being compared.

D1. Host laboratory[4]

Lab. Name	*BIPM*
Contact person	*Lennart Robertsson*
Address	*Pavillon de Breteuil, 92312 SEVRES CEDEX , France*
Tel.	*(33) 1 45 07 70 53*
e-mail	*Lroberts@BIPM.org*

D2. Measurements[4]

Quantity compared	*The frequency of the output beam of the laser when this is stabilized to the f component of the 11-5, R(127) transition in* $^{127}I_2$ *contained in a glass tube.*
Period	*25/11/04-05/12/04*
Describe measurements	*The absolute frequency of the laser was measured using the BIPM femtosecond laser comb set-up following the technical protocol for the method BIPM.L-K11 m1. Initially the laser was compared with a second iodine system for the determination of some sensitivity parameters*
References and/or other documentation	

[4] To be filled in by the host laboratory

Detailed description of standard[5]

Give description of the standard, one page for each participating standard (here examples for 633 nm)

D3. Laboratory

Lab. Name	*NIM*
Operators	*Qian JIN, Xiuying LIU, Liu Zhongyou*
Address	*NIM, 18, Bei san huan donglu, Bejing, Kina,*
Tel.	
e-mail	*qianjin@nim.ac.cn*

D4. Standard

Designation of laser standard	NIM-D1, Tube and laser NIM.
Standard last compared	
Modification on standard since	
Spectroscopy	*Intracavity saturation spectroscopy*
Modulation technique	*3rd harmonic*
Modulation frequency /kHz	*2.77*
Modulation width or index /	*6 MHz p.p Nominal*
Laser cavity length /cm	*33*
Mirror curvature R1 (tube side) /cm	*60*
Mirror curvature R2 (cell side) /cm	*120*
Mirror transmission T1 (tube side) / %	*0.8*
Mirror transmission T2 (cell side) / %	*0.3*
Output mirror, 1 or 2.	
Designation of iodine cell	*PTB 1987*
Cell length /Brewster /flat windows/origin	*10 cm / Brewster/PTB*

[5] To be filled in by the participating NMI.

D5. Description of measurements[4,5]

Give a brief description of the measurements made and the techniques used.

- Method: *A femtosecond laser comb system (BIPM C1) is used to measure the absolute frequency of the 633 nm standard. The standard is beating with a buffer laser, which also beats with the comb. The two beats are then subtracted and counted. All counters and frequency generators are referenced to a hydrogen maser. This maser is frequency calibrated by the BIPM time-section which thus provide the link between the measured frequency and the SI.*

- Conditions: *The measurements are made in accordance with the BIPM quality system. Groups of 3 data records of approximately 300 seconds are taken*

- Special observation. *A set of 3 records are used for the final result (files ,291104-1506, -1514, -1522). The frequency value is taken as the weighted average value with uncertainties scaled to obtain a reduced χ^2 value of one (Birge ratio equal to one).*

1) References to measuring system if there are: *The BIPM laser standards at 633 nm and 532 nm simultaneously linked to the SI second using a femtosecond laser in an optical clock configuration, Ma L. S., Robertsson L., Picard S., Chartier J.-M., Karlsson H., Prieto E., Ranka J. K., Windeler R. S., IEEE Trans. Instrum. Meas., 2003,* ***52****, 232-235.*

D6. Sensitivity coefficients[5]

Parameter	**Sens. Coeff. Value**	**Uncertainty**	**Unit**	**Comments.**
Modulation width	*-11.1*	*1.1*	kHz/MHz	
Iodine pressure	*-7.86*	*0.37*	kHz/Pa	
Power (output)	*-0.155*	*0.028*	kHz/µW	
Cell wall temperature	*0.20*	*0.06*	kHz/ °C	*This parameter is not well known so the value 0.2 is proposed as default value . The uncertainty of 0.06 results from a tolerance of ± 0.1*

The list of parameters that influence the frequency of the standard might vary for different wavelengths and system. Some of the ones relevant for a typical 633 nm standard is included in the list.

D7. Measurements and parameter settings[5]

Parameter settings (different parameters can be important for different kind of standards)

Parameter	**value**	**Uncertainty**	**Unit**	**Comments**
Output power	*92*	*2*	μW	
Modulation width	*6.0*	*0.1*	MHz	
Iodine cell cold finger temperature	*14.87*	*0.1*	°C	
Cell wall temperature	*26*	*2*	°C	

Compilation of measurement and results

Two types of uncertainty can be identified in the measurements, the one that comes from the measurement of the standard, u_1, and the one that results from the uncertainty in the parameter setting for the standard, u_2.

D8. u_1.
Typical sources of uncertainty in the measurements could be[4,5]

source	**Value**	**unit**	**comments**
Frequency reference	*25*	Hz	
Stat. disp. of results	*81*	Hz	
Uncertainty in measurement method	*20*	Hz	
Total	*87*	Hz	

D9. u_2.
Typical contributions to the uncertainty from the parameter settings[5]

Source	**Value**	**unit**	**comments**
Laser power	*0.32*	kHz	
Modulation width	*1.12*	kHz	
Iodine cold finger temperature	*1.26*	kHz	
Cell wall temp	*0.12*	kHz	
Electronic offset	*0.5*	kHz	
Alignment	*0.58*	kHz	
Total	*1.88*	kHz	

D10. Results:

Name of standard	Lab.	Result	u_c	Unit	Comments
NIM-D1	*NIM*	*473 612 353 595.1*	*1.9*	*kHz*	*Given at a conf. level of 68% assuming a large number of degrees of freedom.*

Appendix 2, LNE-INM.
Comparison report, BIPM.L-K11.

After each series of comparison measurements a copy of this report is to be sent Lennart Robertsson at the BIPM by e-mail for inclusion in the key comparison. Add new lines in the tables as needed and modify names of sensitivity coefficients and operational parameters as relevant for the standard being compared.

D1. Host laboratory[6]

Lab. Name	*BIPM*
Contact person	*Lennart Robertsson*
Address	*Pavillon de Breteuil, 92312 SEVRES CEDEX , France*
Tel.	*(33) 1 45 07 70 53*
e-mail	*Lroberts@BIPM.org*

D2. Measurements[6]

Quantity compared	*The frequency of the output beam of the laser when this is stabilized to the f component of the 11-5, R(127) transition in* $^{127}I_2$ *contained in a glass tube.*
Period	*26-26 November 2004*
Describe measurements	*The absolute frequency of the laser was measured using the BIPM femtosecond laser comb set-up following the technical protocol for the method BIPM.L-K11 m1. Initially the laser was compared with a second iodine system for the determination of some sensitivity parameters*
References and/or other documentation	

[6] To be filled in by the host laboratory

Detailed description of standard[7]

Give description of the standard, one page for each participating standard (here examples for 633 nm)

D3. Laboratory

Lab. Name	*LNE-INM*
Operators	*Jean-Pierre Wallerand*
Address	*CNAM, 292 rue Saint Martin, 75003 Paris*
Tel.	
e-mail	*jpw@cnam.fr*

D4. Standard

Designation of laser standard	INM9, tube NEC, GLT 20-40
Standard last compared	
Modification on standard since	
Spectroscopy	*Intracavity saturation spectroscopy*
Modulation technique	*3rd harmonic*
Modulation frequency /kHz	*5.555*
Modulation width or index /	*6 MHz p.p Nominal*
Laser cavity length /cm	*40*
Mirror curvature R1 (tube side) /cm	*inf*
Mirror curvature R2 (cell side) /cm	*60*
Mirror transmission T1 (tube side) / %	*1*
Mirror transmission T2 (cell side) / %	*1*
Output mirror, 1 or 2.	
Designation of iodine cell	*BIPM-9 (1975)*
Cell length /Brewster /flat windows/origin	*10 cm / Brewster/BIPM*

[7] To be filled in by the participating NMI.

D5. Description of measurements[6,7]

Give a brief description of the measurements made and the techniques used.

- Method: *A femtosecond laser comb system (BIPM C1) is used to measure the absolute frequency of the 633 nm standard. The standard is beating with a buffer laser, which also beats with the comb. The two beats are then subtracted and counted. All counters and frequency generators are referenced to a hydrogen maser. This maser is frequency calibrated by the BIPM time-section which thus provide the link between the measured frequency and the SI.*

- Conditions: *The measurements are made in accordance with the BIPM quality system. Groups of 3 data records of approximately 300 seconds are taken*

- Special observation. *A set of 3 records are used for the final result (files ,261104-1515, -1523, -1529). The frequency value is taken as the weighted average value with uncertainties scaled to obtain a reduced χ^2 value of one (Birge ratio equal to one).*

2) References to measuring system if there are: *The BIPM laser standards at 633 nm and 532 nm simultaneously linked to the SI second using a femtosecond laser in an optical clock configuration, Ma L. S., Robertsson L., Picard S., Chartier J.-M., Karlsson H., Prieto E., Ranka J. K., Windeler R. S., IEEE Trans. Instrum. Meas., 2003,* ***52****, 232-235.*

D6. Sensitivity coefficients[7]

Parameter	Sens. Coeff. Value	Uncertainty	Unit	Comments.
Modulation width	*-10.*	*0*	kHz/MHz	
Iodine pressure	*-8.4*	*0.33*	kHz/Pa	
Power (output)	*-0.15*	*0.03*	kHz/µW	
Cell wall temperature	*0.20*	*0.06*	kHz/ °C	*This parameter is not well known so the value 0.2 is proposed as default value . The uncertainty of 0.06 results from a tolerance of ± 0.1*

The list of parameters that influence the frequency of the standard might vary for different wavelengths and system. Some of the ones relevant for a typical 633 nm standard is included in the list.

D7. Measurements and parameter settings[7]

Parameter settings (different parameters can be important for different kind of standards)

Parameter	**value**	**Uncertainty**	**Unit**	**Comments**
Output power	*80*	*2*	µW	
Modulation width	*5.94*	*0.1*	MHz	
Iodine cell cold finger temperature	*15.04*	*0.01*	°C	
Cell wall temperature		*2*	°C	

Compilation of measurement and results

Two types of uncertainty can be identified in the measurements, the one that comes from the measurement of the standard, u_1, and the one that results from the uncertainty in the parameter setting for the standard, u_2.

D8. u_1.

Typical sources of uncertainty in the measurements could be[6,7]

source	**Value**	**unit**	**comments**
Frequency reference	*25*	Hz	
Stat. disp. of results	*17*	Hz	
Uncertainty in measurement method	*20*	Hz	
Total	*36*	Hz	

D9. u_2.

Typical contributions to the uncertainty from the parameter settings[7]

Source	**Value**	**unit**	**comments**
Laser power	*0.31*	kHz	
Modulation width	*1.0*	kHz	
Iodine cold finger temperature	*0.13*	kHz	
Cell wall temp	*0.42*	kHz	
Electronic offset	*0.5*	kHz	
Alignment	*1.0*	kHz	
Total	*1.59*	kHz	

D10. Results:

Name of standard	Lab.	Result	u_c	Unit	Comments
INM9	*LNE-INM*	*473 612 353 602.3*	*1.6*	*kHz*	*Given at a conf. level of 68% assuming a large number of degrees of freedom.*

Appendix 3, NMi.
Comparison report, BIPM.L-K11.

After each series of comparison measurements a copy of this report is to be sent Lennart Robertsson at the BIPM by e-mail for inclusion in the key comparison. Add new lines in the tables as needed and modify names of sensitivity coefficients and operational parameters as relevant for the standard being compared.

D1. Host laboratory[8]

Lab. Name	**BIPM**
Contact person	*Lennart Robertsson*
Address	*Pavillon de Breteuil, 92312 SEVRES CEDEX , France*
Tel.	*(33) 1 45 07 70 53*
e-mail	*Lroberts@BIPM.org*

D2. Measurements[8]

Quantity compared	*The frequency of the output beam of the laser when this is stabilized to the f component of the 11-5, R(127) transition in* $^{127}I_2$ *contained in a glass tube.*
Period	*15-19 November 2004*
Describe measurements	*The absolute frequency of the laser was measured using the BIPM femtosecond laser comb set-up following the technical protocol for the method BIPM.L-K11 m1. Initially the laser was compared with a second iodine system for the determination of some sensitivity parameters*
References and/or other documentation	

[8] To be filled in by the host laboratory

Detailed description of standard[9]

Give description of the standard, one page for each participating standard (here examples for 633 nm)

D3. Laboratory

Lab. Name	*NMi Van Swinden Laboratorium B. V.*
Operators	*Steven Van den Berg*
Address	*Thijsseweg 11, 2629 JA Delft, The Netherlands*
Tel.	*+31-15-2691523*
e-mail	*svdberg@nmi.nl*

D4. Standard

Designation of laser standard	*NMi-5*
Standard last compared	-
Modification on standard since	-
Spectroscopy	*Intracavity saturation spectroscopy*
Modulation technique	*3rd harmonic*
Modulation frequency /kHz	*8.333*
Modulation width or index /	*6 MHz p.p Nominal*
Laser cavity length /cm	*26*
Mirror curvature R1 (tube side) /cm	*30*
Mirror curvature R2 (cell side) /cm	*Infinite*
Mirror transmission T1 (tube side) / %	*0.7*
Mirror transmission T2 (cell side) / %	*0.4*
Output mirror, 1 or 2.	*1*
Designation of iodine cell	*BIPM 430S*
Cell length /Brewster /flat windows/origin	*10 cm / Brewster/BIPM*

[9] To be filled in by the participating NMI.

D5. Description of measurements[8,9]

Give a brief description of the measurements made and the techniques used.

- Method: *A femtosecond laser comb system (BIPM C1) is used to measure the absolute frequency of the 633 nm standard. The standard is beating with a buffer laser, which also beats with the comb. The two beats ate then subtracted and counted. All counters and frequency generators are referenced to a hydrogen maser. This maser is frequency calibrated by the BIPM time section which thus provide the link between the measured frequency and the SI.*

- Conditions: *The measurements are made in accordance with the BIPM quality system. Groups of 3 data records of approximately 300 seconds are taken*

- Special observation. *A set of 3 records are used for the final result (files ,161104 1121, -1127, - 1133). The frequency value is taken as the weighted average value with uncertainties scaled to obtain a reduced* χ^2 *value of one (Birge ratio equal to one).*

3) References to measuring system if there are: *The BIPM laser standards at 633 nm and 532 nm simultaneously linked to the SI second using a femtosecond laser in an optical clock configuration, Ma L. S., Robertsson L., Picard S., Chartier J.-M., Karlsson H., Prieto E., Ranka J. K., Windeler R. S., IEEE Trans. Instrum. Meas., 2003,* ***52****, 232-235.*

D6. Sensitivity coefficients[9]

Parameter	Sens. Coeff. Value	Uncertainty	Unit	Comments.
Modulation width	*-9.7*	*1.6*	kHz/MHz	
Iodine pressure	*-9.3*	*0.4*	kHz/Pa	
Power (output)	*-0.14*	*0.09*	kHz/µW	
Cell wall temperature	*0.20*	*0.06*	kHz/ °C	*This parameter is not well known so the value 0.2 is proposed as default value. The uncertainty of 0.06 results from a tolerance of ± 0.1*

The list of parameters that influence the frequency of the standard might vary for different wavelengths and system. Some of the ones relevant for a typical 633 nm standard is included in the list.

D7. Measurements and parameter settings[9]

Parameter settings (different parameters can be important for different kind of standards)

Parameter	value	Uncertainty	Unit	Comments
Output power	*109*	*2*	*µW*	
Modulation width	*6.22*	*0.1*	*MHz*	
Iodine cell cold finger temperature	*14.96*	*0.05*	*°C*	*15.159 kΩ*
Cell wall temperature		*1*	*°C*	

Compilation of measurement and results

Two types of uncertainty can be identified in the measurements, the one that comes from the measurement of the standard, u_1, and the one that results from the uncertainty in the parameter setting for the standard, u_2.

D8. u_1.
Typical sources of uncertainty in the measurements could be[8,9]

source	**Value**	**unit**	**comments**
Frequency reference	*25*	Hz	
Stat. disp. of results	*215*	Hz	
Uncertainty in measurement method	*20*	Hz	
Total	*217*	*Hz*	

D9. u_2.
Typical contributions to the uncertainty from the parameter settings[9]

Source	**Value**	**unit**	**comments**
Laser power	*0.33*	*kHz*	
Modulation width	*0.98*	*kHz*	
Iodine cold finger temperature	*1.12*	*kHz*	
Cell wall temp	*0.21*	*kHz*	
Electronic offset	*1.41*	*kHz*	
Alignment	*1.00*	*kHz*	
Total	*2.32*	*kHz*	

D10. Results:

Name of standard	**Lab.**	**Result**	u_c	***Unit***	**Comments**
NMi-5	NMi	473 612 353 597.6	2.3	kHz	Given at a conf. level of 68% assuming a large number of degrees of freedom.

Appendix 4, SP.
Comparison report, BIPM.L-K11.

After each series of comparison measurements a copy of this report is to be sent Lennart Robertsson at the BIPM by e-mail for inclusion in the key comparison. Add new lines in the tables as needed and modify names of sensitivity coefficients and operational parameters as relevant for the standard being compared.

D1. Host laboratory[10]

Lab. Name	*BIPM*
Contact person	*Lennart Robertsson*
Address	*Pavillon de Breteuil, 92312 SEVRES CEDEX , France*
Tel.	*(33) 1 45 07 70 53*
e-mail	*Lroberts@BIPM.org*

D2. Measurements[10]

Quantity compared	*The frequency of the output beam of the laser when this is stabilized to the f component of the 11-5, R(127) transition in* $^{127}I_2$ *contained in a glass tube.*
Period	*22-26 November 2004*
Describe measurements	*The absolute frequency of the laser was measured using the BIPM femtosecond laser comb set-up following the technical protocol for the method BIPM.L-K11 m1. Initially the laser was compared with a second iodine system for the determination of some sensitivity parameters*
References and/or other documentation	

[10] To be filled in by the host laboratory

Detailed description of standard[11]

Give description of the standard, one page for each participating standard (here examples for 633 nm)

D3. Laboratory

Lab. Name	*SP Swedish National Testing and Research Institute*
Operators	Reine Johansson, Håkan Skoogh
Address	*Brinellgatan 4, 504 62 BORÅS, Sweden*
Tel.	
e-mail	reine.johansson@sp.se

D4. Standard

Designation of laser standard	*SP2 / Melles Griot/ SP inv. no. SP 600983*
Standard last compared	*June -89 (Metrologia 91, 28, 95 - 98)*
Modification on standard since	
Spectroscopy	*Intracavity saturation spectroscopy*
Modulation technique	*3rd harmonic*
Modulation frequency /kHz	*2.5*
Modulation width or index /	*6 MHz p.p Nominal*
Laser cavity length /cm	*~39*
Mirror curvature R1 (tube side) /cm	*60*
Mirror curvature R2 (cell side) /cm	*Flat mirror*
Mirror transmission T1 (tube side) / %	*0.90*
Mirror transmission T2 (cell side) / %	*< 1*
Output mirror, 1 or 2.	
Designation of iodine cell	*BIPM 133*
Cell length /Brewster /flat windows/origin	*10 cm / Brewster/*

[11] To be filled in by the participating NMI.

D5. Description of measurements[10,11]

Give a brief description of the measurements made and the techniques used.

- Method: *A femtosecond laser comb system (BIPM C1) is used to measure the absolute frequency of the 633 nm standard. The standard is beating with a buffer laser, which also beats with the comb. The two beats are then subtracted and counted. All counters and frequency generators are referenced to a hydrogen maser. This maser is frequency calibrated by the BIPM time-section which thus provide the link between the measured frequency and the SI.*

- Conditions: *The measurements are made in accordance with the BIPM quality system. Groups of 3 data records of approximately 300 seconds are taken*

- Special observation. *A set of 3 records are used for the final result (files ,241104-1010, -1012, -1030). The frequency value is taken as the weighted average value with uncertainties scaled to obtain a reduced χ^2 value of one (Birge ratio equal to one).*

4) References to measuring system if there are: *The BIPM laser standards at 633 nm and 532 nm simultaneously linked to the SI second using a femtosecond laser in an optical clock configuration, Ma L. S., Robertsson L., Picard S., Chartier J.-M., Karlsson H., Prieto E., Ranka J. K., Windeler R. S., IEEE Trans. Instrum. Meas., 2003,* ***52****, 232-235.*

D6. Sensitivity coefficients[11]

Parameter	**Sens. Coeff. Value**	**Uncertainty**	**Unit**	**Comments.**
Modulation width	*0.6*	*0.5*	kHz/MHz	
Iodine pressure	*-4.8*	*0.5*	kHz/Pa	
Power (output)	*0.8*	*0.09*	kHz/µW	
Cell wall temperature	*0.2*	*0.06*	kHz/ °C	*This parameter is not well known so the value 0.2 is proposed as default value . The uncertainty of 0.06 results from a tolerance of ± 0.1*

The list of parameters that influence the frequency of the standard might vary for different wavelengths and system. Some of the ones relevant for a typical 633 nm standard is included in the list.

D7. Measurements and parameter settings[11]

Parameter settings (different parameters can be important for different kind of standards)

Parameter	**value**	**Uncertainty**	**Unit**	**Comments**
Output power	*115*	*3*	µW	
Modulation width	*6.0*	*0.1*	MHz	
Iodine cell cold finger temperature	*15.06*	*0.05*	°C	
Cell wall temperature	*23.5*	*0.9*	°C	

Compilation of measurement and results

Two types of uncertainty can be identified in the measurements, the one that comes from the measurement of the standard, u_1, and the one that results from the uncertainty in the parameter setting for the standard, u_2.

D8. u_1.
Typical sources of uncertainty in the measurements could be[10,11]

source	**Value**	**unit**	**comments**
Frequency reference	*25*	Hz	
Stat. disp. of results	*731*	Hz	
Uncertainty in measurement method	*20*	Hz	
Total	*731*	Hz	

D9. u_2.
Typical contributions to the uncertainty from the parameter settings[11]

Source	**Value**	**unit**	**comments**
Laser power	*2.42*	kHz	
Modulation width	*0.08*	kHz	
Iodine cold finger temperature	*0.48*	kHz	
Cell wall temp	*0.18*	kHz	
Electronic offset	*2.0*	kHz	
Alignment	*6.0*	kHz	
Total	*6.79*	kHz	

D10. Results:

Name of standard	Lab.	Result	u_c	Unit	Comments
SP2	*SP*	*473 612 353 602.9*	*6.8*	*kHz*	*Given at a conf. level of 68% assuming a large number of degrees of freedom.*