Results from additional measurements carried out within the BIPM.L-K11 ongoing key comparison.

L. Robertsson, M. Zucco, R. Felder L.-S. Ma
BIPM, Pavillon de Breteuil, 92312 Sèvres, France

Jin QUIN, Xiuying LIU, Zhongyou LIU
NIM, 18, Bei san huan donglu, Bejing, Kina,

Hajime Inaba, Jun Ishikawa
AIST/NMIJ, 3-1 Tsukuba-central, 1-1-1 Umezono,
Tsukuba, Ibaraki, Japan 305-8563

R. Hamid ,
UME, P.K. 54, 41470 Gebze-Kocaeli, Turkey

Abstract

Lasers from three national metrological institutes (NMIs) have been measured following the protocol 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 at 633 nm was measured for two of these lasers in their home institutes, AIST/NMIJ and UME, while the b_5 component of the R(106) 28-0 transition at 543 nm was measured on a standard from NIM at the BIPM. 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

Three NMI's report in this paper results from measurements on their standards, cf. Table 1.

1. NIM brought a 543 nm HeNe laser to the BIPM for measurements in the period 25 November –3 December 2004.
2. NMIJ measured the frequency of their 633 nm HeNe laser, O3, at the NMIJ institute using an in house Ti:saph laser comb on the days 10/11 and 18/11 2004.
3. The UME measured the frequency of the 633 nm HeNe laser standard, UME –L3, at the UME laboratory using an in house Ti:saph laser comb the 20-25/06/05.

The measurements carried out are compatible with the protocol of K11. For the NMIJ and the UME laser, the f-component of the R(127) 11-5 transition in iodine was measured being the reference component recommended in the MeP. For the NIM laser the b_5 component of the R(106) 28-0 transition in $^{127}I_2$ was measured. The fact that the frequency range reachable with this type of laser depends on the laser tube used prohibit this laser to use the b_{10} component. Instead was the b_5 component used and then the frequency value for the b_{10} component calculated using the splitting b_{10}-b_5 given in MeP 2003. Additional uncertainty is included due to the uncertainty in the listed splitting.

Country	NMI	Contact person	Standard
China	NIM	Jin QUIN	NIM L2
Japan	AIST/NMIJ	H. Ibana	O3
Turkey	UME	R. Hamid	UME L3

Table 1. Participants

Measurements at the BIPM.

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. The beat had a typical S/N of ~28-30 db in a 300 kHz bandwidth. Four data records of about 300-800 samples were taken using a counter gate time of one second.

Measurements at the NMIJ.

The absolute frequency measurement was carried out using an optical frequency comb. The absolute frequency of O3 was measured at the NMIJ after the international laser comparison APMP.K-11 was completed. Typical signal S/N were more than 60 dB in 300 kHz BW (repetition rate frequency), 35 dB in 300 kHz BW (carrier envelope offset (CEO) frequency) and 25 dB in 300 kHz BW (beat frequency between a HeNe/I_2 laser and the optical comb). For the counting of latter beat frequency a divider and redundant counting was used to guarantee correct counting. The beat signal was filtered, amplified and divided into three signals. One of these signals was frequency-divided by 10 and used for the ratio counting. One of the remaining two signals was also used for ratio counting and the last signal was used for frequency counting. All the radio frequency synthesizers and counters were referenced to the 10 MHz or 100 MHz output of an Hydrogen maser linked to the time scale UTC(NMIJ).

Measurements at the UME [6].

The UME-L3 laser was activated for one week to bring it to a better stability condition before the absolute frequency measurement at UME. Before and after the absolute frequency measurement, the laser output power and the frequency modulation width were measured to be (79.4 ± 0.6) μW and (6.05 ± 0.10) MHz respectively.
The frequency for the UME-L3 laser when locked to the f-component was measured using the UME frequency comb (Menlo Systems GmbH) in the period from 20 to 25 June 2005. During the experiment, the UME-L3 He-Ne/$^{127}I_2$ stabilized laser and the absolute frequency measurement system including the femtosecond laser comb were located in the same laboratory. During the measurement the temperature of the laboratory was (20.0 ± 0.5) °C. After the determination of the working parameters for the laser the laser output beam is directly sent to the UME comb system which is externally referenced to the 10 MHz signal from the UME Cs atomic clock. As a result of the absolute frequency measurement, the weighted average of the measured frequency f of the f-component was found to be (473 612 353 600.6 ± 1.1) kHz.

Standard	Power[1] [μW]	I_2 temp.[2] [°C]	Modulation width[3] [MHz]
NIM L2	100(11)	0(0.2)	3(0.2)
O3	60(3)	15.0(0.1)	6.0(0.1)
UME L3	79.4(0.6)	14.999(0.003)	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 1-3.

Data reduction and results

In Tables 3a and 3b are listed the recorded data series. The frequencies in column 4 are offset by the values 551 579 908 000 kHz for Table 3a and 473 612 353 000 kHz for table 3b. For table 3a the file names or identifier give the date and time for the registration of the record in the format *ddmmyy hhmm*.

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

Standard	File/Identifier	N	f [kHz]	$s(f)$ [kHz]
NIM-L2	291104 1904	345	674.022	0.296
	291104 1923	860	674.156	0.184
	291104 1949	779	677.196	0.204
	291104 2021	472	679.346	0.239

Table 3a. Absolute frequency measurement data records. N – number of 1 s data samples, f – frequency relative to 551 579 908 000 kHz, and $s(f)$ – the statistical fluctuations of the frequency of the laser standard itself given as one standard deviation of the mean.

Standard	File/Identifier	N	f [kHz]	$s(f)$ [kHz]
O3	10/11/2004	620	606.66	0.11
	18/11/2004	929	607.65	0.13
UME-L3	23/06/2005	530	600.1	0.06

Table 3b Absolute frequency measurement data records. N – number of 10 s (NMIJ) 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 during the measurement given as one standard deviation of the mean.

A weighted mean value from the data in Table 3a was calculated using the standard deviation of the mean as the weight of each data record with the individual uncertainties inflated so as to obtain a reduced χ^2-value of 1.

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 of the weighted mean and additional uncertainty from the frequency reference and a general estimated maximum uncertainty of the comb measurement method cf. Appendices.

In Table 4 are listed the final results for each laser.

Institute	Standard	f [kHz]	$u_1(f)$ [kHz]	$u_2(f)$ [kHz]	$u_c(f)$ [kHz]
NIM	NIM L2(b_5)	**551 579 908 676**	1.2	46	**46**
	NIM L2(b_{10})	**551 580 162 351**	1.2	46	**46**
NMIJ	O3	**607.2**	0.7	5.3	**5.3**
UME	UME-L3	**600.6**	0.1	1.2	**1.2**

Table 4. Final frequency values f for the standards relative to 473 612 353 000 kHz in the case of the 633 nm standards. 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.

Conclusion

Frequency measurements have been carried out on 3 primary wavelength standards. In one case, NMIJ, served the present measurement to assure a good frequency transfer to a regional laser comparison, APMP.L-K11, in which frequency difference measurements only were used. The uncertainty of the laser frequencies is in the 633 nm case 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.

[6] Ramiz Hamid, Ersoy Sahin, Mehmet Celik, Gönül Özen, Massimo Zucco, Lennart Robertsson and Long Sheng Ma, "10^{-12} level reproducibility of an iodine-stabilized He–Ne laser endorsed by absolute frequency measurements in the BIPM and UME", 2006 *Metrologia*, **43,** 106-108.

Appendix A, 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

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

Quantity compared	*The frequency of the output beam of the laser when this is stabilized to the b_5 component of the R(106) 280 -transition in $^{127}I_2$ contained in a glass tube is measured. The frequency of the b_5 component and the hfs splitting listen in the MeP is the frequency of the b_{10} component calculated.*
Period	*25 November –3 December 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.*
References and/or other documentation	

Detailed description of standard

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

D3. Laboratory

Lab. Name	*NIM*
Operator	*LIU Xiuying*
Address	*18, BEISANDONGLU BEIJING*
Tel.	*861064211631-3320*
e-mail	*qianjin@nim.ac.cn*

D4. Standard

Designation of laser standard	*NIM L2*
Standard last compared	*2002,2*
Modification on standard since	*2003*
Spectroscopy	*Extracavity saturation spectroscopy*
Modulation technique	*3rd harmonic*
Modulation frequency /kHz	*1.0 4kHz*
Modulation width or index /	*3 MHz p.p*
Laser cavity length /cm	*26.5*
Mirror curvature R1 (tube side) /cm	*100*
Mirror curvature R2 (cell side) /cm	*100*
Mirror transmission T1 (tube side) / %	*0.05*
Mirror transmission T2 (cell side) / %	*0.05*
Output mirror, 1 or 2.	*1*
Designation of iodine cell	*G2*
Cell length /Brewster /flat windows/origin	*9.5 cm Brewster*

D5. Description of measurements

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 543 nm standard. The standard was beating with the comb directly without any buffer laser. 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: 4 data *records of 345, 860, 779 and 472 seconds were taken*

- Special observation. *The set of 4 records are used for the final result (files ,291104 1907, 291104 1923 , 291104 1949 and 291104 2021). 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).*

- *The fact that the frequency range reachable with this type of laser depends on the laser tube used prohibits this laser to use the* b_{10} *component. Instead was the* b_5 *component used and then the frequency value for the* b_{10} *component calculated using the splitting given in MeP 2003. Additional uncertainty is included due to the uncertainty in the listed splitting.*

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

Parameter	Sens. Coeff. Value	Uncertainty	Unit	Comments.
Modulation width	*-11.9*	*9*	*kHz/MHz*	
Iodine pressure	*-4.6*	*12.4*	*kHz/Pa*	
Power (output)	*-0.4*	*4*	*kHz/μW*	
Cell wall temperature	-	-	*kHz/ ℃*	

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

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

Parameter	value	Uncertainty	Unit	Comments
Output power	*100*	*11*	*μW*	*? check calibration at home*
Modulation width	*3*	*0.2*	*MHz*	
Iodine cell cold finger temperature	*0*	*0.2*	*℃*	
Frequency shift due to optical fedback	*0*	*4.3k*	*kHz*	

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

source	**Value**	**unit**	**comments**
Frequency reference	*25*	*Hz*	
Stat. disp. of results	*1230*	*Hz*	
Uncertainty in measurement method	*20*	*Hz*	
Total	*1230*	*Hz*	

D9. u_2.

Typical contributions to the uncertainty from the parameter settings

Source	Value	unit	comments
Laser power	*44.2*	*kHz*	
Modulation width	*3.0*	*kHz*	
Iodine cold finger temperature	*1.1*	*kHz*	
Cell wall temp		*kHz*	
Electronic offset	*0.5*	*kHz*	
alignment	*10*	*kHz*	
Freq. Push and pulling from optical freeback	*4.3*	*kHz*	*Obtanied from a tolerans of ±7.5 kHz -> 15/sqrt(12)=4.3*
Total	*45.6*	*kHz*	

Transfer from b5 to b10

	Value	**unit**	**comments**
Frequency difference	*253675*	*kHz*	*Hfs slitting from MeP (2003)*
With uncertainty u_3	*7*	*kHz*	*SQRT(5^2+5^2) from the uncertainty of the hfs component in MeP(2003)*

D10. Results:

Name of standard	**Lab.**	**Result**	u_c	***Unit***	**Comments**
NIM L2 b_5 component	*NIM*	*551 579 908 676*	*46*	*kHz*	*Given at a conf. level of 68% assuming a large number of degrees of freedom.*
NIM L2 b_{10} component	*NIM*	*551 580 162 351*	*46*	*kHz*	*Given at a conf. level of 68% assuming a large number of degrees of freedom.*

Appendix B. NMIJ
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

Lab. Name	*National Institute of Advanced Industrial Science and Technology*
Contact person	*Hajime Inaba*
Address	*3-1 Tsukuba-central, 1-1-1 Umezono, Tsukuba, Ibaraki, JAPAN 305-8563*
Tel.	*+81-29-861-6807*
e-mail	*h.inaba@aist.go.jp*

D2. Measurements

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	*10-18 November 2004*
Describe measurements	*The absolute frequency of the laser was measured using the NMIJ femtosecond laser comb set-up following the technical protocol for the method BIPM.L-K11 m1.* *The He-Ne/*I_2 *laser O3 joined the international laser comparison of He-Ne/*I_2 *lasers APMP.L-K11 in Beijing held 25-30 October 2004 prior to the absolute measurements.*
References and/or other documentation	

Detailed description of standard

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

D3. Laboratory

Lab. Name	*National Institute of Advanced Industrial Science and Technology (AIST/NMIJ)*
Operators	*Jun Ishikawa*
Address	*3-1 Tsukuba-central, 1-1-1 Umezono, Tsukuba, Ibaraki, JAPAN 305-8563*
Tel.	*+81-29-861-4272*
e-mail	*j.ishikawa@aist.go.jp*

D4. Standard

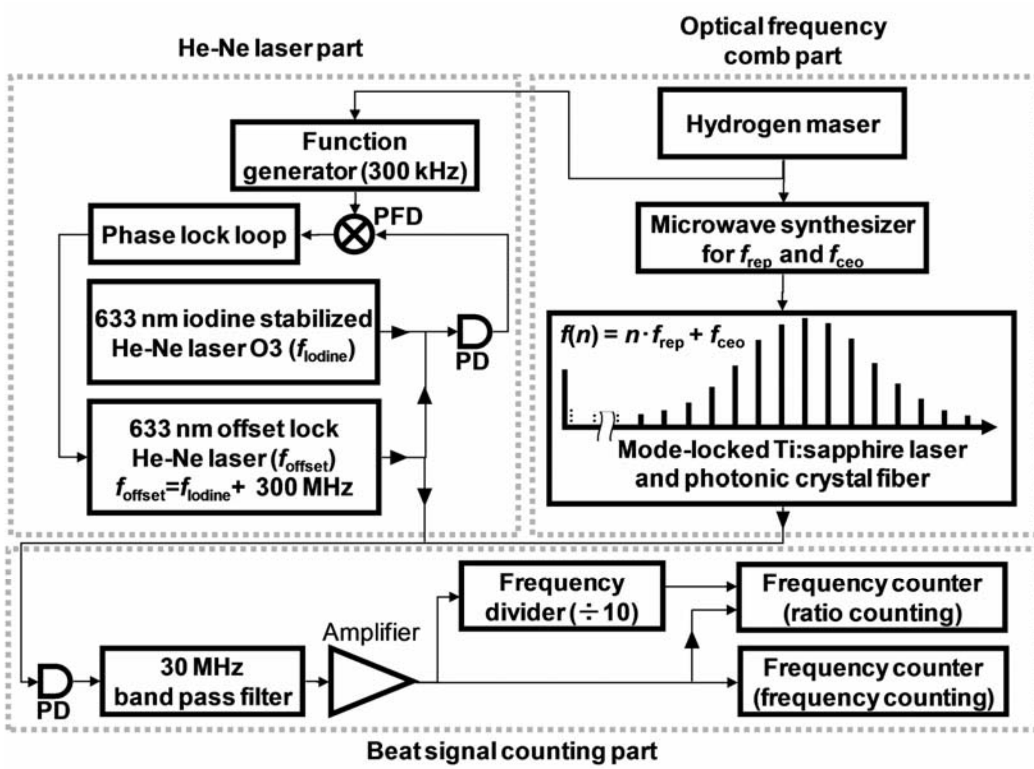
Designation of laser standard	*NRLM Open Laser / O3*
Standard last compared	
Modification on standard since	
Spectroscopy	*Intracavity saturation spectroscopy*
Modulation technique	*3:rd harmonic techn.*
Modulation frequency /kHz	*3*
Modulation width or index /	*6.03 (MHz)*
Laser cavity length /cm	*25*
Mirror curvature R1 (tube side) /cm	*flat*
Mirror curvature R2 (cell side) /cm	*60*
Mirror transmission T1 (tube side) / %	*0.5*
Mirror transmission T2 (cell side) / %	*0.5*
Output mirror, 1 or 2.	*Both*
Designation of iodine cell	*AIST, 040925-1*
Cell length /Brewster /flat windows/origin	*7 cm/Brewster for 633 nm/AIST*

D5. Description of measurements

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

Method: Absolute frequency measurement using optical frequency comb. The absolute frequency of O3 was measured at the NMIJ after the international laser comparison APMP.K-11 was completed.

➢



Schematic of the experimental setup for measuring the absolute frequency of an iodine-stabilized helium-neon (HeNe/I_2) laser. DBM: double balanced mixer, PD: photo detector, PFD: phase/frequency discriminator. A frequency ratio technique was used to assure correct counting.

All the radio frequency synthesizers and counters were referenced to the 10 MHz or 100 MHz output of an Hydrogen maser linked to the timescale UTC(NMIJ).

Measurement results for He-Ne/I_2 O3 are shown in the table below. The mean frequency on each day is given as (473 612 353 604 + Δf) kHz. Measurement runs consisted of 620-929 10 s measurements. The values of statistical uncertainty in Table 1 are the standard deviations of the means of every 100 measured values (averaging time: 1000 s).

Date	Data points	Statistical uncertainty	Δf
25-30 October 2004		APMP LK-11	
10 November 2004	620	0.11	+2.66
18 November 2004	929	0.13	+3.65

We conclude the frequency of O3 from above results as follows.

……………………… f_{O3} = 473 612 353 607.16(71) kHz ……………………….

➢ Conditions*: More than 60 dB in 300 kHz BW (repetition rate frequency), 35 dB in 300 kHz BW (carrier envelope offset (CEO) frequency) and 25 dB in 300 kHz BW (beat frequency between a HeNe/I_2 laser* *and an optical comb) For the counting of f_{beat}, we employed ratio counting, as shown in the schematic of the experimental setup, using a frequency divider to check the counter's behaviour. The f_{beat} signal was filtered, amplified and divided into three signals. One of these signals was frequency-divided by 10 and used for the ratio counting. One of the remaining two signals was also used for ratio counting and the last signal was used for frequency counting.*

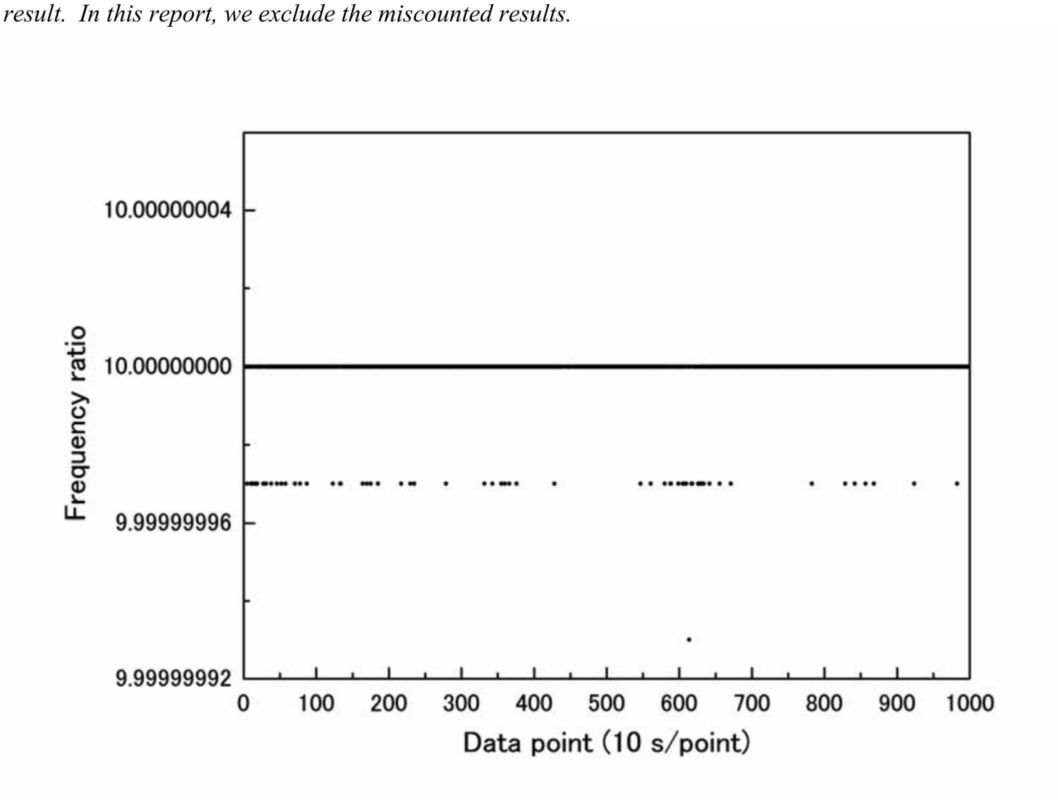
- Special observation:

Criteria for disqualifying data points (phase (cycle) slips)

1. More than 1 time phase slipped data points (CEO frequency)

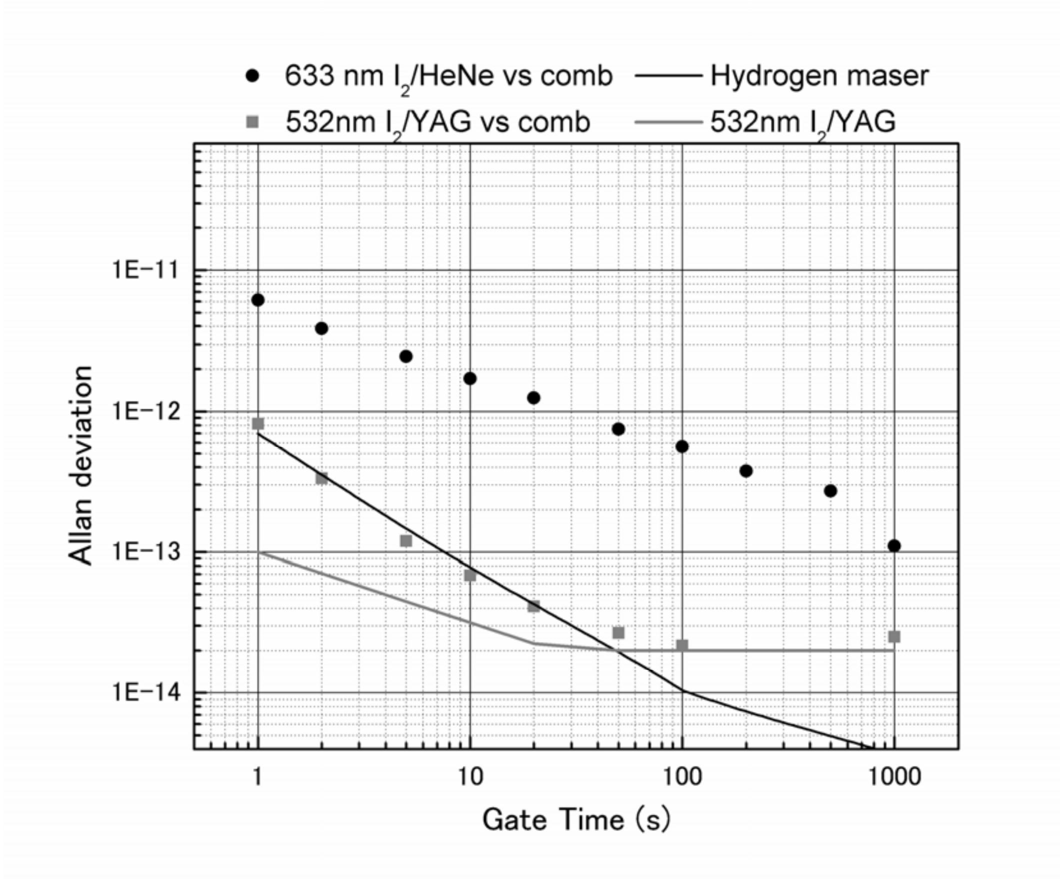
2. More than 1 times phase slipped data points (ratio counting in "Schematic of the experimental setup")

The figure below shows a train of the frequency ratio counting for f_{beat}. If the counter and frequency divider perform properly the counter should indicate exactly 10.000 000 00. Although most of the results were exactly 10.000 000 00, some of the results indicated a 3×10^{-8} lower value, which suggests that the frequency counter miscounted once (phase slip) in a gate time. A 7×10^{-8} lower value suggests that the counter miscounted twice. The difference between the correct value and the twice-miscounted value is not simply double the difference between the correct value and the once miscounted value because of the resolution limit of the ratio counting and the rounding up of the counter. One cycle slip corresponds to an error of 0.1 Hz in the frequency measurement result. In this report, we exclude the miscounted results.



Frequency ratio measurements with l0 s gate times.

- *Allan variance to compare stability to the stability of the standard measured*



The diagram above shows the stability of frequency measurement. Allan standard deviations of the laser O3 (filled circles, ●). Independently measured Allan deviation of the YAG/I$_2$ *laser in NMIJ is also shown (gray squares, ■). The black line indicates the typical stability of a YAG/I*$_2$ *laser in NMIJ and the gray line shows the typical stability of a hydrogen maser in NMIJ. As regards the stability for an averaging time of less than 5 s, we independently acquired an* f_{beat} *data train with an averaging time of 1 s.*

D6. Sensitivity coefficients

Parameter	Sens. Coeff. Value	Uncertainty	Unit	Comments.
Modulation width	*-9.8*	*1.1*	*kHz/MHz*	
Iodine pressure	*-8.6*	*1*	*kHz/Pa*	
Power (output)	*0.13*	*0.028*	*kHz/μW*	
Cell wall temperature	*0.5*	*0.5*	*kHz/°C*	

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

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

Parameter	value	Unit	Uncertainty	Comments
Output power	*60*	*μW*	*3*	
Modulation width	*6.03*	*MHz*	*0.1*	
Iodine cell cold finger temperature	*15*	*°C*	*0.1*	
Cell wall temperature	*24*	*°C*	*1*	

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

source	Value	unit	comments
Frequency reference	*5*	*Hz*	*This value is calculated from the uncertainty of UTC(NMIJ).*
Stat. disp. of results	*0.71*	*kHz*	*This value is calculated from the results on 10 and 18 November.*
Uncertainty in measurement method	*30*	*Hz*	*We do not capitalize this kind of uncertainty in our quality system. But if it is appropriate here I agree with this.*
Total	*0.71*	*kHz*	

D9. u_2.

Typical contributions to the uncertainty from the parameter settings

Source	Value	unit	comments
Laser power	*0.39*	*kHz*	
Modulation width	*0.98*	*kHz*	
Iodine cold finger temperature	*1.30*	*kHz*	$dp = \frac{dp}{dt} dt =$ $1.54 * 0.1 = 0.15 Pa$
Cell wall temp	*0.2*	*kHz*	
Electronic offset	*0.50*	*kHz*	
alignment	*5.00*	*kHz*	
Total	*5.3*	*kHz*	

D10. Results:

Name of standard	Lab.	Result	u_c	*Unit*	Comments
O3	*NMIJ*	*473 612 353 607.2*	*5.3*	*kHz*	*Given at a conf. level of 68% assuming a large number of degrees of freedom.*

Appendix C. UME
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

Lab. Name	*UME*
Contact person	*Ramiz Hamid*
Address	*Ulusal Metroloji Enstitusu (UME), P.K. 54, 41470 Gebze-Kocaeli, Turkey*
Tel.	*+09 262 679 50 00*
e-mail	*ramiz.hamid@ume.tubitak.gov.tr*

D2. Measurements

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	*23/06/05*
Describe measurements	*The absolute frequency of the laser was measured using the UME femtosecond laser comb set-up following the technical protocol for the method BIPM.L-K11 m1.*
References and/or other documentation	*Ramiz Hamid, Ersoy Sahin, Mehmet Celik, Gönül Özen, Massimo Zucco, Lennart Robertsson and Long Sheng Ma, "*10^{-12} *level reproducibility of an iodine-stabilized He–Ne laser endorsed by absolute frequency measurements in the BIPM and UME", 2006 Metrologia,* **43,** *106-108.*

Detailed description of standard

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

D3. Laboratory

Lab. Name	*UME*
Operators	*Ramiz.Hamid*
Address	*Ulusal Metroloji Enstitusu (UME), P.K. 54, 41470 Gebze-Kocaeli, Turkey*
Tel.	
e-mail	*ramiz.hamid@ume.tubitak.gov.tr*

D4. Standard

Designation of laser standard	*UME-L3*
Standard last compared	*At BIPM in September 2003*
Modification on standard since	
Spectroscopy	*Intracavity saturation spectroscopy*
Modulation technique	*3rd harmonic*
Modulation frequency /kHz	*26.727*
Modulation width or index /	*6 MHz p.p Nominal*
Laser cavity length /cm	*36*
Mirror curvature R1 (tube side) /cm	*60*
Mirror curvature R2 (cell side) /cm	*Inf*
Mirror transmission T1 (tube side) / %	*0.9*
Mirror transmission T2 (cell side) / %	*0.9*
Output mirror, 1 or 2.	*(intra cavity power 8.8 mW)*
Designation of iodine cell	*PTB 1999*
Cell length /Brewster /flat windows/origin	*12 cm / Brewster/PTB*

D5. Description of measurements

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

The UME-L3 laser was activated for one week to bring it to a better stability condition before the absolute frequency measurement at UME. Before and after the absolute frequency measurement, the laser output power and the frequency modulation width were measured to be (79.4 ± 0.6) μW and (6.05 ± 0.10) MHz respectively.

The frequency f_f for the UME-L3 laser when locked to the f-component was measured using the UME frequency comb (Menlo Systems GmbH) during the dates from 20 to 25 June 2005. The schematic diagram of the experimental setup is given in Fig. 1. During the experiment, the UME-L3 He-Ne/$^{127}I_2$ stabilized laser and the absolute frequency measurement system including the femtosecond laser comb were located in the same laboratory. During the measurement the temperature of the laboratory was (20.0 ± 0.5) °C. To measure the frequency modulation width, the beat signal between the UME-L3 and the UME-L1 laser pair was investigated using standard heterodyne techniques. After the frequency modulation width measurement, the mirror in the Fig. 1 is removed from the experimental set up and the laser output beam is directly sent to the UME comb system which is externally referenced to the 10 MHz signal from the UME Cs atomic clock.

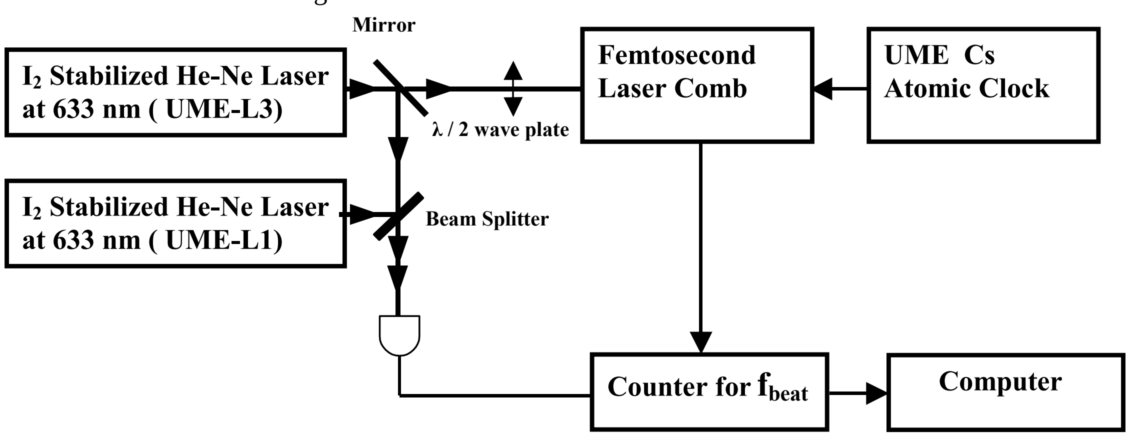


Figure 1. The schematic diagram of the UME experimental setup

As a result of the absolute frequency measurement, the weighted average of the measured frequency f of the f-component was found to be f_f = (473 612 353 600.6 ± 1.1) kHz

The relative Allan deviation for different averaging times and for different pairs of lasers is given in Fig. 2. It can be seen from this figure that under the present comparison conditions, the frequency stability of UME-L3 - BIW167 and UME-L3 – BIPM-4 pairs reaches a flicker floor at 3×10^{-13} for averaging times of about 1000 s.

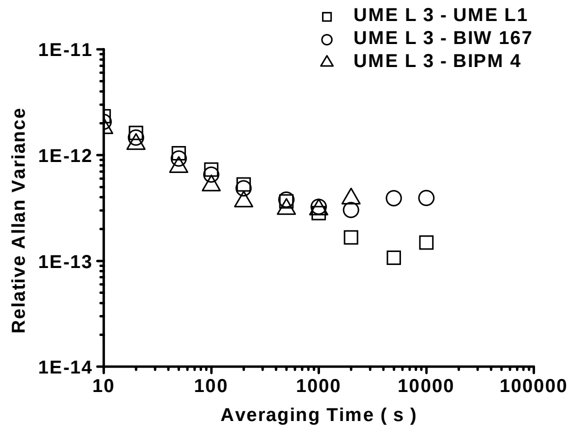


Figure 2**.** The relative Allan deviation for different averaging times and for different pairs of lasers

D6. Sensitivity coefficients

Parameter	Sens. Coeff. Value	Uncertainty	Unit	Comments.
Modulation width	*-9.7*	*0.2*	*kHz/MHz*	
Iodine pressure	*-8.0*	*0.1*	*kHz/Pa*	
Power (output)	*-0.15*	*0.008*	*kHz/μW*	
Cell wall temperature	*-0.05*	*0.05*	*kHz/ ℃*	

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

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

Parameter	value	Uncertainty	Unit	Comments
Output power	*79.4*	*0.6*	*μW*	
Modulation width	*6.05*	*0.1*	*MHz*	
Iodine cell cold finger temperature	*14.99*	*0.03*	*℃*	
Cell wall temperature	*21*	*1*	*℃*	

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

source	**Value**	**unit**	**comments**
Frequency reference	*30*	*Hz*	
Stat. disp. of results	*100*	*Hz*	
Other uncertainty sources	*30*	*Hz*	
Total	*109*	*Hz*	

D9. u_2.

Typical contributions to the uncertainty from the parameter settings

Source	**Value**	**unit**	**comments**
Laser power	*0.09*	*kHz*	
Modulation width	*0.97*	*kHz*	
Iodine cold finger temperature	*0.37*	*kHz*	
Cell wall temp	*0.07*	*kHz*	
Electronic offset	*0.1*	*kHz*	
Alignment	*0.5*	*kHz*	
Total	*1.16*	*kHz*	

D10. Results:

Name of standard	**Lab.**	**Result**	u_c	**Unit**	**Comments**
Ume-L3	*UME*	*473 612 353 600.6*	*1.2*	*kHz*	*Given at a conf. level of 68% assuming a large number of degrees of freedom.*