metrologia

International Comparison

International comparisons of He-Ne lasers stabilized with $^{127}I_2$ at $\lambda \approx 633$ nm (July 2000)

Part X: Comparison of INMETRO (Brazil), INTI (Argentina), NRC-INMS (Canada), CENAM (Mexico), and BIPM lasers at $\lambda \approx 633$ nm

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Abstract. This paper reports the tenth set of results of a series of grouped laser comparisons from national laboratories undertaken by the Bureau International des Poids et Mesures (BIPM) at the request of the Consultative Committee for Length (CCL), formerly the Consultative Committee for the Definition of the Metre (CCDM), for the periods July 1993 to September 1995 and March 1997 to March 2001. As with the previous nine comparisons, this one is expected to be listed as a key comparison in the context of the ongoing BIPM.L-K10 series.
The results of this comparison, involving seven lasers from four countries in the Americas and the BIPM, meet the goals set by the CCDM in 1992 and in 1997 and adopted by the International Committee for Weights and Measures (CIPM) the same year. The standard uncertainty (1 σ) of the frequency of the He-Ne laser stabilized on the saturated absorption of $^{127}I_2$ at $\lambda \approx 633$ nm is reduced to a level of 12 kHz (2.5 parts in 10^{11}) when the lasers compared meet the recommended values of the parameters.
The lasers were first compared with the BIPMP3 laser, with all the lasers set to the parameter values normally used in each laboratory; the results then ranged from –31.5 kHz to +10.0 kHz. After checking and correcting when possible the values of all the parameters, the range stayed about the same, –31.5 kHz to +9.1 kHz. Under the latter conditions, the average frequency difference of the group of seven lasers, with respect to the BIPM4 laser, was –4.4 kHz with a standard uncertainty (1 σ) of 13.2 kHz. If the INMETRO2 laser, considered as a secondary laser, is removed from the group, then the average is –0.5 kHz with a standard deviation (1 σ) of 9.2 kHz. The best relative frequency stabilities, with Allan standard deviations of about 9.3×10^{-13}, 3.5×10^{-13} and 1.4×10^{-13}, were observed with sampling times of 10 s, 100 s and 1000 s, respectively.
Results obtained with NRC and BIPM lasers over a period of five months in two beat-frequency laser comparisons and in an absolute frequency measurement lie within 1 kHz (2 parts in 10^{12}).

1. Introduction

This is the tenth in a series of reports describing the results obtained during an extensive programme of laser comparisons carried out over the period July 1993 to March 2001 [1-10].

At the invitation of the Instituto Nacional de Metrologia (INMETRO, Brazil), the tenth comparison was carried out from 10 to 21 July 2000 and involved seven lasers with participation from the following laboratories: the Instituto Nacional de Metrologia (INMETRO1 and INMETRO2); Instituto Nacional de Tecnología Industrial (INTI1); Centro Nacional de Metrología (CENAM1); National Research Council of Canada (INMS2); and the Bureau International des Poids et Mesures (BIPMP3 and BIW167).

The ongoing aim was to verify that the more restrictive conditions on the operation of lasers described in the practical realization of the definition of the metre of 1997 had been met [11].

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2. Experimental

In order to determine the frequency difference between two lasers, their beams were directed on to an avalanche photodiode to allow beat-frequency detection. Comparisons were made every day between each laser and the BIPMP3 laser. To test the consistency of the measurement system and later to determine the equivalence between all pairs of lasers, all lasers were compared several times in all combinations: agreement within 1 kHz was usually obtained.

The frequency of BIPMP3 was determined at the BIPM before and after the comparison with respect to the BIPM4 stationary laser, for which the absolute frequency is known [12]. Its long-term frequency stability is maintained by regular comparisons between the BIPM laser group and by international comparisons.

Each laser comparison took the form of a matrix measurement [13] in which the frequency intervals were measured for all combinations of the components d, e, f, g of R(127) 11-5 of $^{127}I_2$, with the exception of the main diagonal. As usual, the lasers were stabilized using the third-derivative technique [14].

The INMETRO1, INMETRO2 and INTI1 lasers are of PTB design (produced by PMT, Göttingen, Germany); the CENAM1 and the BIW167 are Winters Electro Optic lasers; the INMS2 is an AXIS laser; and the BIPMP3 laser was designed at the BIPM [15]. The iodine cells were from two different origins: the PTB and the BIPM. Table 1 lists the parameters most likely

Table 1. Compilation of parameters for the different laser systems.

Lasers		INMETRO1 113PTB96	INMETRO2 112PTB96	INTI1 PMT/He/99	INMS2 AXIS103S	CENAM1 WEO144	BIPMP3	BIW167
Laboratory		INMETRO	INMETRO	INTI	NRC	CENAM	BIPM	BIPM
Cavity length/cm					34	26.5	32.5	26
Mirror								
Transmission × 100	T_1*	0.5	1.5	0.5	0.8	0.5	0.9	0.4
	T_2**	1.5	2.0	1.23	0.8	0.65	0.9	0.7
Radius of curvature/cm	R_1*	100	100	100	∞	∞	∞	∞
	R_2**	100	100	100	60	30	60	30
Gain tube								
Manufacture					NEC	REO	NEC	REO
Type					GLT 2700	LTRP 0051-BW	GLT 2700	LTRP-0051 BW
Gas pressure/Pa					333		333	
$p_{\mathrm{He+Ne}}/p_{\mathrm{He}}$					7/1		7/1	
Iodine cell								
Absorption length/cm					8	8	8	8
Origin		PTB	PTB	PTB	BIPM	BIPM	BIPM	BIPM
Number			112	3430/17	131	207	192	296
Date of filling			1996	1999/98	1991	1993	1993	1998
Temp. of wall/°C					26-28	28	22	26
Output power/µW		145	113	134	103.1	117	90	88
Intracavity power/mW		9.7	5.7	10.9	12.9	18.0	10	12.5
Modulation frequency/kHz		2.7	2.7	2.7	1.172	8.33	1.092	1.172

*R_1, T_1 describe the characteristics of the M_1 mirror located on the iodine-cell side of the lasers.
**R_2, T_2 describe the characteristics of the M_2 mirror located on the gain-tube side of the lasers.

Table 2. Raw preliminary beat-frequency measurements between lasers from different laboratories (laser 1) and the BIPMP3 laser together with parameter settings at the beginning of the comparison. Here, Δf is defined as the difference, $f_{\text{laser 1}} - f_{\text{BIPMP3}}$, of the frequencies between laser 1 and laser BIPMP3, u is the estimated standard uncertainty (1 σ), θ_{I_2} is the temperature of the cold finger of the iodine cells, f_w is the width of the frequency modulation, and P_{in} is the intracavity power of the lasers.

Laser 1	Δf/kHz	u/kHz	θ_{I_2}/°C		f_w/MHz		P_{in}/mW	
			Laser 1	BIPMP3	Laser 1	BIPMP3	Laser 1	BIPMP3
INMETRO1	+10.0	6.0	14.81	14.99	5.71	5.98	2.5	9.7
INMETRO2	–31.5	3.4	14.86	15.00	6.9	6.0	5.9	10.0
INTI1	–17.5	0.5	14.86	14.99	5.96	6.05	11.3	9.7
INMS2	–1.2	0.6	14.99	14.99	6.02	6.0	13.0	9.4
CENAM1	–15.4	3.3	14.99	14.99	6.10	5.98	18.8	9.7
BIW167	–3.1	1.7	14.99	14.99	5.99	6.05	11.1	9.8

to cause variations in the results. The INMETRO2 laser was considered as a secondary standard, so it was used less frequently during the comparison.

3. Results

3.1 Frequency reproducibility

Table 2, column 2, lists the frequency differences, Δf, for the first matrix measurements between the other lasers and the BIPMP3 laser, all working in their usual fashion with operational parameters normally close to the values recommended by the CIPM. Considering the five lasers belonging to the national laboratories, for two lasers the results are in the region of the 12 kHz standard uncertainty (1 σ) given by the CIPM. Regarding the other lasers, two lie inside the 2 σ range, and the other lies inside the 3 σ range. Only small differences from the recommended values for the modulation widths and the iodine temperature of the cold finger of the cells were observed, except for the INMETRO2 laser, for which the modulation width was 6.9 MHz peak-to-peak, thus accounting for part of its frequency shift.

The value recommended by the CIPM for the peak-to-peak modulation width is (6.0 ± 0.3) MHz. In this comparison it was measured at the maxima of the amplitude of the beat-frequency signal between the two compared lasers when only one laser is modulated. The signal is observed on an rf spectrum analyser. The temperature of the cold finger of each iodine cell was checked using a calibrated platinum thermometer with an uncertainty less than 0.1 °C.

At the beginning the mean intracavity power of all the lasers was between 2.5 mW and 18.8 mW (see Table 2). Then the INMETRO1 laser was realigned to run with an intracavity power inside the range recommended by the CIPM [(10 ± 5) mW]. Only INMETRO2 and CENAM1 lie outside this range, which results in a contribution to the frequency differences between the lasers when their power coefficients are not well known.

Table 3 lists, for each laser, the iodine temperature and pressure coefficients, the modulation width factor and the intracavity power coefficient determined before

Table 3. Effects of iodine temperature and pressure, modulation amplitude and power on the d, e, f, g components of the transition 11-5, R(127) of $^{127}I_2$: $\Delta f/\Delta\theta_{I_2}$ is the iodine temperature coefficient, $\Delta f/\Delta p_{I_2}$ is the iodine pressure coefficient, $\Delta f/f_w$ is the modulation width factor and $\Delta f/\Delta P_{ex}$ is the extracavity power coefficient. L is the slope of a linear fit to the data points and u the estimated standard uncertainty (1 σ) of one measurement.

		INMETRO1		INMETRO2		INTI1		INMS2		CENAM1		BIPMP3		BIW167	
		L	u	L	u	L	u	L	u	L	u	L	u	L	u
$(\Delta f/\Delta\theta_{I_2})$/(kHz/K)	d							–16.5	0.6	–13.3	0.7	–14.2	0.2	–13.5	0.7
	e							–15.9	0.5	–13.6	0.7	–14.1	0.1	–13.5	0.6
	f							–15.9	0.5	–12.9	0.8	–14.2	0.3	–13.6	0.6
	g							–16.1	0.4	–14.7	1.5	–14.3	0.6	–12.9	0.4
	average							–16.1		–13.6		–14.2		–13.4	
	u							0.5		0.9		0.3		0.6	
$(\Delta f/\Delta p_{I_2})$/(kHz/Pa)	d							–10.5	0.4			–9.0	0.1	–8.6	0.3
	e							–10.1	0.3			–9.0	0.2	–8.7	0.2
	f							–10.1	0.3			–9.0	0.2	–8.7	0.3
	g							–10.3	0.3			–9.1	0.2	–8.2	0.1
	average							–10.25				–9.0		–8.55	
	u							0.3				0.2		0.22	
$(\Delta f/f_w)$/(kHz/MHz)*	d							–7.6	0.2	–4.7	0.7	–6.5	0.5	–3.8	0.7
	e							–10.7	0.4	–10.9	0.2	–9.7	0.2	–9.0	0.4
	f							–10.9	0.4	–10.4	0.4	–9.6	0.3	–7.7	0.5
	g							–12.2	0.4	–13.7	0.3	–10.8	0.2	–11.5	0.3
	average							–10.4		–9.9		–9.2		–8.0	
	u							0.4		0.4		0.3		0.5	
$(\Delta f/\Delta P_{ex})$**/(kHz/µW)	d							+0.22	0.02	–0.042	0.030	–0.003	0.010	–0.007	0.008
	e							+0.18	0.01	–0.136	0.024	–0.083	0.016	–0.066	0.013
	f							+0.18	0.01	–0.125	0.018	–0.040	0.013	–0.076	0.006
	g							+0.16	0.01	–0.131	0.022	–0.067	0.014	–0.124	0.005
	average							+0.18		–0.110		–0.048		–0.068	
	u							0.01		0.023		0.013		0.008	

*The modulation width is always given in megahertz peak-to-peak.
**External power of the laser.

Table 4. Frequency differences ($\Delta f = f_{\text{laser 1}} - f_{\text{laser 2}}$) between the pairs of lasers compared with no correction applied. Here, u_s is the estimated standard uncertainty (1 σ) and represents the frequency repeatability during the ten-day comparison, u_f is the mean frequency shift of each d, e, f, g component relative to their mean frequency, and n is the number of matrix measurements.

	Frequency difference Δf/kHz Standard uncertainties in frequency u_s/kHz (u_f/kHz) Number of matrix measurements n						
Laser 1 Laser 2	INMETRO1	INMETRO2	INTI1	INMS2	CENAM1	BIPMP3	BIW167
INMETRO1		–40.4 (3.2) 1	–28.6 0.4 (2.6) 3	–11.6 0.1 (2.4) 3	–24.1 0.6 (2.9) 3	–9.0 0.8 (2.7) 5	
INMETRO2	+40.4 (3.2) 1			+29.3 0.6 (2.8) 2	+17.3 (1.3) 1	+31.5 (3.4) 1	
INTI1	+28.6 0.4 (2.6) 3			+16.6 0.2 (0.6) 2	+4.2 0.7 (2.4) 4	+18.7 0.8 (0.6) 7	
INMS2	+11.6 0.01(2.4) 3	–29.3 0.6 (2.8) 2	–16.6 0.2 (0.6) 2		–12.7 0.5 (2.3) 2	+2.0 0.5 (0.5) 4	–1.2 (1.2) 1
CENAM1	+24.1 0.6 (2.9) 3	–17.3 (1.3) 1	–4.2 0.7 (2.4) 4	+12.7 0.5 (2.3) 2		+14.8 0.6 (2.9) 6	
BIPMP3	+9.0 0.8 (2.7) 5	–31.5 (3.4) 1	–18.7 0.8 (0.6) 7	–2.0 0.5 (0.5) 4	–14.8 0.6 (2.9) 6		–3.4 0.3 (1.6) 3
BIW167				+1.2 (1.2) 1		+3.4 0.3 (1.6) 3	

the comparison or given by the laboratories. For the CENAM1 laser the modulation width factor was determined during the comparison. As has been demonstrated in previous studies [16-22], it is through knowledge of such factors and coefficients that good frequency reproducibility is likely to be achieved.

Tables 4 and 5 list the frequency differences between the lasers, the former containing the raw data and the latter the results obtained from the following procedure. For those parameters that were adjustable, the values recommended by the CIPM were adopted; otherwise, the results were evaluated by performing calculations using the coefficients listed in Table 3. For all cases only the average of the measurement was adjusted.

Table 6 presents the frequency differences of all lasers with respect to the BIPM4 stationary laser, which is usually taken as the reference. The characteristics of the latter are described elsewhere [16, 23]. To evaluate these frequency differences, values were first assigned to the difference between the BIPMP3 and the BIPM4 lasers. This was taken to be the mean value of measurements made at the BIPM before and after the comparison and is

$f_{\text{BIPMP3}} - f_{\text{BIPM4}} = +3.8$ kHz
(standard uncertainty, 1 $\sigma = 0.4$ kHz).

The required frequency differences were then calculated by combining these values with those given in the second-last column of Table 5. The uncertainties were combined quadratically. These results are also presented in Figure 1.

Although from the beginning of the adoption of the Definition of the Metre in 1983, the frequency reference value is that of component i, the d, e, f, g components were used during these laser comparisons. This situation is largely explained by the fact that the use of He-Ne discharge tubes filled with natural neon places these components at the top of the gain curve, and often the lasers are only single-mode around this frequency range and not close to component i. Thus, as most of the participating lasers were single-mode over a frequency range covering the seven components d to j, we took the opportunity to check if the frequency differences between the lasers remained constant: first, using the usual d, e, f, g components; second, the h, i, j components; and third, the frequency interval (i – e). The results, presented in Table 7, show that with the exception of one laser they give values inside 1 kHz, possibly also confirming the degree of confidence in the frequency reproducibility of the laser frequency.

Table 5. Corrected frequency differences after adjustment of the lasers to the recommended parameters. Here, u_c is the estimated combined uncertainty (1 σ).

	Frequency difference Δf/kHz Standard uncertainties in frequency u_c/kHz Number of matrix measurements n						
Laser 1 Laser 2	INMETRO1	INMETRO2	INTI1	INMS2	CENAM1	BIPMP3	BIW167
INMETRO1		–40.4 3.2 1	–28.6 0.4 3	–16.2 0.2 3	–16.8 1.2 3	–9.1 0.8 5	
INMETRO2	+40.4 3.2 1			+24.8 0.7 2	+24.7 1.8 1	+31.5 3.4 1	
INTI1	+8.6 0.4 3			+12.3 0.3 2	+11.2 1.2 4	+18.6 0.8 7	
INMS2	+16.2 0.2 3	–24.8 0.7 2	–12.3 0.3 2		–1.1 1.2 2	+6.0 0.6 4	+4.1 1.2 1
CENAM1	+16.8 1.2 3	–24.7 1.8 1	–11.2 1.2 4	+1.1 1.2 2		+7.7 1.2 6	
BIPMP3	+9.1 0.8 5	–31.5 3.4 1	–18.6 0.8 7	–6.0 0.6 4	–7.7 1.2 6		–2.7 0.4 3
BIW167				–4.1 1.2 1		+2.7 0.4 3	

Table 6. Frequency differences with respect to the BIPM4 reference laser, where u_c is the estimated combined uncertainty (1 σ), using $f_{BIPMP3} - f_{BIPM4} = +3.8$ kHz, $u = 0.4$ kHz. The averaged offset relative to the BIPM4 laser is –4.4 kHz, $u = 13.2$ kHz (all lasers) and –0.5 kHz with $u = 9.2$ kHz (without INMETRO2).

	Frequency difference Δf/kHz Standard uncertainties in frequency u_c/kHz						
	INMETRO1	INMETRO2	INTI1	INMS2	CENAM1	BIPMP3	BIW167
BIPM4	+12.9 0.9	–27.7 3.4	–14.8 0.9	–2.2 0.7	–3.9 1.3	+3.8 0.4	+1.1 0.6

3.2 Frequency repeatability

Figure 2 shows the frequency differences measured during the ten-day comparison relative to the BIPMP3 laser. This graph illustrates the frequency repeatability of each laser, which is mainly expressed numerically by the standard uncertainties, u, given in Table 4. With the exception of the INMETRO2 laser, on which too few measurements were made, the averaged value is about 0.6 kHz. Note that the frequency difference between INMETRO1 and INMS2 lasers remained less than 0.1 kHz over a period of one week. The quality of the results of this comparison with regard to the frequency stability of the participating lasers may be considered to be high.

3.3 Frequency stability

Several sets of measurements, usually made at night or at lunchtime between pairs of lasers, produced the best results, with relative Allan standard deviations of 9.3×10^{-13}, 3.5×10^{-13} and 1.4×10^{-13} for sampling times of 10 s, 100 s and 1000 s, respectively. Table 8 presents the results in detail.

4. Conclusions

We have again verified that the performance of lasers constructed in different laboratories is capable of satisfying the 12 kHz standard uncertainty (1 σ) requirement set by the CIPM in the 1997 practical realization of the definition of the metre, with the

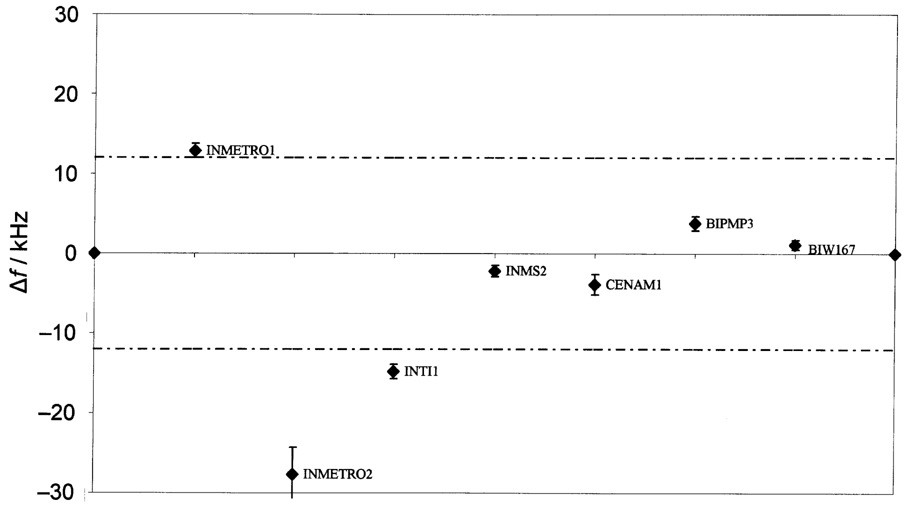

Figure 1. Compilation of the average corrected frequency differences of all lasers relative to the BIPM4 laser. The standard uncertainty (1 σ) given by the CCL, 12 kHz (2.5 parts in 10^{11}), is indicated by the broken lines.

Table 7. Consistency of the frequency differences between pairs of lasers when frequencies are measured for the following components: d, e, f, g (from three to seven measurements); h, i, j (one or two measurements); or i, e (one or two measurements).

Lasers	Δf (d, e, f, g)/kHz	u/kHz	Δf (h, i, j)/kHz	u/kHz	Δf (e, i)/kHz	u/kHz
INMETRO1 – BIPMP3	+9.0	0.8			+9.5	1.2
INTI1 – BIPMP3	–18.7	0.8	–17.7	0.9	–18.4	0.7
CENAM1 – BIPMP3	–14.8	0.6	–12.5	0.8	–13.1	2.0
INTI1 – CENAM1	–4.2	0.7	–5.1	0.6	–4.9	1.5
INMETRO1 – INTI1	+28.6	0.4	+36.4	1.8		

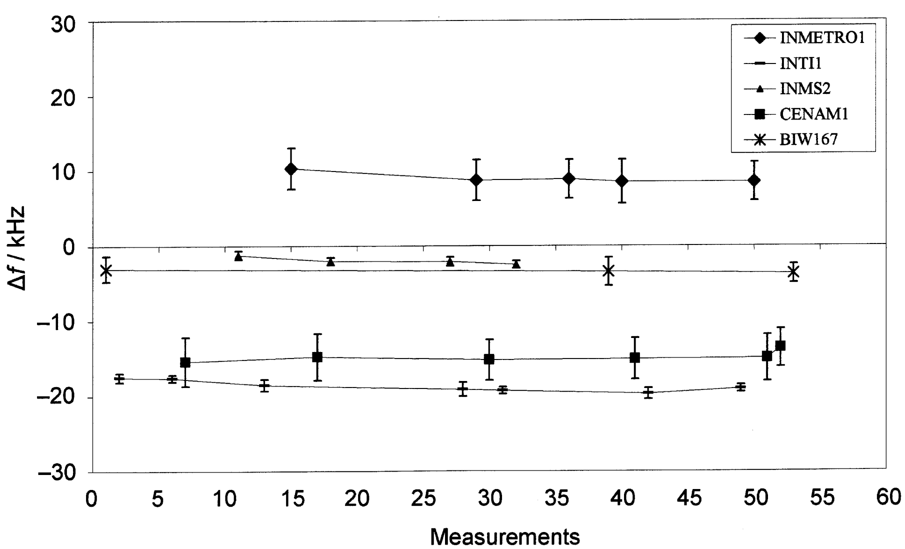

Figure 2. Frequency repeatability over the ten-day comparison of each laser using the BIPMP3 laser as reference.

exception of one laser which lies just outside the 2 σ range. The observed range of the corrected results is from –27.7 kHz to +12.9 kHz. The averaged offset from the BIPM4 laser is –4.4 kHz, with a standard uncertainty (1 σ) of 13.2 kHz when all the lasers are considered.

For certain lasers, better results may be obtained by adjusting the modulation width and intracavity power closer to the recommended values, thus avoiding large corrections, or by accurately determining the values of the main parameters affecting the laser frequency. Knowledge of these values allows a deeper understanding of the behaviour of each laser, with a consequent improvement in performance.

The CENAM1 and INMS2 lasers have already been used in the NORAMET comparison in 1997 [7], the

Table 8. Relative Allan standard deviations for different sampling times and for different pairs of lasers. The best relative frequency stability was 1.4×10^{-13} for a sampling time of 1000 s.

Lasers	Relative Allan standard deviation		
	$\tau = 10$ s	$\tau = 100$ s	$\tau = 1000$ s
INMETRO1 – BIPMP3	2.7×10^{-12}	8.4×10^{-13}	2.7×10^{-13}
INMETRO1 – CENAM1	2.6×10^{-12}	9.0×10^{-13}	3.1×10^{-13}
INMETRO1 – INMS2	9.3×10^{-13}	3.5×10^{-13}	1.4×10^{-13}
CENAM1 – BIPMP3	2.7×10^{-12}	7.9×10^{-13}	2.5×10^{-13}
INTI1 – BIW167	3.0×10^{-12}	9.3×10^{-13}	2.9×10^{-13}
INTI1 – BIPMP3	3.1×10^{-12}	9.7×10^{-13}	2.9×10^{-13}
INTI1 – CENAM1	1.0×10^{-12}	5.0×10^{-13}	1.6×10^{-13}

results of which are comparable with those obtained here.

Taking into account results from previous beat-frequency comparisons over a period of five months between the NRC with INMS2 and INMS3 lasers and the BIPM with BIPMP3 and BIPM4 lasers, as well as absolute frequency determinations made at the NRC on the same lasers [24], we observed that such He-Ne lasers maintained their absolute frequency within 1 kHz even after transportation. This result may be fortuitous but perhaps it is significant.

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