Bundesamt für Eich- und
Vermessungswesen (BEV)
Vienna, Austria

# CCL Key Comparison CCL-K11
# Comparison of optical frequency and wavelength standards

## Technical protocol

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**Contents**

## 1. Document control

| | |
|---|---|
| Version 1.00 | Issued on 27. March 2008. |
| Version 1.01 | Issued on 12. February 2009. |
| Version 2.00 | discussion basis, not issued (September 2010) |
| Version 2.91 | Draft circulated on 13. June 2018 |
| Version 2.93 | Update on first productive use (November 2018) |
| Version 2.96 | Final draft circulated in September 2019, to become version 3.0 on approval |
| Version 2.97 | Comments incorporated November 2019 |
| Version 3.0 | Approved version December 2020 |

## 2. Introduction

The metrological equivalence of national measurement standards and of calibration certificates issued by national metrology institutes is established by a set of key and supplementary comparisons chosen and organized by the Consultative Committees of the CIPM or by the regional metrology organizations in collaboration with the Consultative Committees.

At its meeting in September 2007, the CCL decided upon a key comparison of optical frequency and wavelength standards, named CCL-K11, with BEV as the pilot laboratory. The comparison was registered in 2008 and it is supposed as an on-going comparison. For reference see Appendix F.

The scheme outlined in this document covers the technical procedure to be followed during the measurements. The goal of the CCL key comparisons is to demonstrate the equivalence of routine calibration services offered by NMIs to clients, as listed in Appendix C of the Mutual Recognition Agreement (MRA). To this end, participants in this comparison agree to use the same apparatus and methods as routinely applied to calibrations of client artefacts.

By their declared intention to participate in this key comparison, laboratories accept the general instructions and to strictly follow the technical protocol of this document.

## 3. Scope

The CCL-K11, being a key comparison, is designed to provide a technical basis for the review of CMCs in the field of standard based optical frequency/wavelength calibrations as far as CCL is concerned. CCL-K11 was selected to be one of the few key comparison topics in the field of length metrology.

Specifically, the service category 1.1.1 from the CMC classification scheme for length services, generally referred to as the DimVIM [1], is its topic. The category 1.1.1 deals with “frequency stabilized laser” as instruments and “vacuum wavelength; optical frequency” as the measurand.

As with most comparisons, it is artefact based. The artefacts are frequency stabilized lasers, which are portable (so that they can be brought to the node labs) and are the national standards of length in their home labs. The CCL-K11 concerns in particular those wavelengths that are important for the field of dimensional metrology. However, only standards of highest metrological quality should be part of the comparison. Typical examples would be the 633 nm, 543 nm and 532 nm iodine stabilized standards but also other sources may become meaningful to include as reference standards as long as the requirements discussed above are met.

Generally, lasers used as light sources in commercial laser interferometers are not acceptable. Neither are frequency combs since the owner’s frequency standard (atomic clocks) are an integral part of those instruments.

Being designed as an artefact-based comparison, CCL-K11 might not be adequate to support all CMC claims under service category 1.1.1. The scope of this category is deliberately rather broad. It is applicable for calibration of client's lasers at the $10^{-8}$ level but also to more demanding work reaching $10^{-14}$. In the latter case transportable lasers either do not exist or other (node) labs might not be able to reach comparable uncertainties. NMIs interested in obtaining evidence for such services must find a way which is beyond this protocol as discussed in a CCL guidance document [2].

Contrary to the predecessor comparisons[1], CCL-K11 is not intended to derive a better value for any of the frequencies from the list of recommended radiations for the realisation of the metre and other optical frequency standards (formally known as MeP [3]). Therefore, it is not mandatory that $f_e$ (see Section 7.1) is a value out of this list, nor is it necessary to correct for the nominal working parameters. It is however necessary for each participant to follow his internal working procedures as for any calibration for the respective CMC entry. This does not imply that a specific user must be present at the node laboratory during comparison. If the internal working procedures are sufficiently clear-cut, any (experienced) technician may operate the laser.

### 3.1 Specifics of CCL-K11

This technical protocol follows as far as possible the guide CCL/WG-MRA/GD-1 [4]. In contrast to other key or supplementary comparisons in the length field, CCL-K11 has some specific features:

- The artefacts (or standards) are provided by the participant and each participant has their own artefact. (In usual key comparisons a single artefact, to be measured by all participants, is provided by the pilot)
- The measurand (in the meaning of MRA documents or guides issued by JCRB/CIPM) of an artefact taking part is actually not measured in the course of the comparison. It is stated by the participant by taking into account their working procedures and the results of auxiliary measurements.
- The Key Comparison Reference Value (KCRV) is determined by the node laboratory on a per participant basis. Each participant has thus an individual KCRV.
- The linking between different participants is assured by the respective node laboratories taking part on CCTF-K001.UTC. The actual procedure is outlined in section 8.5.
- It is not necessary (but often practical) to ask a number of participants to convene at the site of a node or host laboratory for a measurement campaign. On the other hand, it is perfectly adequate for a single participant to take part in CCL-K11 for a given period. More details can be found in section 4.2.

## 4. Organization

### 4.1 Pilot, Node, and Host Laboratories

BEV (AT) acts as the pilot and is supported by 4 NMIs, here called node laboratories: MIKES (FI), NMIJ-AIST (JP), NPL (GB) and NRC (CA). In some cases, it can be more efficient to perform measurements on an alternate site (so called host laboratory) under attendance of a node laboratory. This has to be negotiated with the pilot. The contacts of the node laboratories can be found in Table 1.

[1] BIPM.L-K10 and BIPM.L-K11

**Table 1. List of node laboratories**

| Laboratory, Country code, RMO | Role | Contact person, Laboratory | Phone, Fax, email |
|---|---|---|---|
| BEV (AT)<br>EURAMET | Pilot, Node | Michael Matus<br>Bundesamt für Eich- und Vermessungswesen<br>Arltgasse 35, 1160 Wien<br>Austria | Tel. +43 1 21110 826540<br>Fax +43 1 21110 996000<br>E-Mail: michael.matus@bev.gv.at |
| NPL (GB)<br>EURAMET | Node | Helen Margolis<br>National Physical Laboratory<br>Hampton Road, Teddington<br>Middlesex TW11 0LW<br>England | Tel. +44 208943 6113<br>Fax —<br>E-Mail: helen.margolis@npl.co.uk |
| MIKES (FI)<br>EURAMET | Node | Jeremias Seppä<br>MIKES Metrology, VTT Technical Research Centre of Finland Ltd, Tekniikantie 1, FIN-02150 Espoo<br>Finland | Tel. +358 50 410 5503<br>Fax —<br>E-Mail: jeremias.seppa@vtt.fi |
| NMIJ-AIST (JP)<br>APMP | Node | Hajime Inaba<br>National Metrology Institute of Japan, National Institute of Advanced Institute of Science and Technology<br>Tsukuba-central 3-1, Umezono 1-1-1, Tsukuba, Ibaraki 305-8563<br>Japan | Tel. +81-29-861-6807<br>Fax —<br>E-Mail: h.inaba@aist.go.jp |
| NRC (CA)<br>SIM | Node | John Bernard<br>National Research Council of Canada<br>1200 Montreal Road, Bldg. M-36, Ottawa, Ontario K1A 0R6<br>Canada | Tel. +1-613-993-2181<br>Fax +1-613-952-1394<br>E-Mail: john.bernard@nrc-cnrc.gc.ca |

## 4.2 Schedule

Generally, a comparison should not take more than one to two weeks. The date and duration for each laboratory should be agreed upon mutually. The participating laboratories have to negotiate a measurement time slot with their preferred node laboratory. It is often beneficial to plan participation at the yearly RMO TC-L meetings. In any case the pilot lab (BEV) has to be informed on an agreed participation by sending the completed form of Appendix A.

In the traditional procedure the participant travels to the node laboratory and prepares and operates his standard laser according to his normal procedures.

Alternatively, the participant provides complete instructions on how to prepare and operate his standard laser so the personnel at the node laboratory can reproduce, with a high degree of certainty, the actions that are performed in the participant's laboratory for a normal calibration according to the participant's CMC's. In this case the participant is responsible for a safe transportation. There is always a risk of damage by maloperation, so the node laboratory might not accept this procedure.

A working communication channel between the node and the participant during the time of the actual laboratory work is very important. In case of unexpected problems with the artefact, the node may have to terminate the measurements if there is no timely advice by the participant.

## 4.3 Reception, transportation, insurance, costs

Since the artefacts of this comparison are provided by the participants, they have to arrange for transportation themselves. If help from the node or host laboratory is needed, this must be arranged in time.

Participants must ensure that they fulfil the respective customs requirements for the import of the standards into the recipient country of the chosen node laboratory. In summary the organisation and costs for the transport of the equipment and personnel is totally the responsibility of the participating laboratory.

# 5. Artefacts

## 5.1 Description of artefacts

Artefacts in this campaign are provided by the participants. Usually, the artefacts are the participant's primary or working standards for length. Throughout this document the terms standard/artefact/laser are used interchangeably.

The majority of artefacts concerned in this comparison are iodine stabilized He-Ne lasers at $\lambda \approx 633$ nm, stabilized on the $a_{16}$ or f component of the $^{127}I_2$ R(127) 11-5 transition as described in the MEP 2003 document [3]. However as discussed in the scope (Section 3) it is perfectly legal to choose a different component or even a different laser type as artefact, as long as it is used as the participant's standard for calibration work. Additionally, the chosen node laboratory must be capable of estimating the KCRV for this type of laser according to Appendix E of this document.

Since the artefacts are best known by the participants who own them, a detailed description of the artefacts is essential. In any case the completed tables in Appendix A must be available at the time of the actual comparison work.

Depending on the actual application of the standard, it might be necessary for the participant to report reference values for working parameters and associated sensitivity coefficients (together with their uncertainties). In this case these values are considered a necessary part of the artefact description and must be reported in Table B.3.

# 6. Measuring instructions

## 6.1 Measurands

Contrary to other key comparisons, the participant does not perform any measurements in the course of CCL-K11. The value of the participant's measurand (in the meaning of the MRA documents or guides issued by JCRB/CIPM) is stated by them before the node laboratory determines the KCRV. This stated value must be in accordance with the quality system and working documents applied when using the laser for calibration work and must include the associated measurement uncertainty (Section 6.2).

## 6.2 Measurement uncertainty

The uncertainty of measurements (i.e., the actual measurements at the node lab as well as the measurand according to section 6.1) shall be estimated according to the ISO Guide to the Expression of Uncertainty in Measurement [5]. Participating laboratories are encouraged to use their usual model for the uncertainty calculation. All measurement uncertainties shall be stated as standard uncertainties. For guidance document CCL-GD8 [2] may be consulted.

## 6.3 Reference condition

The participant states the measurand under specific reference conditions which have to be documented in Table B.3. The specific choice of the reference conditions depends on the artefact and its intended use. Typical examples are as follows:

- Artefact: He-Ne lasers at $\lambda \approx 633$ nm, stabilized on the f component of the $^{127}I_2$ R(127) 11-5 transition as described in the MEP 2003 [3]. The participant operates the laser as exemplified in the MeP.

- Artefact same as before. The participant uses the recommended frequency (MeP 2003) value while the uncertainty is estimated from the tolerated range of the deviations of working parameters' deviations from reference conditions.
- Artefact same as before. Laser was calibrated by an NMI (or the same NMI). The user has to estimate the uncertainty as above. A drift has to be considered as well.

The goal of CCL-K11 is primarily to test the participant's claims in the CMC, not the physical frontiers of a specific laser realisation. It is therefore quite common to operate the artefacts under somewhat relaxed conditions and higher uncertainties. At the end, the participant has to support his claim of CMC uncertainty.

The selection between these three options is not as arbitrary as it might seem. Many NMI still have CMC entries refereed under the MeP regulations for $^{27}I_2$ He-Ne lasers. Consequently, they must adopt the first option in this case. A deviation from this procedure must be clearly communicated by the participant and documented in the final report.

#### 6.3.1 Typical working parameters

The controlled working parameters (and the respective reference values) are artefact specific. One can take the specifications of the aforementioned laser as guidance for generalisation.

- Optical laser output power (as a measure of the intracavity power)
- Frequency modulation width
- Iodine cell cold finger temperature (as a measure of the iodine vapour pressure)
- Iodine cell wall temperature

Each node laboratory should be able to measure at least these parameters with sufficient accuracy on request. Since the values and uncertainties of those parameters can contribute to the KCRV, the responsibility of the relevant measurements is at the node lab.

#### 6.3.2 Sample time

According to common practice, the measurand (frequency) is defined as an average value over a given sample time. For this comparison the default (and minimum) sample time targeted is 1 000 s, but longer measurement times are preferred. All frequency values used in this document (notably in equations) are with the implicit understanding that they are considered as average values over the sample time.

In reporting frequency values and uncertainties, the used sample time must be documented. The node laboratory is advised to validate applied statistical analysis during the comparison work (at least by an Allan-variance plot or table).

## 7. Results

### 7.1 Results and standard uncertainties as reported by participants

Each participant has to state the frequency $f_e$ with its standard uncertainty $u_e$, of his artefact when it is operated under participant's defined conditions. The result has to be reported and documented in Appendix C.1, the reference conditions (if applicable) in Appendix C.3.

It is important that these values are given before any measurements are performed by the node laboratory!

# 8. Analysis

## 8.1 Estimation of the key comparison reference value (KCRV)

It is a distinctive feature of this key comparison, that the KCRV is determined on a per participant basis. Thus, each participant has its own KCRV which is used to test consistency.

Simply speaking the KCRV is determined by the node laboratory by measuring the frequency $f_0$ of the artefact and estimating the standard uncertainty $u_0$. The host/node laboratory has different choices to measure the frequency; the most important techniques are listed in Appendix D.

### 8.1.1 Correction of raw value

If requested by the participant, the raw frequency must be corrected to account for parameters deviating from the reference conditions (Section 6.3). The determination of the parameter values is performed by the node laboratory in the course of the comparison, consequently the actual calculations are performed by the node. The procedure is anticipated in Table C.3. In any case the participant has full control over this calculation.

Denote the measured (uncorrected) frequency $f_0$ with standard uncertainty $u_0$, and the measured frequency, corrected for influence of operational parameters $f_{\mathrm{m}}$ with standard uncertainty $u_{\mathrm{m}}$. Then the following holds:

$$f_{\mathrm{m}} = f_0 - f_{\mathrm{p}} \tag{1}$$

The symbol $f_{\mathrm{p}}$ denotes the condensed information about the influence of the actual working parameters and other quantities on the laser frequency. A linear model is usually sufficient:

$$f_{\mathrm{p}} = \sum_i s_i \cdot \Delta x_i \tag{2}$$

Where the $s_i$ denotes the sensitivity coefficients and $\Delta x_i$ the deviations of the respective working parameters from the reference values (care must be taken choosing the correct signs for both quantities). The uncertainties are thus derived in a straightforward way as:

$$u_{\mathrm{p}} = \sqrt{\sum_i \left(u(s_i)\cdot \Delta x_i\right)^2 + \sum_i \left(s_i \cdot u(\Delta x_i)\right)^2} \tag{3}$$

and

$$u_{\mathrm{m}} = \sqrt{u_{\mathrm{p}}^2 + u_0^2} \tag{4}$$

In the case that no correction due to working parameters is requested by the, one can formally set $f_{\mathrm{p}}$ and $u_{\mathrm{p}}$ equal to zero.

## 8.2 Degree of Equivalence

Given the measurement result from section 7.1 and the KCRV from section 8.1 one can construct for a particular participant $i$, the dimensionless (relative) quantities

$$\Delta f_{\mathrm{r}}(i) = \frac{f_{\mathrm{e}}(i) - f_{\mathrm{m}}(i)}{f_{\mathrm{m}}(i)} \tag{5}$$

$$u_{\mathrm{r}}(i) = \frac{\sqrt{u_{\mathrm{e}}^2(i) + u_{\mathrm{m}}^2(i)}}{f_{\mathrm{m}}(i)} \tag{6}$$

These values are presented in the final report.

### 8.3 Consistency by $E_n$ values

To test consistency between the measured values and the expected ones, hypothesis testing at a confidence level of 95 % is to be performed. The result will serve as a basis for the review of the CMC and indicate the compatibility with the claimed capabilities. In this framework the “degree of equivalence” (DoE) can be obtained in the usual way. Thus the (relative) DoE is $\Delta f_r$ (Eq. 5) with its standard uncertainty $u_r$ (Eq. 6). The consistency can thus be checked by the following condition:

$$-1 \leq E_n = \frac{\Delta f_r(i)}{U_r(i)} \leq 1 \quad \text{with} \quad U_r(i) = 2 \cdot u_r(i) \tag{7}$$

As discussed at the 14th CCL meeting [6], it is neither necessary nor useful to determine a pair-wise degree of equivalence. For all results reported the expanded uncertainty to a 95 % confidence level can be obtained by multiplying the standard uncertainties with $k = 2$.

### 8.4 Reviewing of results (CMC)

The review is performed according to the guidance set up by CCL [4] and is included in the final report. In short, the $E_n$ criterion (Eq. 7) must hold and the stated uncertainty of the result (section 7.1) must be compatible with the published CMC claim:

$$U_e \equiv 2 \cdot u_e \leq U_{CMC} \tag{8}$$

Often the numerical value of $u_p$ is the dominating uncertainty thus obfuscating a conclusion. It is at the discretion of the reviewer to check the uncertainty budget of $u_e$ to be compatible with the CMC claims.

### 8.5 Linking of result to other comparisons

Plotting the DoE of all participants in the same graph links the results of this on-going key comparison. This is possible even for different kinds of lasers (e.g., one working at 633 nm, the other at 532 nm wavelength) since the DoE are defined as relative quantities.

## 9. Reporting

Generally, the CCL guidance document CCL/WG-MRA/GD-3 [7] on how to prepare and submit reports of a key comparison in dimensional metrology is followed. Since the workload is balanced between different node laboratories a few modifications are necessary, mainly to inform the pilot on the progress.

### 9.1 Draft A Report

The participant and the node laboratory have to complete the forms in Appendix A, Appendix B, Appendix C and Appendix D. This information constitutes essentially the Draft A report and can be sent to the participant for comment. In case of a campaign with many participants this process must comply with anonymity (by sending the specific draft A reports individually).

Often the first draft can be discussed personally in course of the participant’s stay at the node lab. If the participant is not on site (see section 4.2) timely e-mail communication is necessary. After reaching consensus, the node labs should send the Draft A reports to the pilot.

### 9.2 Draft B Report and Final Report

These reports are to be prepared by the pilot lab. They are essentially a collection of the tables in the Appendices A to D.

# Appendix A Participant data

Details of the participant must be provided in advance to the actual measurements by sending the completed Table A to the pilot lab's contact (michael.matus@bev.gv.at). An agreement with the node laboratory is a matter of course. The actual date of measurement might be updated in the final report at a later stage.

Note: Text shown in green serves as guideline/fill-in assistance and is for information only, replace on use!

| **A.1 Participant data** | |
|---|---|
| Laboratory (Country code) | NMISA (ZA) |
| RMO | AFRIMETS |
| Contact person, Operator | Faith Hungwe |
| Address | Building 5 CSIR Campus,<br>Brummeria, Pretoria 0184<br>South Africa |
| Phone, Fax, Email | Tel. +27 12 841 4936<br>E-mail: fhungwe@nmisa.org |
| Artefact's designation | NMISA - Musafa |
| CMC | $U$ = 10 MHz @ 633 nm (He-Ne laser) |
| Date of measurements | 15.11.2018 – 20.11.2018 |

| **A.2 Host/node data** | |
|---|---|
| Laboratory (Country code) | |
| Contact person, Operator | |
| Address | |
| Phone, Fax, Email | |

## Appendix B Description of artefact

Details of the standard relevant to the comparison must be collated in the following tables. The participant has to decide in advance of the actual measurements to what extent they wish to correct for deviations of working parameters. The parenthesis notation for stating standard uncertainties is used in B.3.

Note: Text shown in green serves as guideline/fill-in assistance and is for information only, replace on use! Data in B.2 and B.3 are examples for a MeP 633 nm laser.

| **B.1 Description of artefact (mandatory)** | |
|---|---|
| Designation | NMISA - Musafa |
| Manufacturer<br>Model / Type<br>Serial Number | Winters Electro Optics<br>W100<br>294 |
| Wavelength (approx.) | 633 nm |
| Operation principle | MEP 2003 |
| Last compared | Never |
| Comments | New laser<br>…<br>… |

| **B.2 Detail information of artefact (mutable)** | |
|---|---|
| Laser type | He-Ne laser |
| Stabilisation technique | Saturation spectroscopy on iodine vapour, 3*f* frequency modulation |
| Dither frequency | 8.333 kHz |
| Modulation width | 6.0 MHz |
| Iodine cell | BIPM 1114, 10 cm, Brewster windows |
| Laser cavity length | 26,5 cm |
| Cavity mirrors (curvature, transmission, location) | M1: 30 cm, 0.7 % , front, output mirror<br>M2: ∞, 0.25 %, rear |

| **B.3 Reference conditions and sensitivity coefficients of artefact (optional)** | | | |
|---|---|---|---|
| **Parameter** | **Nominal value** | **Sensitivity coefficient (standard uncertainty)** | **Comment** |
| Output power | 70 µW | +0.007 (0.010) kHz/µW | From literature |
| Modulation width | 6.0 MHz | −10.0 (1.0) kHz/MHz | From literature |
| Iodine cell cold finger temperature | 15.0 °C | −15.0 (0.2) kHz/°C | From literature |
| Cell wall temperature | 25 °C | +0.5 (0.5) kHz/°C | From literature |
| … | | | |
| … | | | |

**B2** The nature and extent of data depends on the operation principle and the normal operation of the laser. This table can be modified by the participant.

**B3** The nature and extent of data depends on the operation principle and use of the laser. This table can be modified or even completely deleted by the participant.

## Appendix C Participant Results Report Form

The measurement result (C.1) of the comparison has to be determined by the participant in advance, before measurements are performed by the node/host lab. The remainder of the table has to be filled by the node laboratory. The parenthesis notation for stating standard uncertainties is used here.

Note: Text shown in green serves as guideline/fill-in assistance and is for information only, replace on use!

| **C.1 "Measurement result" of participant (stated before C.2!)** | |
|---|---|
| Expected frequency $f_e$ | 473 612 353 604.0 (10.0) kHz |

| **C.2 Frequency measurement of host laboratory (to be performed after C.1!)** | |
|---|---|
| Measured frequency $f_0$ (uncorrected) | 473 612 353 602.068 (0.064) kHz |

| **C.3 Correction due to working parameters (optional)** | | |
|---|---|---|
| **Parameter** | **Measured value** | **Frequency correction** |
| Output power | 88.8 (5.0) µW | -0.132 (0.191) kHz |
| Modulation width | 5.725 (0.100) MHz | −2.740 (1.037) kHz |
| Iodine cell cold finger temperature | 14.955 (0.050) °C | −0.600 (1.503) kHz |
| Cell wall temperature | 25 (3) °C | +0.000 (1.000) kHz |
| … | … | … |
| … | … | … |
| Overall frequency correction $f_p$ | −3.557 (2.091) kHz | |

| **C.4 Measurement of host laboratory (KCRV)** | |
|---|---|
| Measured frequency $f_m = (f_0 - f_p)$ | 473 612 353 598.520 (2.091) kHz |

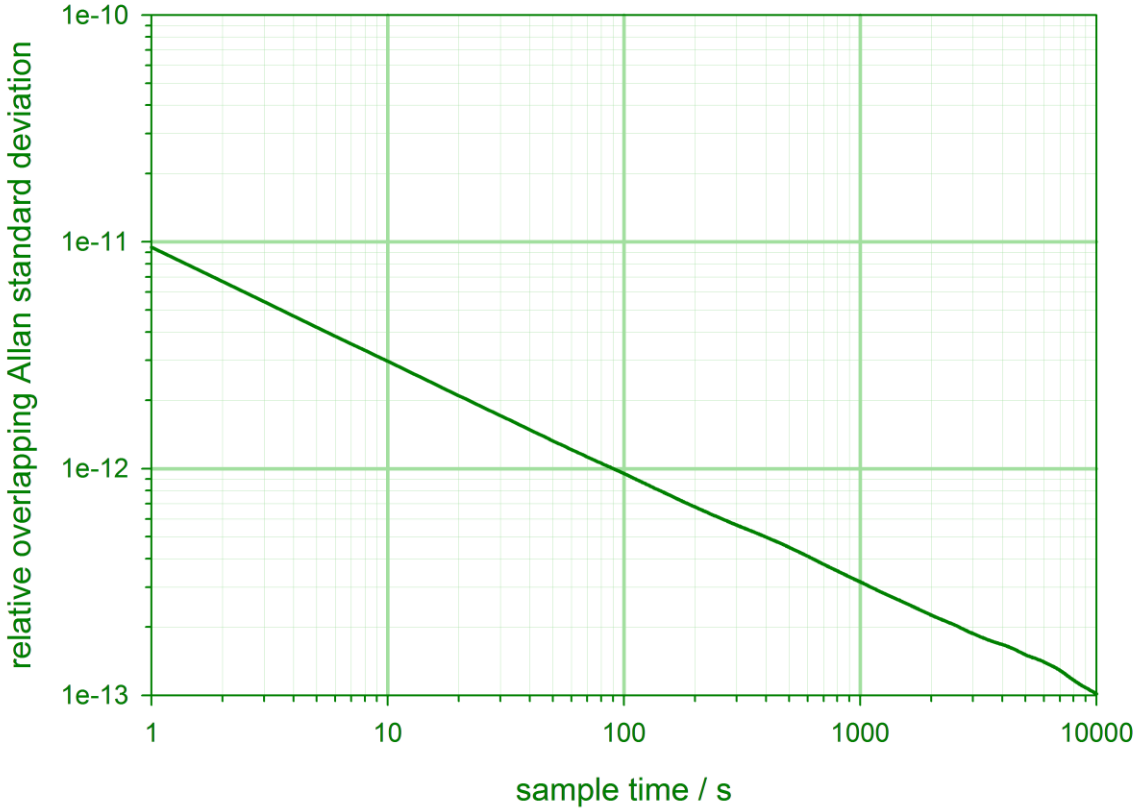
| **C.5 Comparison Result** | |
|---|---|
| Frequency difference $\Delta f = f_e - f_m$ | +5.480 (10.216) kHz |
| Fractional frequency difference $\Delta f / f_e$ | +11.6 (21.6) $\cdot 10^{-12}$ |
| Degree of equivalence stated as $E_n$ value | +0.54 |

## Appendix D Description of Measurements

Here a short summary of the actual measurement technique shall be given by the node lab.

Note: Text shown in green serves only as guideline/fill-in assistance and is for information only, replace on use!

- Method: A femtosecond fiber laser comb generator (BEV) is used to measure the absolute frequency of the 633 nm standard. The output beam of the standard is transferred to the comb via free space, avoiding optical feedback using a double stage Faraday isolator. All counters and synthesizers are referenced to an active hydrogen maser. This maser is part of the BEV clock assemble which takes part in the CCTF-K001.UTC key comparison thus providing a link to the SI.
- Conditions: The measurements are made in accordance with the BEV quality system (respective working document A_0118). After some test runs, mainly to use the warmup period, one 420 000 s long measurement was made with a sample time of 1 s (raw data filename NMISA_03.dat). Possible cycle slips and outliers are automatically detected and removed using a schema described in the references of the technical protocol and the working document A_0118.
- Special observation: —
- Allan variance stability: A long run absolute frequency measurement of the laser was used to determine the relative overlapping Allan standard deviation (raw data filename NMISA_03.dat, 420 000 s).



# Appendix E Guideline to determine the KCRV (for node and host labs)

As discussed in section 8.1 for the determination of the KCRV, the frequency $f_0$ of the participant's artefact has to be measured by the host lab. Three methods are commonly used, and others are conceivable. It is expected that the qualified node labs (section 4.1) always perform absolute frequency measurements, here denoted by [m1]. The method [m1] has the shortest traceability chain, thus providing smallest measurement uncertainties.

Methods [m2] and [m3] were used in the former comparison work on 633 nm He-Ne laser standards. The actual choice of method depends on the host laboratory's resources and procedures. Additionally, the method's intrinsic uncertainty must be considered and balanced against the CMC claim.

- Absolute frequency measurement [m1]
- Matrix measurement [m2]
- Heterodyne measurements between the same components using an AOM [m3]
- Any other method [m4]

**General requirements**

All methods base on optical beat frequency measurements (heterodyne measurements) between two laser beams. The beat frequencies are chosen to lie in a convenient range, usually a radio frequency below about 1 GHz. Such frequencies can easily and precisely be determined by standard electronic equipment.

Additionally, a heterodyne measurement always demands a substantial difference between the two optical frequencies. For beat frequencies near to 0 Hz, the sign of the difference might change during the course of measurement. The reason for the sign alteration might be drift, scatter, or an intentional frequency modulation. In particular the iodine stabilized He-Ne lasers utilize a frequency modulation of about 6 MHz (peak to peak) thus limiting the average frequency difference between two of these lasers to something greater than this value.

Moreover, practical counters used to measure the beat frequency are often sensitive to residual frequency modulation of the input signal, thus limiting the lower frequency value to be measured even more. All these effects must be carefully characterized and considered when performing any of the following measurement methods. At least following facts common to all methods must be known and documented:

- Traceability to the SI (RF-frequency sources and/or calibration of reference laser).
- Beat scheme / measurement scheme (optical set up, free space or fiber based).
- Electronic set up (photo detector, amplifier, RF-filter)
- Frequency counter
- Beat signal conditions (e.g., 40 dB in a 250 kHz bandwidth as observed in a spectrum analyzer). Criteria for disqualifying data points as outliers (phase slips).

**[m1] Absolute frequency measurement**

An absolute frequency measurement is performed by a beat measurement of the laser under test and a specific comb mode. This comb mode is produced by an optical femtosecond comb generator, usually referenced to a high accuracy RF-oscillator (Cs-clock or active H-maser). Beside the precautions discussed above, effects of neighboring comb modes must be considered and avoided. Additionally, one should disclose following information:

- References describing the comb measurement system;
- Documentation of validation of the system.

**[m2] Matrix measurement**

Here the reference standard is a laser of the same kind as the standard to be measured. Each of the two lasers can be operated on a number of different (but nominally pairwise identical) optical frequencies. Without loss of generality the technique is explained here on the widespread iodine stabilized He-Ne laser operating at 633 nm. It can be locked to at least to 4 different hyperfine transitions (or components, denominated by d, e, f, g). The absolute frequency of a single component (say f) of the reference laser must have been calibrated to ensure the traceability to the second.

The technique involves the measurement of beat frequencies of all meaningful combinations of components. This leads to 12 values: $\Delta f$(d,e'), $\Delta f$(d,f'), $\Delta f$(d,g'), $\Delta f$(e,d'), $\Delta f$(e,f'), … $\Delta f$(f,g') in this example.

From these values it is possible to derive all absolute frequencies for both lasers by a matrix inversion technique. In particular the KCRV of the standard taking part in this comparison can be found. Since the system is over determined, the technique can be modified in two ways:

- measure only the beat frequencies of a subset out of the complete set of combinations;
- more than a single component of the reference laser may be calibrated in an absolute way.

In any case this method is quite time consuming and needs frequent operator intervention for the re-locking of both lasers to the different components. Since the KCRV is determined from many different data taken over relatively long time, it is not straight forward to perform time-series measurements.

Beside the items common to all methods as discussed under general requirements, following facts must be known and documented:

- Additional uncertainty contributions caused by reference laser (calibration, drift, working parameters);
- Closure of matrix inversion (*a posteriori* uncertainty of the adjustment calculation).

Note: In the former BIPM.L-10 key comparison matrix measurements were performed also, however no absolute frequency was stated. Instead, an average (over the components d, e, f, g) frequency difference relative to laser BIPM-P3 was determined. The evaluation technique as outlined by Bayer-Helms et al. [8] is still useable for the present application.

**[m3] Heterodyne measurements between the same components using an AOM**

As in the preceding technique [m2] here too, the reference standard is a laser of the same kind as the standard to be measured. In contrast to [m2] however which gives only indirectly the difference in frequency between the f-components between the two lasers, here the f-f difference can be directly measured by the use of an AOM (Acousto-optic modulator). The AOM is used to shift the frequency of one laser by a given amount, typically by a few 10 MHz.

The time-consuming procedure of frequent relocking of both lasers is avoided and even long-term measurements are possible. The frequency difference of two nominally equal components is measured in this technique. By shifting a frequency with the AOM one avoids the zero-crossing problem discussed above. To know the actual introduced frequency shift, one must take care to use the correct diffraction order and sign.

Beside the items common to all methods as discussed under general requirements, following facts must be known and documented:

- Additional uncertainty contributions caused by reference laser (calibration, drift, working parameters).
- Uncertainty of the AOM driver frequency.

**[m4] Other calibration methods**

Other methods to measure a laser frequency are conceivable which do not fit well in one of the above categories and which were not used to date in this comparison. This designation [m4] is essentially a place holder for future use.

## Appendix F Historical note

The BIPM.L-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 metre according to the method (c) in what was called the Mise en Pratique (MeP, refers to the document "Practical realization of the definition of the metre" [9]). Such a comparison seemed of particular importance since the whole field of dimensional metrology had to be traceable to such realizations of the metre. The BIPM.L-K10 comparison took only the 633 nm He-Ne standards into consideration. The measurand of the comparison was the difference of the average frequency of the hyperfine components d, e, f, and g in the R(127) 11-5 line as obtained by matrix measurements. The frequency of the reference laser BIPM-P3 was used as the key comparison reference value, representing the value recommended in the MeP.

The situation for realization of the SI-metre has changed due to the introduction of new techniques for absolute optical frequency measurements. This has opened up the alternative method (b) in the MeP to realize a frequency/wavelength standard traceable to the SI-second [10]. The practical consequences of this development are that at least two methods are at the moment being used to realize the metre, and that standards of different wavelengths, important for dimensional metrology applications, can now demonstrate traceability with relative ease. Considering these circumstances, the 11$^{th}$ CCL meeting, which was held in October 2003 at the BIPM decided to close the K10 comparison and initiate a new key comparison named BIPM.L-K11 [1]. First measurements in BIPM.L-K11 were made at the BIPM in May 2004. Results from BIPM.L-K10 and BIPM.L-K11 can be found at http://kcdb.bipm.org.

Subsequently, the CIPM has decided, that the comb-related work, which used to provide external services, should stop at the BIPM at the end of 2006. This decision had direct implications on the activity which supported the BIPM.L-K11 that consequently were closed down at the end of year 2006. A proposal for a new scheme for the comparison, based on a group of node-laboratories in the different RMOs and piloted by the Bundesamt für Eich- und Vermessungswesen (BEV, Austria) was therefore made. This proposal, which had been agreed on by the President of the CCL, was given support by the CIPM at its 95$^{th}$ meeting and was endorsed by the 13$^{th}$ meeting of CCL in September 2007 [12]. The technical protocol (this document, available from the BIPM web page) defines the procedures to follow in this new comparison, now transferred to the CCL, and named CCL-K11.

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